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MONITORING THE URBAN HEAT ISLAND EFFECT IN BAGHDAD USING SENTINEL-3 AND OSM DATA INTEGRATION FOR SUSTAINABLE URBAN PLANNING

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The rapid expansion of urban areas has accelerated the urban heat island (UHI) phenomenon, exacerbated by climate change's effects. Therefore, the long-term sustainability of the urban regions faces a severe challenge. The study investigates the magnitude of the UHI phenomenon in Baghdad using Land Surface Temperature (LST) data acquired from the Sentinel-3 satellite and OpenStreetMap (OSM) urban infrastructure data. This study examines the changes in the UHI between 2016 and 2023. It tends to determine the spatial distribution of UHI concerning different cities and investigate the relationship between the effects of urban development and the magnitude of UHI. In this regard, the data indicated that the magnitude of UHI increased significantly during the measured period. The mean temperature rise has reached 1.34°C throughout the city, with a particularly significant increase of 2.6°C in the highly populated regions inside the municipality boundaries. An empirical investigation reveals a strong positive correlation between building density (0.89) and road density (0.823) with the intensity of the UHI. Conversely, the green areas display a moderate negative correlation (-0.56) linked to the UHI intensity. The results illustrate the substantial impact of urban infrastructure development on the UHI, defined by remarkably high UHI coefficients in heavily populated areas. Thus, the study results will provide valuable policy suggestions that will significantly help the relevant policymakers and urban planners in their efforts to enhance urban resilience and public health in Baghdad. It is also a systematic and organized approach that can be applied in other rapidly urbanizing areas.

Keywords: urban heat island (UHI), land surface temperature (LST), OpenStreetMap (OSM), sustainable urban planning, remote sensing and GIS

1 INTRODUCTION

Urban Heat Island (UHI) is defined by the significantly elevated temperature of urban areas compared to their rural environments [1]. This effect is predominantly caused by urbanization, which has been found to raise the temperature contrast between urban and rural areas by absorbing and retaining heat using large impervious surfaces such as concrete and asphalt. This is due to the decrease in vegetation cover, the increase in heat caused by human activities, and the presence of impervious surfaces, among other reasons that have led to the temperature of cities being higher than in rural areas [2]. The intensification of UHI effects is caused by rapid urbanization and industrialization; hence, this has had a significant impact on both urban residents and ecosystems [3]. The study of UHI is important because, in most cities, the central business district is warmer than the remote areas. According to Tang [4], UHI greatly affects every densely populated area, where social-economic activities and human transformations are the main drivers that cause temperature rise. For example, in cities such as Shanghai in China, the UHI effect is linked with heat waves, which cause adverse health effects on residents of the area concerned [5].

Some recent works have employed remote sensing and GIS techniques to assess the spatial-temporal variation and analyze UHIs at global and regional scales. For example, by remote sensing through satellite image(s) in the thermal infrared spectrum, surface temperature can be tracked along with land-use/land-cover changes that are very important in understanding UHI and its underlying causes [6]. Some of the key drivers of UHI, as identified through these technologies, are impervious surface areas, vegetation cover, landscape layout, albedo, and climate-all critical in determining the pattern of UHI [7].

Sentinel-3, among other remote sensing technologies, is necessary for monitoring the environment since it provides data for monitoring various ecological and environmental parameters. Based on satellite imagery, thermal bands, and many other sensors, these technologies produce data on environmental indicators concerning vegetation health, land cover, land surface temperature, etc [8]. Remote sensing data analysis allows the monitoring and mapping of ecosystem change, locates where environmental degradation occurs, and provides a basis to evaluate various impacts of human activities on the environment [9].

Geographic Information Systems (GIS) represents the primary key to the spatial analysis approach, and it provides the means for integrating, analyzing, and visualizing this geospatial data concerned with land cover/land use and land surface temperature change, among many other environmental parameters. Further, in urban areas, using technologies such as remote sensing and GIS will allow the mapping of heat islands and heat island patches, hence assessing their dynamics spatially and temporally [10]. Geostatistical analysis and spatial modelling permit the quantification of the intensities of UHI, the assessment of the relationship between land surface temperatures and land cover type, and the description of future trends of UHI formation [11].

Numerous studies have analyzed the utility of remote sensing and GIS in studying and monitoring UHI in many places worldwide. Recently, some research has been conducted to identify the causative factors of UHI, consider the effect of artificial patterns on temperatures, and develop planning strategies to reduce heat island effects by considering urban and green infrastructure systems [12]. Remote sensing and GIS technologies have been effectively utilized in vital areas, such as the spatial and temporal patterns of UHIs, the importance of vegetation in reducing heat island effects and determining planning priorities for green infrastructure [13].

Rapid urban expansion and climate change conditions in Baghdad highlight the need to consider the UHI phenomenon. The dynamics of the UHI in Baghdad may provide an understanding that can support urban planners and policymakers in taking appropriate interventions to reduce this aspect's negative impact on urban livability and public health [14]. Therefore, mapping the spatial and temporal variations of Baghdad's UHI allows for identifying hotspots and susceptible areas that will be targeted concerning prioritization; immediate remedial actions will be taken to avoid heat-related illnesses and discomfort among the population [15]. Moreover, investigating the relationship between urban development, land use changes, and UHI intensity in Baghdad can provide valuable insights for sustainable urban growth and climate resilience strategies [16].

The current study developed and applied a new methodological approach by integrating high-resolution Sentinel-3 satellite data with the detailed OpenStreetMap urban infrastructure data, allowing for an accurate determination of UHI dynamics across Baghdad. This provides important insights into how various urban planning elements interact, such as road and building densities, green spaces, and their impact on UHI intensity. Unlike most studies of the past that are static in UHI, this investigation carried out a temporal analysis between 2016 and 2023. It indicates that rapid urban development brought a significant increase in the intensity of UHI over time through dynamic representation of urban temperature patterns. It also discussed practical actions that can be recommended to urban planners and decision-makers in developing effective strategies for mitigating UHI effects, enhancing urban sustainability, and improving public health in Baghdad. Besides, such a methodological approach may be applied to other cities with similar challenges, which promises valuable inputs and practical solutions in urban planning and policy development for such cities.

2 MATERIALS AND METHOD

2.1 Study area

Baghdad is located at 33°13′ N latitude, 44°13′ E longitude, and 34 meters altitude. The urban activities are mainly concentrated in the city Centre (within the municipality border), as shown in Fig. 1 [17, 18]. With a population of over 8 million, Baghdad is vulnerable to urbanization and climate change. The city has severe temperatures and hot summers [19]. Urban expansion and climate change are the two major contributing elements to UHIs [14, 15, 20]. The studies found that rapid urban sprawl increased the surface temperatures in Baghdad, thus increasing daytime and nighttime UHIs [15]. Factors contributing to the creation of surface temperatures in Baghdad include land use change through reduced vegetation cover and change of natural land use to impervious surfaces [21].

Population growth, increased energy use, waste accumulation, and transportation congestion are some of the variables that amplify the impact of urban expansion on climate change in Baghdad [22]. Green open spaces have been identified under the City Master Plans as valuable in modifying climatic effects that would improve the local environment, aesthetics, and quality of life in the urban area [23]. Moreover, urban expansion in Baghdad has significantly enhanced the degradation of natural vegetation, directly leading to higher temperatures [24].

Some previous studies applied GIS and remote sensing to monitor urban development, assess water quality, and investigate bioclimatic indices in Baghdad [25-27]. While remote sensing and GIS have contributed significantly to sustainable urban development and environmental policy [28], there has been a lacked geographical distribution of UHIs. Spatial evaluation of UHI is essential because it will determine the long-term sustainability of the larger city. In turn, heat patterns and their causes may be selected to improve strategies or measures to reduce the impacts of the urban heat index and ensure a more resilient urban environment over time for Baghdad.

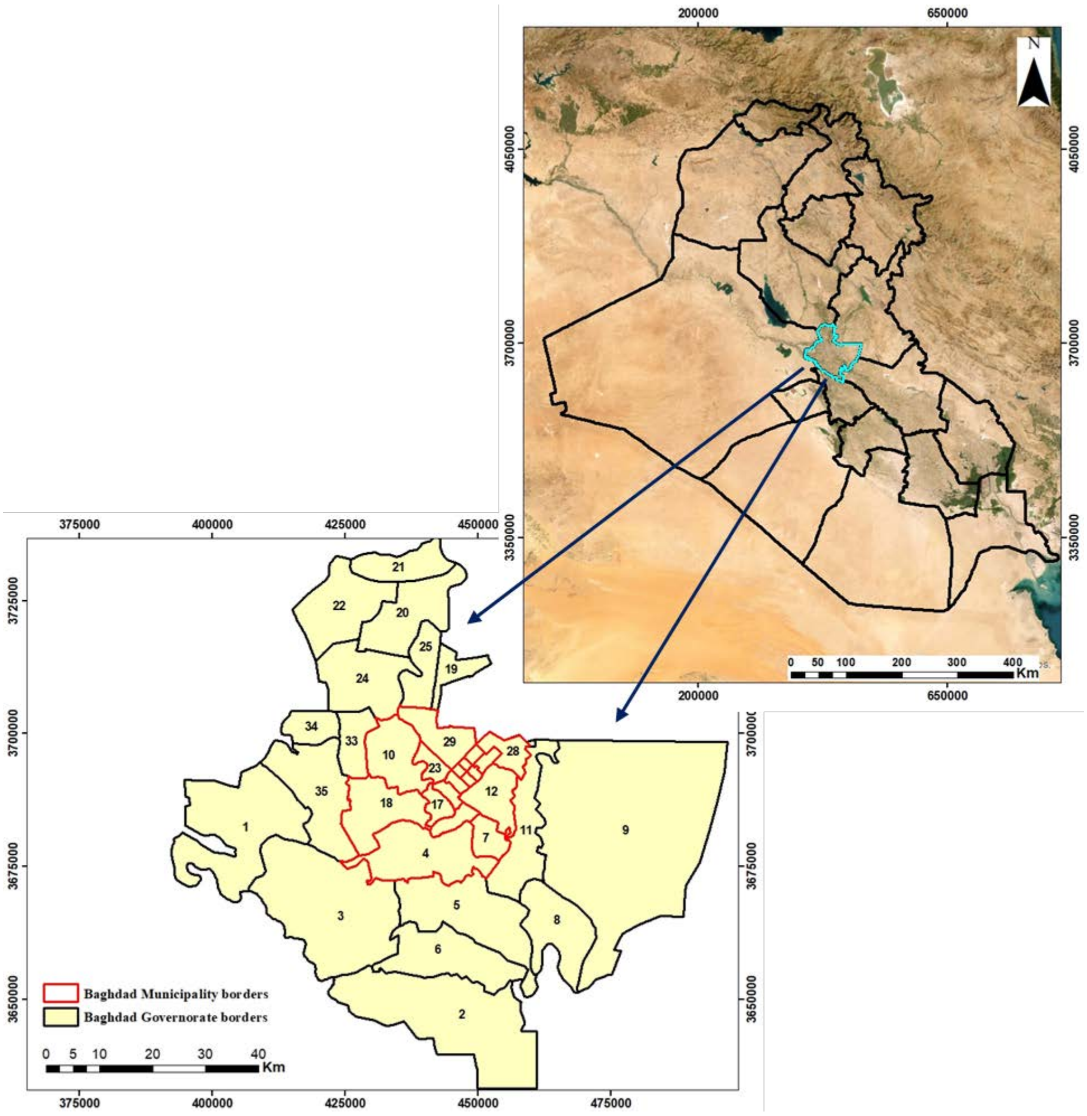

Fig. 1. Geographic location and urban extent of Baghdad Governorate

2.2 Data

The Sea and Land Surface Temperature Radiometer (SLSTR) is one of the instruments carried on the Copernicus Sentinel-3 mission and is designed for a wide range of applications covered under Earth observation. SLSTR shows critical information concerning the measurement of land surface temperature (LST) [29]. Several thermal infrared bands are carried by SLSTR, which enables the retrieval of LST, one of the most important parameters in climate monitoring and environmental studies [30]. The Sentinel-3 mission is designed to have a dual-view capability in SLSTR. It captures near-nadir and oblique observations that will allow for proper atmospheric corrections, further enhancing LST retrievals [30-32]. The SLSTR provides a spatial resolution of 1 km in the thermal infrared bands and a swath width of 1,400 km, thus allowing comprehensive coverage with significant detail on the Earth's surface. Moreover, it enables frequent acquisitions over the globe in one to two days, which would be advantageous in environmental monitoring and climate studies by tracking changes in LST over time [33]. Advanced processes of calibration and validation increase the SLSTR reliability for applications such as assessment of urban heat islands, monitoring of droughts, and health analysis of vegetation [34, 35].

Sentinel-3A and B satellites pass over the Baghdad Region around 6:00 to 8:00 a.m. in the daytime and 6:00 to 8:00 p.m. in the nighttime. Generally, urban surfaces during the daytime absorb sunlight and retain heat, while at night, that heat dissipates. However, due to differences in how materials retain heat, urban objects like concrete and asphalt lose heat much more slowly than rural areas or green spaces, creating a constant temperature difference. This difference allows the nighttime LST data to measure the UHI effect more accurately, showing the residual heat in urban areas after sunset [36]. Thus, this makes nighttime imagery more appropriate for UHI assessments than daytime data, in which solar heating and temporary heat emissions from anthropogenic activities (e.g., traffic, industry) can obscure the analysis.

In this study, two nighttime Sentinel-3 images were selected, one from 2 July 2016 and another from 2 July 2023. While Sentinel-3 nighttime images are acquired between 6:00 and 8:00 PM, which coincides with sunset in Baghdad (around 7:09 PM in July 2016 and 7:10 PM in July 2023), urban surfaces remain significantly warmer than rural areas due to their higher thermal inertia. Research suggests that even early nighttime data can adequately capture the thermal characteristics of urban areas, which facilitates accurate UHI assessments [37, 38]. Rural areas start cooling immediately after sunset, while urban surfaces remain warmer for some time because of their higher thermal inertia, thereby maintaining a distinct temperature contrast. Studies based on MODIS and Landsat data have proven that urban-rural temperature differences are significant soon after sunset, reinforcing the importance of capturing this difference for UHI studies [39, 40]. Although Sentinel-3 data were acquired before the full nighttime cooling phase, delayed heat influx from urban areas guarantees that temperature differences will remain detectable.

The Sentinel-3 images were used to perform a temporal analysis and examine changes in UHI in relation to urban development patterns. After downloading the images, they were corrected using the Sentinel Toolbox within the Sentinel Application Platform (SNAP) software, version 9.0.0. The nighttime LST for both dates was then retrieved for Baghdad. These LST images were subsequently exported in Geotiff format to ArcGIS software, version 10.4.1, for further analysis. Then, in ArcGIS, we integrated OpenStreetMap data with the LST images to enhance the analysis.

2.3 Methodology

The applied methodology in this study is presented in Fig.2. In this study, Sentinel-3 LST products are used to investigate spatial distribution and the intensity of the UHI effect in Baghdad. Pre-processing of Sentinel-3 LST images has been done with major steps to guarantee data accuracy. First, the subset of the images was done using SNAP to be limited to the area of interest within the Baghdad region. The images have been reprojected into UTM Zone 38N to match the Open Street Map infrastructure data layers over Baghdad city. This reprojection ensures that the LST data matches the OSM layers in space.

The intensity of UHI was assessed based on some reference points outside the city limits that had very few or no artificial structures; hence, their natural temperatures were low. The values of the LST in urban zones were subtracted from the average temperature from those reference points to determine the magnitude of the UHI effect [41, 42]. The UHI images were then exported to ArcGIS software for further analysis.

The main infrastructure layers in OSM were used to segment Baghdad into zones (Fig.1). Major roads and urban districts formed the absolute physical base in the zone boundary, and each zone consisted of a mix of residential, commercial, and industrial land uses. The segmentation was done to capture the variety in each zone regarding the density of buildings, road networks, and green spaces.

Building density for each zone was calculated based on OSM vector data which represents the current urban setting. OSM has been acknowledged to offer global coverage and instantaneous information in which volunteer contributions ensure data validity, even in fast-developing areas[43, 44]. Through this collaborative methodology, accurate updates can be made, making OSM a highly reliable source for any type of urban studies[45]. Detailed building footprint data within each zone were used to quantify urbanization effects on UHI. The total built-up area was extracted using ArcGIS by taking the sum of the area of all building polygons in square kilometers (km²). Building density was calculated as a ratio of the built-up area over the total land area of the particular zone such as follows:

$$The\ building\ density\ (\%) = \frac{Total\ Built\ up\ area\ (km^2)}{Total\ Zone\ Area\ (km^2)} x(100) \quad (1)$$

The areas of green spaces such as farms, meadows, orchards, grass, and greenery were estimated to give an idea about the distribution and magnitude of areas with green spaces in different zones, considering the share of the green spaces in each zone in relation to the total area of the specific zone. This analysis reflects the current state of urban greenery, as it is based on OpenStreetMap (OSM) data, which is constantly updated through global contributions. Therefore, the green-space ratio for each zone represents the sum of the areas of the green spaces within the zone, divided by the total area of the zone, as follows:

$$Green\ Space\ Ratio\ (\%) = \frac{Area\ of\ Green\ Spaces\ (km^2)}{Total\ Zone\ Area\ (km^2)} x(100) \quad (2)$$

Road density was calculated for each zone to assess the influence of roads on UHI. It is defined as the length of all roads in the unit area of each specified zone divided by the overall area of that zone. This categorization has helped quantify the contribution of road infrastructure to the UHI effect. Given that OSM is constantly updated to reflect existing situations, using OpenStreetMap data ensures that this analysis will reflect the existing road network.

$$Density\ of\ Roads = \frac{Total\ length\ of\ roads\ (km)}{Total\ Zone\ Area\ (km^2)} \quad (3)$$

Before conducting statistical analysis between UHI and other variables (building density ratio, green space ratio, and road density), zonal statistics were performed using ArcGIS to obtain the mean UHI values for each zone. This provided a summary measure of UHI for each segmented area. Subsequently, Pearson correlation analysis was conducted to determine the relationships between UHI intensity and urban infrastructure variables, such as building density, road density, and green space ratio. A significance level of $p < 0.05$ was used to assess the statistical validity of the correlations.

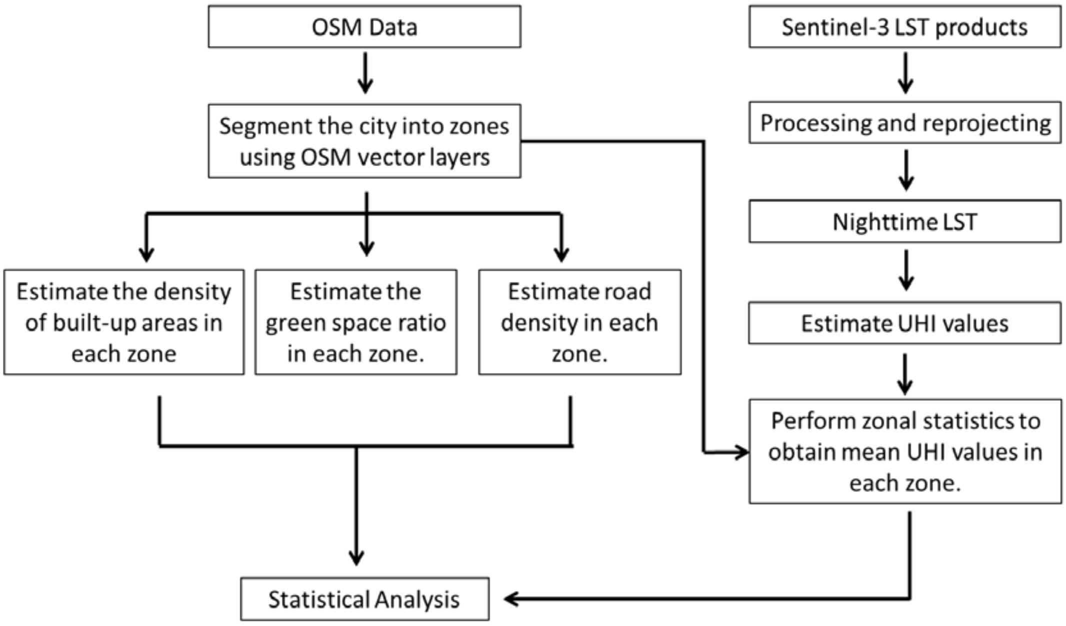

Fig. 2. Methodological Workflow for UHI Assessment

Integration of Sentinel-3 LST data with Open Street Map vector data allows an in-depth spatial analysis of urban infrastructure with respect to temperature patterns. This technique provides a new light on the relationship between UHI intensity and other planning parameters in different zones, demonstrating its versatility for urban sustainability research.

3 RESULTS AND DISCUSSION

3.1 Land use classification in Baghdad city

Based on data from OSM, the following land use distribution in Baghdad city has high information value about the urban structure and its contribution to the UHI effect. Five main land uses dominate Baghdad city: residential, commercial, industrial, green spaces, and infrastructure/construction surfaces, as shown in Fig.3.

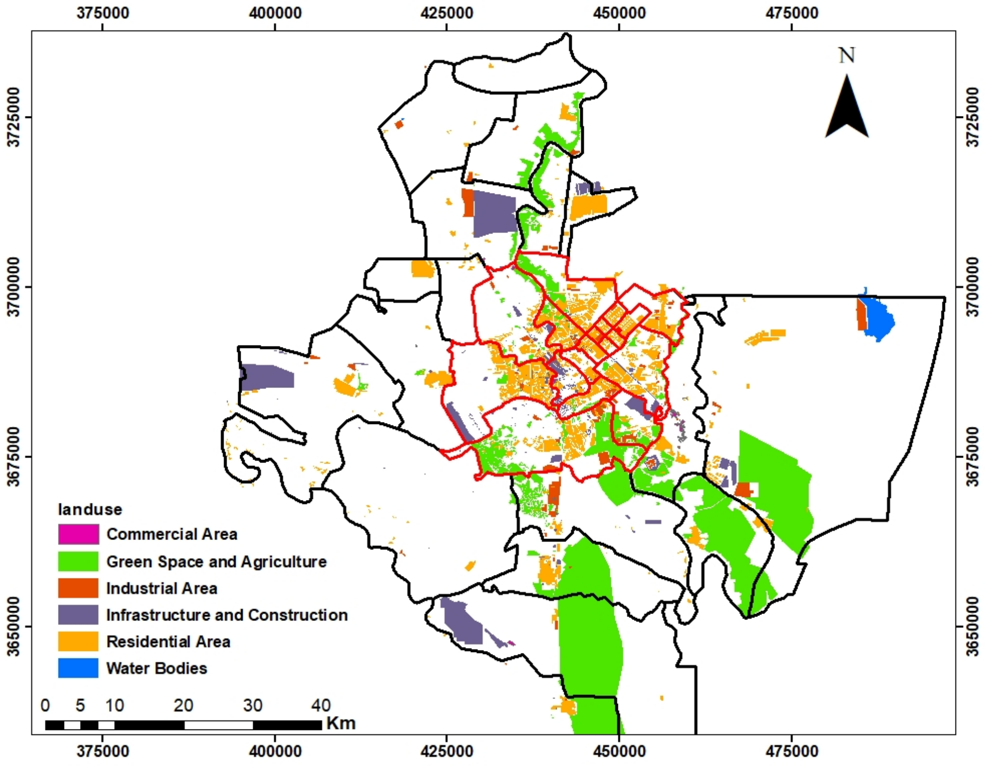

Fig. 3. Land use classification map of Baghdad City

Residential areas are concentrated within the municipality border, with most of the green spaces outside, and therefore pose a considerable challenge and opportunity in urban planning. The highly concentrated residential zones within the city contribute to the heat island issue since high building and infrastructure concentration in an area tends to trap heat. This effect is enhanced by limiting green spaces throughout the municipality, which constrains the natural cooling effect of vegetation. This causes the core area to be hotter than the outskirts of the urban area, which tends to be cooler due to the greater prevalence of green spaces.

The other land use classes, such as commercial, industrial, infrastructure, and water bodies, play an essential role in configuring Baghdad's urban environment. Commercial and industrial areas are relatively small compared to the total area but are likely to be dispersed throughout the city; hence, they contribute to the localized heat due to high activity levels and energy use. Infrastructures and construction areas are highly dispersed in the municipality, which can be considered as the continuous development and extension of the city. Even though these places were to be used for urban development purposes, they tend to replace green spaces, which could worsen UHI. The difficulty is mainly related to the balancing development of infrastructures with the need for green spaces to make the urban environment sustainable. In general, this distribution of land use classes indicates a very complex urban environment in Baghdad, whereby the different classes of land use are highly concentrated inside and outside the municipality border, thereby highly influencing the city's microclimate and quality of life.

3.2 Road network map

The road network in Baghdad city, especially within the municipality borders, is highly concentrated with roads, particularly residential ones, compared to areas that extend to the governorate borders (Fig. 4). This indicates that the urban core of Baghdad has a very high density of streets within its municipality boundary, showing the dense population and increased urban development in the area. It likely supports the residents' daily mobility needs to access residential areas, commercial centers, and essential services.

This effect is reversed once outside municipality borders, where the road network significantly thins, showing a transition from urban to more rural. The less-dense network heightens the expectation of lower intensities of development, probably larger, less frequent road types that connect distant localities rather than service densely residential neighborhoods. The bringing of road concentration within the municipality underpins the urban-centric development pattern of Baghdad, which is highly concentrated on infrastructure investments in the city core as a supporting role of its major functions for economic, social, and political activities.

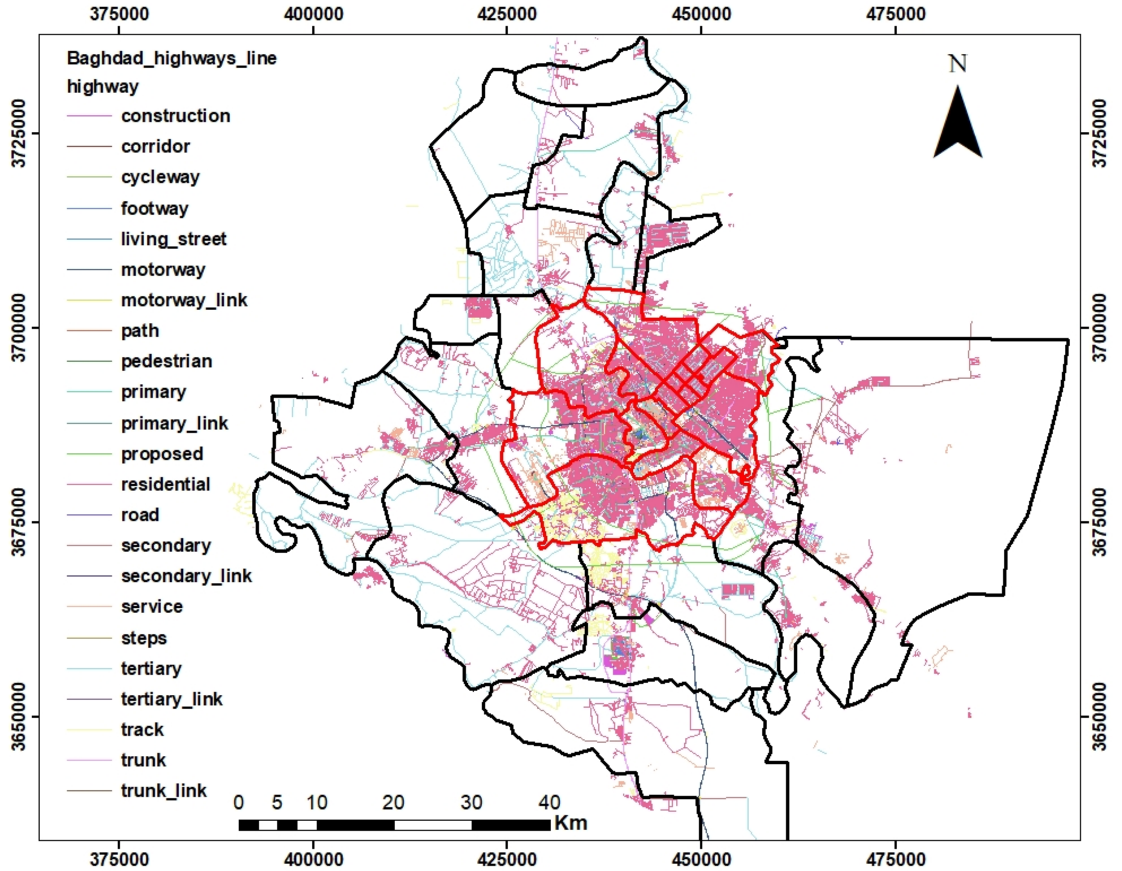

Fig. 4. Road network distribution in Baghdad City

3.3 UHI Intensity and distribution

After dividing the study area into several zones using Open Street Map vector layers, the mean UHI for each zone was calculated from Sentinel-3 UHI images in ArcGIS using the zonal statistics tool, as illustrated in Fig. 5. The UHI intensity maps illustrate clear patterns across Baghdad and hotspots in certain areas. Remarkably, it is noticed that the zones, which are confined within the heart of the urban center, show outstandingly high values of UHI, indicating strong heat retention. Contrasting that, the rural zones on the city's outskirts present lower UHI values. Such UHI intensity differences outline the effect of different urban densities and types of land use: higher temperatures were found in more central areas because of high infrastructure concentration and very scarce green spaces. More vegetation and open spaces regained lower temperatures in rural zones. Higher UHI values have clustered in central urban areas dominated by high-density residential and commercial classes. This provides little green space to cool down the environmental temperature, though a high concentration of buildings, roads, and infrastructure usually dominates it. The dense network of roads within the municipality's borders, especially the residential and commercial areas, contributes significantly to the trapping of heat and, hence, the higher values of UHI in these regions. In contrast, outskirt areas with abundant green space and less intensive land use display lower values of the UHI.

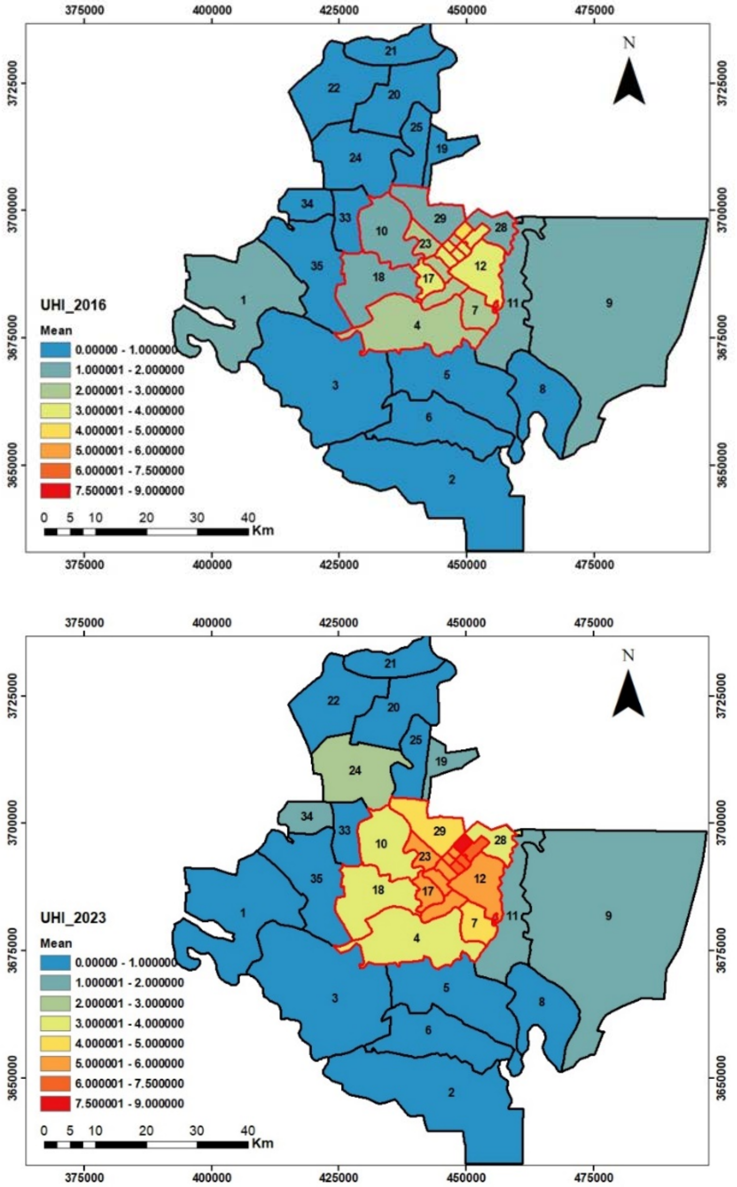

Fig. 5. Urban Heat Island (UHI) intensity maps of Baghdad City for the years (2016 and 2023)

3.4 Correlation between urban infrastructure and UHI

The zoning of Baghdad facilitates the distribution analysis of urban infrastructure and its effect on the Urban Heat Islands UHI. The zone definition allows a practical study to be carried out on the influence of building density, road networks, and green spaces on local temperature variations. The analysis utilizes OpenStreetMap (OSM) data, an up-to-date source that reflects current land use, and it focuses on the 2023 UHI image to confirm that results reflect the present conditions of the city. The UHI patterns of 2016 can be used as a baseline for historical reference;

however, OSM data reflects land use in the most recent period and, therefore, is more appropriate for giving context to the current land relationship between urban infrastructure and UHI. Because land use and urbanization have changed significantly between 2016 and the present, applying OSM land use data to analyze UHI patterns from 2016 will not provide a valid picture of what existed at that time. This methodology aligns UHI analysis with the latest urban features, thus clarifying how present-day infrastructure contributes to UHI, making feasible area-specific mitigation design recommendations for different zones within Baghdad.

3.4.1 Influence of building density on UHI intensity

The urban density in a polygon is calculated as the ratio between the area covered by buildings and the total area of the polygon. It measures the proportion of area utilized for urban purposes and reflects the intensity of land use. Urban density is an indication measure that has been considered essential for the proxy understanding of the pattern of UHI as an indication of the level of urbanization in an area. This clearly shows how much of the land is covered by building structures- a good indicator of how urbanization affects local climate patterns.

As shown in Fig. 6, the significant positive correlation strongly demonstrates the dependence of building density on the UHI, with a correlation coefficient of +0.89. This high correlation value reflects that with an increase in building density, the intensity ascertained by UHI consistently increases, underlining strong urbanization influence on local temperature patterns. Higher building densities come with more impervious surfaces that absorb and retain more heat than natural landscapes. Therefore, these areas usually record higher temperatures than other regions, exacerbated by the reduced air circulation that traps heat. The strong correlation of +0.89 confirms the strong association between building density and UHI intensity, underscoring the important role of densely built environments in driving local temperature increases. Clearly, this relationship illustrates well that urbanization, especially in a highly built-up form, is one of the major causes of the origin and development of UHIs.

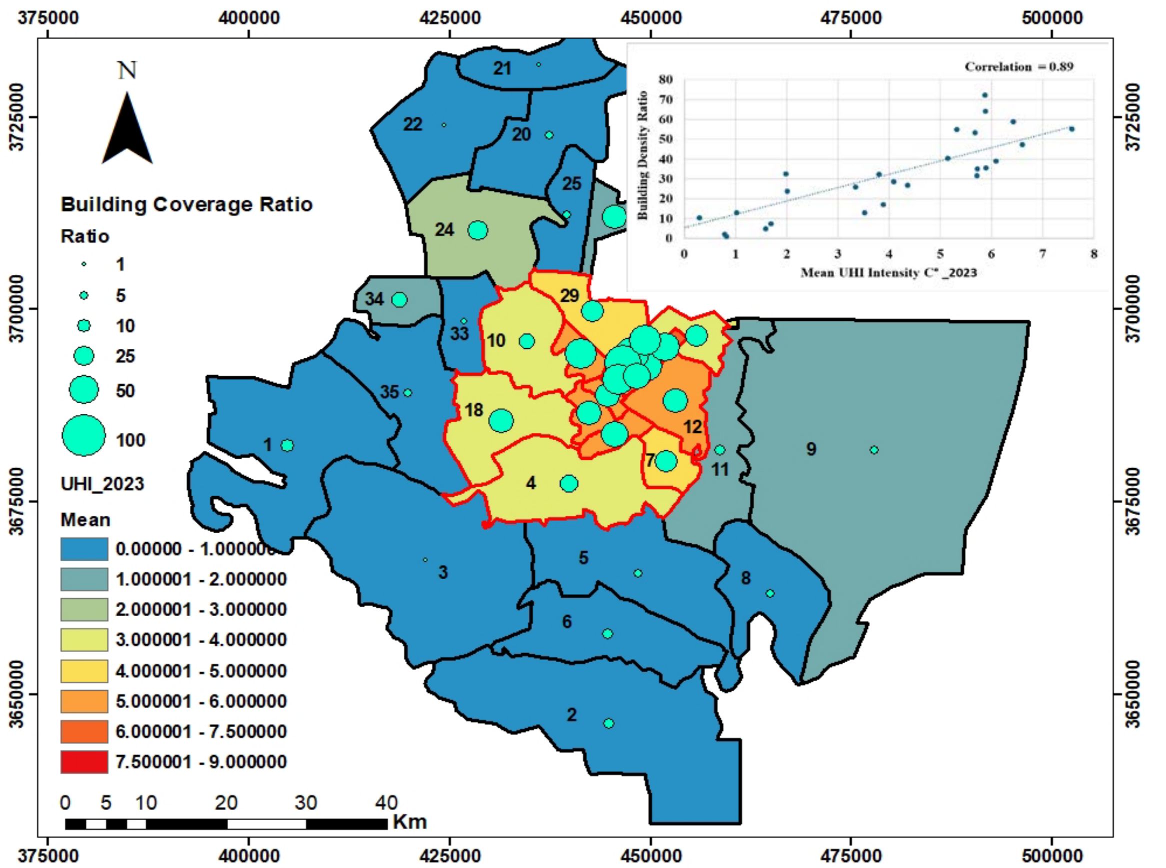

Fig. 6. Correlation and distribution map showing the relationship between building density and UHI intensity in Baghdad City

3.4.2 Role of green spaces in modulating UHI

This study focused only on green spaces and road density within municipality boundaries since the UHI intensities are already observed to be lower in rural areas (Fig.5 and 6). The most practical reason for this is that urban areas have denser infrastructure and fewer green spaces, making them particularly vulnerable to high temperatures. Therefore, narrowing the scope of the study to an urban area allowed to address the most urban-affected areas of the UHI, where introducing more green spaces would be effective.

Estimating the ratio of green spaces in a polygon involves determining the area covered by green spaces like parks, agricultural land, meadows, orchards, grasslands, and greenery and then dividing it with the overall area of the polygon. This ratio is expressed as a percentage, indicating the proportion of land occupied by green spaces. Understanding this scale is critical to assessing the role of vegetation in mitigating UHI effects.

Green space is the most influential factor in mitigating UHI impacts. Vegetation in the urban area will cool the surrounding temperatures through evapotranspiration and shading. While impervious surfaces absorb and retain heat, the green spaces release air moisture into the atmosphere, further cooling the air and lowering ambient temperatures within the locality. Fig. 7a and c show that higher green space ratios tend to lower UHI intensities, which underlines the effectiveness of green spaces in moderating urban temperatures and improving thermal comfort. This is further supported by the fact that the green space ratio and UHI intensity correlation stand at -0.56, meaning there is a moderate inverse relation: with an increase in green space, there is a decrease in UHI intensity and vice versa.

3.4.3 Impact of road networks on UHI

Road density, defined as the total length of roads per unit area within each zone, has been calculated and is accompanied by UHI values that reflect the degree of temperature anomalies or heat accumulation in these areas. An analysis of road density and the UHI relationship reveals a strong positive correlation of approximately 0.823 (Fig. 7 b and c). This significant correlation indicated that those zones with higher road densities may exert a more intensive UHI effect. These findings have important implications for urban planning, showing that consideration must be released on the impact of road infrastructure on the pattern of urban heating.

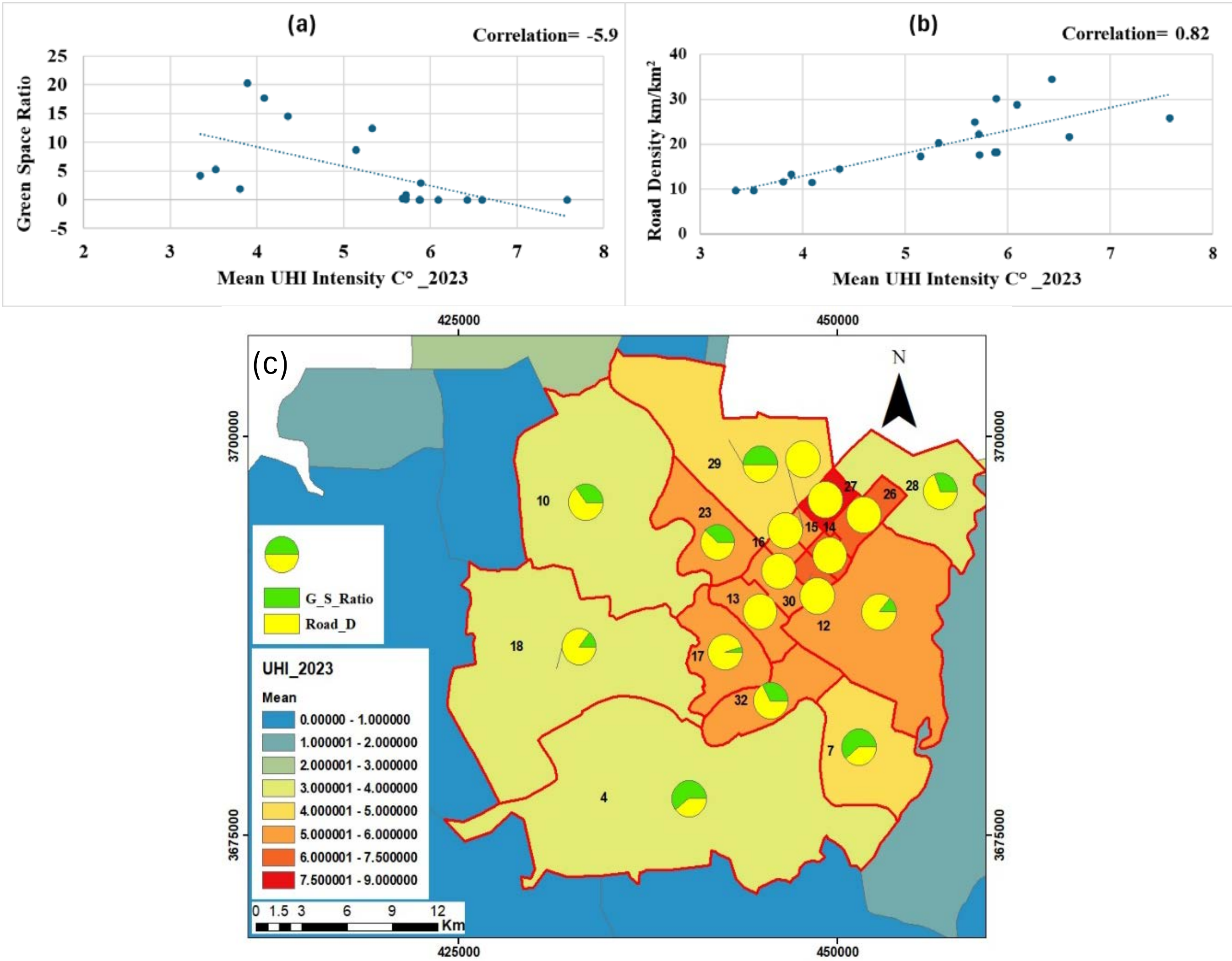

Fig. 7. The influence of green space and road density on Urban Heat Island (UHI) intensity in Baghdad City. (a) The relationship between green space and UHI intensity. (b) The relationship between road density and UHI intensity. (c) A distribution map displaying the spatial effects of green space and road density on UHI intensity across the city

3.5 Temporal changes in UHI

The UHI observations for Baghdad from 2016 to 2023 (shown in Fig. 5) depict a significant increase in the UHI of the majority of the city. During this period, the average change in UHI across all assessed regions is an increase of about 1.34°C. More specifically, zones within the municipality boundaries show a stronger rise, with the average UHI rising by 2.6°C, indicating the effects of rapid urban expansion and land transformation in recent years.

However, some areas showed different patterns. Zone 1, for example, shows a decrease in the intensity of the UHI values, falling from 1.15°C in 2016 to 0.30°C in 2023. This contrasts with the overall upward trend and suggests that local factors, for instance, land use change, potential increase in green space, or infrastructure development, all contributed to the local cooling. This phenomenon supports previous findings that while urbanization overall amplifies the impacts of UHI, rural areas expose a cooling trend due to the increased vegetation cover, lower population density, or land management practices that retain less heat [14, 46].

More evidence indicates that the cities of Baghdad suffer the most from urban heat due to the growth of dense infrastructure and the reduction of green spaces. Some rural and peri-urban areas might show declining trends for urban temperatures because of environmental planning and microclimate regulation[47, 48], but this local decline within zone 1 indicates how spatial variation in land use and urban planning can drive urban temperature trends, thus highlighting the need for specific mitigation strategies to manage the temperature disparity between the different regions of the city.

3.6 Implications for urban planning

3.6.1 Urban design and planning considerations

Increased Urban Heat Island Intensity from 2016 to 2023 reflects critical urban design and planning concerns. Rapid urbanization has exacerbated UHI by expanding developed areas and shrinking natural space, mainly in the most populated regions. The current scenario calls for re-evaluating urban planning strategies to harmonize environmental sustainability with economic and social development. Urban planners need to implement appropriate measures to balance population and economic growth with the environmental implications of urban sprawl. Coherent development strategies must be incorporated to match economic growth with social welfare and ecological conservation in sustainable urban planning, especially at the urban-rural boundary [49].

3.6.2 Policy implications and recommendations

Public authorities should pay more attention to park and green territory design and conservation in cities, including green infrastructure, as the core of development policies within urban areas. Such measures may be exemplified by extending parklands, encouraging green roofs, and preserving natural landscapes to mitigate the heat retention effect from a heavily built-up environment [50-52]. In addition, urban road network development should incorporate a UHI effect mitigation strategy. This could include reflectivity and permeable materials on the surface of the roads and tree-lined streets with shade to decrease the surface temperature. Some studies show that street geometry and material changes could reduce UHI in cities [53, 54]. Other strategies could be compact and mixed-use developments that minimize impervious surface area. Each will reduce large road network demands, thereby mitigating UHI.

These urban planning strategies can only be actively implemented by coordination and cooperation among policymakers and planners. Policymakers should establish incentives to encourage green infrastructure integration into urban development projects [55]. These can involve tax breaks or grants to those initiatives that include green roofs, urban parks, and permeable construction materials. Additionally, regulations should be implemented to limit urban expansion and require new areas to contain sufficient green spaces, emphasizing sustainable land use practices that balance urban growth and environmental protection. This requires reorganizing urban development to limit or at least reduce the negative impacts of urban expansion and ensure sustainable urban growth [56]. Public awareness campaigns are also being promoted to support them educating residents about the benefits of green infrastructure and energy-efficient practices which can ensure community support for strategies to mitigate the effects of UHI.

3.7 Mitigation strategies

3.7.1 Enhancing urban greenery and reflective materials

Increased greening of the urban environment by parks, gardens, and even green roofs is crucial for mitigating the Urban Heat Island effect through decreasing surface and air temperatures, especially in any part of the city with a greater population and thus more excellent heat retention. Moreover, using reflective materials on building and road surfaces will significantly reduce ambient temperatures by reducing heat absorption [57]. This is effective in highly built-up surface areas, such as along main roads [58]. Land use contexts make these varied approaches differ in efficiency. For instance, while increased vegetation provides cooling efficiency in residential areas, using reflective materials may serve better in commercial and industrial zones where space is often limited.

3.7.2 Promoting energy-efficient practices

Encourage energy-efficient building materials and designs, like reflective roofing and improved insulation, which can reduce air conditioning demands, thus lowering overall heat emissions [59]. Reflective roofing materials used in cool roofs manage to reflect more sunlight without much heat absorption. In effect, they significantly reduce cooling demand in buildings by at least improving insulation that minimizes heat transfer, reducing overall energy consumption in cooling.

Beyond mitigating UHI, these energy-efficient practices are most likely to reduce greenhouse gas emissions, lower household energy costs, and improve indoor comfort for the residents [60]. Such practices will be paramount in making the urban environment sustainable through the reduction of environmental impact from buildings while offering a better quality of life with comfortable indoor temperatures in a world with lower utility costs. The incorporation of energy-efficient strategies into the processes of urban planning is an essential consideration for addressing long-term sustainability goals [61].

3.7.3 Strategies for rural conservation and sustainable development

Protecting natural landscapes in rural areas is very important for ecological balance and the support of biodiversity. Nature conservation areas provide the critical function of preservation of local climates in these places, which may mitigate the extension of UHI effects to their regions [62]. Enhancing environmentally friendly rural development while using sustainable agriculture and land use practices to manage pressures due to urban growth is also necessary. This must be accomplished by carefully preserving natural habitats and reducing environmental impacts from infrastructure development in road network planning [63, 64]. While urban areas are expanding further, it is crucial to seek a balance between their growth and the preservation of natural landscapes. This will involve infrastructure planning that does not overburden rural areas with unimportant projects and steps to ensure that urbanization is not carried out at the cost of environmental sustainability [65].

4 CONCLUSIONS

The current study considers the UHI effect in Baghdad, confirming the predominant role of urbanization in enhancing temperature at a local scale. Integrating data from the Sentinel-3 satellite on LST with the information on urban infrastructure from OSM made it possible to map UHI's spatial and temporal dynamics within Baghdad's urban areas between 2016 and 2023. Results indicated that higher building and traffic density are associated with the positive intensity of the UHI urban heat island while the green area is vice versa. Specifically, high building and road densities magnify the intensity of urban heat islands. In contrast, a decrease in the area of greenery would enhance the UHI. Over seven years, the considerable increase in UHI intensity points to rapid urbanization's impact on the city's microclimate.

The study highlights the necessity of incorporating sustainable urban planning approaches that focus on maintaining and extending green spaces and incorporating reflective materials into the construction of urban amenities as a viable measure for attenuation of UHI effects. The results of this study are appropriate for urban planners and decision-makers within Baghdad because they present useful, applicable knowledge for enhancing urban resilience and promoting public health. Furthermore, the methodology developed in this research might be easily adapted for other cities with similar challenges and thus further contribute to a broader discussion related to sustainable cities in response to climate change and rapid urbanization.

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6 REFERENCES

[1] Barbieri, T., Despini, F., and Teggi, S. (2018). A Multi-Temporal Analyses of Land Surface Temperature Using Landsat-8 Data and Open Source Software: The Case Study of Modena, Italy. Sustainability, vol. 10, no. 5, 1678, DOI: 10.3390/su10051678.

[2] Mohamed, M. (2024). Urbanization and Heat Island Effect: A Comparative Study in Egypt. International Journal of Climatic Studies, vol. 3, no. 1, 12-23, DOI: 10.47604/ijcs.2479.

[3] Wang, G. and Yang, H. (2024). Optimization of Green Space Pattern for Alleviating the Urban Heat Island Effect in Qiantang District. Proceedings of the 2023 5th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2023), p. 274-282.DOI: 10.2991/978-94-6463-398-6_27.

[4] Tang, C. F. (2022). A Study of the Urban Heat Island Effect in Guangzhou. Iop Conference Series Earth and Environmental Science, vol. 1087, no. 1, 012015, DOI: 10.1088/1755-1315/1087/1/012015.

[5] Tan, J., Zheng, Y., Tang, X., Guo, C., Zhang, L., Song, G.-J., Zhen, X., Dong, Y., Kalkstein, A. J., Feng, L., and Chen, H. t. (2009). The Urban Heat Island and Its Impact on Heat Waves and Human Health in Shanghai. International Journal of Biometeorology, vol. 54, no. 1, 75-84, DOI: 10.1007/s00484-009-0256-x.

[6] Zhou, D., Xiao, J., Bonafoni, S., Berger, C., Deilami, K., Zhou, Y., Frolking, S., Yao, R., Qiao, Z., and Sobrino, J. A. (2018). Satellite Remote Sensing of Surface Urban Heat Islands: Progress, Challenges, and Perspectives. Remote Sensing, vol. 11, no. 1, 48, DOI: 10.3390/rs11010048.

[7] Islam, H. E., Noha, S. D., and Effat, H. A. (2021). Monitoring the Urban Heat Island Phenomenon Using Thermal Infrared Bands of Lands at Images From 1998 to 2018, El-Senbellaween City, Egypt. Journal of Environmental Science, vol. 50, no. 8, 287-323, DOI: 10.21608/jes.2021.223394.

[8] Jiao, Z. (2024). The Application of Remote Sensing Techniques in Ecological Environment Monitoring. Highlights in Science Engineering and Technology, vol. 81, 449-455, DOI: 10.54097/7dqegz64.

[9] Cheng, J. X. (2021). Application of Remote Sensing Technology in Ecological Engineering—A Case Study of Phase I Tao River Water Diversion Project. 2021 5th International Conference on Water Conservancy, Hydropower and Building Engineering (WCHBE 2021), p. 01033(1-7).DOI: 10.1051/e3sconf/202127601033.

[10] Zhang, Y., Jiang, P., Zhang, H., and Cheng, P. (2018). Study on Urban Heat Island Intensity Level Identification Based on an Improved Restricted Boltzmann Machine. International Journal of Environmental Research and Public Health, vol. 15, no. 2, 186, DOI: 10.3390/ijerph15020186.

[11] Zhao, S., Wang, Q., Li, Y., Liu, S., Wang, Z., Zhu, L., and Wang, Z. (2017). An Overview of Satellite Remote Sensing Technology Used in China's Environmental Protection. Earth Science Informatics, vol. 10, no. 2, 137-148, DOI: 10.1007/s12145-017-0286-6.

[12] Murayama, Y. (2023). Editorial: Special Issue on Geographical Analysis and Modeling of Urban Heat Island Formation. Remote Sensing, vol. 15, no. 18, 4474, DOI: 10.3390/rs15184474.

[13] Tsou, J. Y., Chao, M. C., Xiang, L., and Chen, K.(2014). Applying RS and GIS to Study the Impacts of Urban Regeneration on Thermal Environment in Built-Up Areas: A Case Study of Kowloon, Hong Kong. R. R. Issa and I. Flood (Eds.), Computing in Civil and Building Engineering. American Society of Civil Engineers, New York, p. 593-600, DOI: 10.1061/9780784413616.074.

[14] Moussa, Y. K. H. and A. Alwehab, A. (2022). The Urban Expansion Impact on Climate Change for the City of Baghdad. Iraqi Journal of Science, vol. 63, no. 11, 5072-5085, DOI: 10.24996/ijs.2022.63.11.41.

[15] Naif, S. S., Al-Jiboor, M., and Hadi, N. M. (2020). Study of Temporal Variations of Nocturnal and Daytime Urban Heat Island in Baghdad. Przegląd Naukowy Inżynieria I Kształtowanie Środowiska, vol. 29, no. 3, 355-365, DOI: 10.22630/pniks.2020.29.3.30.

[16] Mukhlas, A. B., Nugraha, S. B., Hariyanto, H., and Tjahjono, H. (2022). The Relationship between Urban Heat Island on Land Use Changes and Environment Critical Index in Semarang City. Geographica: Science and Education Journal, vol. 4, no. 1, 7-20, DOI: 10.31327/gsej.v4i1.1732.

[17] Al-Khuwaylidee, I. K. R., Hassoon, A. F., and Al-Ramahi, F. K. M. (2023). Assessment Vertical and Spatial Distribution of SO2 Concentration over Baghdad City (Case Study at 2022). IOP Conference Series: Earth and Environmental Science, vol. 1223, no. 1, 012013, DOI: 10.1088/1755-1315/1223/1/012013.

[18] Nasir, B. (2024). Efficiency Assessment of an Inverter Based on Solar PV Energy in Baghdad. Engineering Technology & Applied Science Research, vol. 14, no. 2, 13425-13429, DOI: 10.48084/etasr.6948.

[19] Chaichan, M. T., Mahdi, M. T., Kazem, H. A., Al-Waeli, A. H., Fayad, M. A., Al-Amiery, A. A., Wan Nor Roslam Wan, I., Kadhum, A. A. H., and Takriff, M. S. (2022). Modified Nano-Fe2O3-Paraffin Wax for Efficient Photovoltaic/Thermal System in Severe Weather Conditions. Sustainability, vol. 14, no. 19, 12015, DOI: 10.3390/su141912015.

[20] Wahab, B. I., Naif, S. S., and Al-Jiboori, M. H. (2022). Development of Annual Urban Heat Island in Baghdad Under Climate Change. Journal of Environmental Engineering and Landscape Management, vol. 30, no. 1, 179-187, DOI: 10.3846/jeelm.2022.16374.

[21] Ali, J. M., Marsh, S., and Smith, M. J. (2017). A Comparison Between London and Baghdad Surface Urban Heat Islands and Possible Engineering Mitigation Solutions. Sustainable Cities and Society, vol. 29, no. February, 159-168, DOI: 10.1016/j.scs.2016.12.010.

[22] Alwan, N. F. and Al-Nuaimi, M. (2018). The Role and Important of Internet of Things in Building Sustainable City. Engineering and Technology Journal, vol. 36, no. 1C, 22-29, DOI: 10.30684/etj.36.1c.5.

[23] Majeed, F. A. and Abaas, Z. R. (2023). An Analysis of Baghdad's Masterplans Based on the Development of Green Areas. Acta Scientiarum Polonorum Administratio Locorum, vol. 22, no. 2, 193-208, DOI: 10.31648/aspal.8234.

[24] Fazaa, N. A., Ali, A. B., Al-Jabinawi, A. J., Francksen, R. M., and Whittingham, M. J. (2022). Land Use Change in Baghdad City and Assessment of the Jadriyah and Umm Al- Khanazeer Island Important Bird Area (IBA) From 1984 to 2020. Baghdad Science Journal, vol. 19, no. 6(Suppl.), 1471, DOI: 10.21123/bsj.2022.7033.

[25] Al-Lami, A. M. (2023). Assessment of Some Bioclimatic Indices Using RayMan Model for Baghdad-Iraq. Iop Conference Series Earth and Environmental Science, vol. 1223, no. 1, 012019, DOI: 10.1088/1755-1315/1223/1/012019.

[26] Jabar, S. S. and Hassan, F. M. (2022). Monitoring the Water Quality of Tigris River by Applied Overall Index of Pollution. Iop Conference Series Earth and Environmental Science, vol. 1088, no. 1, 012015, DOI: 10.1088/1755-1315/1088/1/012015.

[27] Mohsen, A.-Z. A., Al-Jiboori, M. H., and Al-Timimi, Y. K. (2021). Investigating the Aerodynamic Surface Roughness Length Over Baghdad City Utilizing Remote Sensing and GIS Techniques. Baghdad Science Journal, vol. 18, no. 2(Suppl.), 1048, DOI: 10.21123/bsj.2021.18.2(suppl.).1048.

[28] Al-Hameedi, W. M. M., Chen, J., Faichia, C., Al-Shaibah, B., Nath, B., Kafy, A. A., Hu, G., and Al-Aizari, A. (2021). Remote Sensing-Based Urban Sprawl Modeling Using Multilayer Perceptron Neural Network Markov Chain in Baghdad, Iraq. Remote Sensing, vol. 13, no. 20, 4034, DOI: 10.3390/rs13204034.

[29] Smith, D. L., Hunt, S. E., Etxaluze, M., Peters, D. M., Nightingale, T., Mittaz, J. P. D., Woolliams, E., and Polehampton, E. T. (2021). Traceability of the Sentinel-3 SLSTR Level-1 Infrared Radiometric Processing. Remote Sensing, vol. 13, no. 3, 374, DOI: 10.3390/rs13030374.

[30] Luo, B. and Minnett, P. J. (2020). Comparison of SLSTR Thermal Emissive Bands Clear-Sky Measurements With Those of Geostationary Imagers. Remote Sensing, vol. 12, no. 20, 3279, DOI: 10.3390/rs12203279.

[31] Nie, J., Ren, H., Zheng, Y., Ghent, D., and Tansey, K. (2021). Land Surface Temperature and Emissivity Retrieval From Nighttime Middle-Infrared and Thermal-Infrared Sentinel-3 Images. Ieee Geoscience and Remote Sensing Letters, vol. 18, no. 5, 915-919, DOI: 10.1109/lgrs.2020.2986326.

[32] Pérez-Planells, L., Niclòs, R., Puchades, J., Coll, C., Göttsche, F.-M., Valiente, J., Valor, E., and Galve, J. M. (2021). Validation of Sentinel-3 SLSTR Land Surface Temperature Retrieved by the Operational Product and Comparison With Explicitly Emissivity-Dependent Algorithms. Remote Sensing, vol. 13, no. 11, 2228, DOI: 10.3390/rs13112228.

[33] Zheng, Y., Ren, H., Guo, J., Ghent, D., Tansey, K., Hu, X., Nie, J., and Chen, S. (2019). Land Surface Temperature Retrieval From Sentinel-3a Sea and Land Surface Temperature Radiometer, Using a Split-Window Algorithm. Remote Sensing, vol. 11, no. 6, 650, DOI: 10.3390/rs11060650.

[34] Adeniran, I. A., Zhu, R., Yang, J., Zhu, X., and Wong, M. S. (2022). Cross-Comparison Between Sun-Synchronized and Geostationary Satellite-Derived Land Surface Temperature: A Case Study in Hong Kong. Remote Sensing, vol. 14, no. 18, 4444, DOI: 10.3390/rs14184444.

[35] Musyimi, P. K., Sahbeni, G., Timár, G., Weidinger, T., and Székely, B. (2023). Analysis of Short-Term Drought Episodes Using Sentinel-3 SLSTR Data Under a Semi-Arid Climate in Lower Eastern Kenya. Remote Sensing, vol. 15, no. 12, 3041, DOI: 10.3390/rs15123041.

[36] Kasmaee, S. and Tinti, F. (2018). A method to evaluate the impact of urbanization on ground temperature evolution at regional scale. Rudarsko-geološko-naftni zbornik, vol. 33, no. 5, DOI: 10.17794/rgn.2018.5.1.

[37] Sánchez-Sánchez, F. A., Vega-De-Lille, M., Castillo-Atoche, A. A., López-Maldonado, J. T., Cruz-Fernandez, M., Camacho-Pérez, E., and Rodríguez-Reséndiz, J. (2024). Geo-Sensing-Based Analysis of Urban Heat Island in the Metropolitan Area of Merida, Mexico. Sensors, vol. 24, no. 19, 6289, DOI: 10.3390/s24196289.

[38] Sanecharoen, W., Nakhapakorn, K., Mutchimwong, A., Jirakajohnkool, S., and Onchang, R. (2019). Assessment of Urban Heat Island Patterns in Bangkok Metropolitan Area Using Time-Series of LANDSAT Thermal Infrared Data. Environment and Natural Resources Journal, vol. 17, no. 4, 87-102, DOI: 10.32526/ennrj.17.4.2019.34.

[39] Nandi, N. and Dede, M. (2021). Urban Heat Island Assessment Using Remote Sensing Data in West Java, Indonesia: From Literature Review to Experiments and Analyses. Indonesian Journal of Science and Technology, vol. 7, no. 1, 105-116, DOI: 10.17509/ijost.v7i1.44146.

[40] Sameh, S., Zarzoura, F., and El-Mewafi, M. (2022). Automated Mapping of Urban Heat Island to Predict Land Surface Temperature and Land use/cover Change Using Machine Learning Algorithms: Mansoura City. International Journal of Geoinformatics, vol. 18, no. 6, 47-67, DOI: 10.52939/ijg.v18i6.2461.

[41] Garcia, D. H. (2022). Analysis of Urban Heat Island and Heat Waves Using Sentinel-3 Images: a Study of Andalusian Cities in Spain. Earth Syst Environ, vol. 6, no. 1, 199-219, DOI: 10.1007/s41748-021-00268-9.

[42] Shumilo, L., Shelestov, A., Yailymov, B., Brazhnyi, A., and Bilokonska, Y. (2021). Remote Sensing Data usage for Smart City Greening Strategy Planning. IEEE EUROCON 2021 - 19th International Conference on Smart Technologies, p. 92-97.DOI: 10.1109/EUROCON52738.2021.9535595.

[43] Forghani, M. A. and Delavar, M. R. (2014). A Quality Study of the OpenStreetMap Dataset for Tehran. Isprs International Journal of Geo-Information, vol. 3, no. 2, 750-763, DOI: 10.3390/ijgi3020750.

[44] Viana, C. M., Encalada, L., and Rocha, J. (2019). The Value of OpenStreetMap Historical Contributions as a Source of Sampling Data for Multi-Temporal Land Use/Cover Maps. Isprs International Journal of Geo-Information, vol. 8, no. 3, 116, DOI: 10.3390/ijgi8030116.

[45] Zhou, X., Chen, Z., Zhang, X., and Ai, T. (2018). Change Detection for Building Footprints With Different Levels of Detail Using Combined Shape and Pattern Analysis. Isprs International Journal of Geo-Information, vol. 7, no. 10, 406, DOI: 10.3390/ijgi7100406.

[46] Tawfeek, Y. Q., Jasim, F. H., and Al-Jiboori, M. H. (2020). A Study of Canopy Urban Heat Island of Baghdad, Iraq. Asian Journal of Atmospheric Environment, vol. 14, no. 3, 280-288, DOI: 10.5572/ajae.2020.14.3.280.

[47] Mohammed, Y. and Salman, A. M. (2018). Effect of Urban Geometry and Green Area on the Formation of the Urban Heat Island in Baghdad City. The 3rd International Conference on Buildings, Construction and Environmental Engineering, BCEE3-2017, p. 05025.DOI: 10.1051/matecconf/201816205025.

[48] Musa, H. and Hussien, A., M.; (2023). Impact of Urban Heat Island on Thermal Comfort in the Outdoor Spaces of Residential Complexes: Insights From the Durrat Karbala Residential Complex in Iraq. Journal of

the International Society for the Study of Vernacular Settlements, vol. 10, no. 12, 544-564, DOI: 10.61275/isvsej-2023-10-12-38.

[49] Boukari, W. and Long, F. (2023). Reducing Urban Sprawl by Optimizing Housing Production. Growth and Change, vol. 54, no. 2, 529-549, DOI: 10.1111/grow.12663.

[50] Barriuso, F. and Urbano, B. (2021). Green Roofs and Walls Design Intended to Mitigate Climate Change in Urban Areas Across All Continents. Sustainability, vol. 13, no. 4, 2245, DOI: 10.3390/su13042245.

[51] Ma, X., Liu, G., Luo, Z., Tan, Y., and Lei, J. (2017). Comprehensive Evaluation of Energy and Environmental Performances of an Extensive Green Roof of a Building in Subtropical Climate. Journal of Architectural Engineering Technology, vol. 06, no. 1, 1-8, DOI: 10.4172/2168-9717.1000192.

[52] Treglia, M., McPhearson, T., Sanderson, E. W., Yetman, G., and Maxwell, E. N. (2022). Examining the Distribution of Green Roofs in New York City Through a Lens of Social, Ecological, and Technological Filters. Ecology and Society, vol. 27, no. 3, 1-15, DOI: 10.5751/es-13303-270320.

[53] Halipah, B. I. S., Izzati, B. A. I. N., Julaihi, B. W., Rose, B. K. D., and Nawi, M. N. M. (2018). The Impact of Road Pavement on Urban Heat Island (UHI) Phenomenon. International Journal of Technology, vol. 9, no. 8, 1597, DOI: 10.14716/ijtech.v9i8.2755.

[54] Turhan, C., Atalay, A. S., and Akkurt, G. G. (2023). An Integrated Decision-Making Framework for Mitigating the Impact of Urban Heat Islands on Energy Consumption and Thermal Comfort of Residential Buildings. Sustainability, vol. 15, no. 12, 9674, DOI: 10.3390/su15129674.

[55] Hsu, K.-W. and Chao, J.-C. (2022). The Impact of Urban Green-Infrastructure Development on the Price of Surrounding Real Estate: A Case Study of Taichung City's Central District. Iop Conference Series Earth and Environmental Science, vol. 1006, no. 1, 012012, DOI: 10.1088/1755-1315/1006/1/012012.

[56] Shawly, H. (2022). Evaluating Compact City Model Implementation as a Sustainable Urban Development Tool to Control Urban Sprawl in the City of Jeddah. Sustainability, vol. 14, no. 20, 13218, DOI: 10.3390/su142013218.

[57] Ziaeemehr, B., Jandaghian, Z., Ge, H., Lacasse, M., and Moore, T. (2023). Increasing Solar Reflectivity of Building Envelope Materials to Mitigate Urban Heat Islands: State-of-the-Art Review. Buildings, vol. 13, no. 11, 2868, DOI: 10.3390/buildings13112868.

[58] Yenneti, K., Ding, L., Prasad, D., Ulpiani, G., Paolini, R., Haddad, S., and Santamouris, M. (2020). Urban Overheating and Cooling Potential in Australia: An Evidence-Based Review. Climate, vol. 8, no. 11, 126, DOI: 10.3390/cli8110126.

[59] Zhang, Y., Long, E., Li, Y., and Pan, L. (2017). Solar Radiation Reflective Coating Material on Building Envelopes: Heat Transfer Analysis and Cooling Energy Saving. Energy Exploration & Exploitation, vol. 35, no. 6, 748-766, DOI: 10.1177/0144598717716285.

[60] Chhetri, D. M., Wangmo, K., Dechen, K., Choden, S., and Chimi, C. (2022). Green Urbanism: Adopting Sustainable Transport in Phuntsholing City. Bhutan Journal of Research and Development, vol. Special Edition, 212-230, DOI: 10.17102/bjrd.rub.10.2.021.

[61] Brik, B., Esseghir, M., Merghem-Boulahia, L., and Hentati, A. (2022). Providing Convenient Indoor Thermal Comfort in Real-Time Based on Energy-Efficiency IoT Network. Energies, vol. 15, no. 3, 808, DOI: 10.3390/en15030808.

[62] Sayad, B., Helmi, M. R., Osra, O. A., Abed, A. M., and Alhubashi, H. H. (2024). Microscale Investigation of Urban Heat Island (UHI) in Annaba City: Unveiling Factors and Mitigation Strategies. Sustainability, vol. 16, no. 2, 747, DOI: 10.3390/su16020747.

[63] Georgescu, I. and Nica, I. (2024). Evaluating the Determinants of Deforestation in Romania: Empirical Evidence From an Autoregressive Distributed Lag Model and the Bayer–Hanck Cointegration Approach. Sustainability, vol. 16, no. 13, 5297, DOI: 10.3390/su16135297.

[64] Hazmi, M., Suryaningrum, D. A., Umarie, I., Oktarina, N., and Hari Swasono, M. A. (2023). Emerging Trends and Future Directions in Organic Agriculture and Environmentally-Friendly Farming Practices: A Bibliometric Analysis. West Science Interdisciplinary Studies, vol. 1, no. 07, 416-425, DOI: 10.58812/wsis.v1i07.124.

[65] Fineschi, S. and Loreto, F. (2020). A Survey of Multiple Interactions Between Plants and the Urban Environment. Frontiers in Forests and Global Change, vol. 3, no. 1, 1-19, DOI: 10.3389/ffgc.2020.00030.

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