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REVIEW

Urban Heat Island From A 3d Modeling Perspective—A Review

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Abstract

The number of studies on the urban heat island has been increasing in recent years. Developments in geospatial analytics, especially in recent years, have made frequent use of three-dimensional 3D modeling techniques in urban heat island research. There is a limited number of studies in the literature that deals with a systematic review of planning strategies and 3D modeling techniques used that are effective in reducing the formation of urban heat islands. The study presents an evaluation of a total of 33 studies that evaluated planning strategies that are effective in reducing the urban heat island effect with 3D modeling. The studies were evaluated in 4 sections. While the parameters used in the studies were evaluated in the first part, a summary of the studies and the criteria they used were evaluated in the second part, and the techniques of the studies were evaluated in the third part. In the last part, the programs used in 3D modeling were evaluated. As a result of the evaluations, it has been determined that buildings, green areas, and pavements, which are the most effective factors in the formation of urban heat islands, should be taken into account in planning strategies. In these 33 studies examined, the cooling effect of green areas on urban areas comes to the fore. These studies show that it has been concluded that the 3D indicators reflect the temperature, built environment, and land cover/use relationship in the best way. This result shows that 3D spatial modeling techniques should be preferred more in urban heat island research since they better reflect 2D land cover variables.

Keywords Climate change · Urban heat island · Sustainable urban planning · 3D modeling

1 Introduction

Today's industrialization and urbanization cause various socio-ecological problems, especially global climate change. In addition to these problems, changes are experienced in the microclimatic structure and regional warming occurs in cities. All these problems affect urban life and the living ecosystem negatively O'Malley et al. [1]; Ozturk et al. [2]; Ozturk [3]; Sharma [4]; Shirani-Bidabadi et al. [5]; Yilmaz and Isinkaralar [6]; IPCC [7]; WHO [8].

The cities built by people according to their lifestyles cause great changes in the existing climate elements. High-rise buildings that prevent the formation of wind by negatively affecting the ecological air corridor, impermeable materials used on building surfaces, and the irregular placement of buildings affecting heat distribution are the main problems that adversely affect the climate of cities Chen and Hu [9]; Hornsey and Fielding [10]; Dorigon and Amorim [11]; Doulos et al. [12]. Urbanization it causes natural landscape areas such as vegetation, water bodies, and agricultural lands to turn into impermeable surfaces. This transformation causes a decrease in the evaporation and transpiration cycle obtained from the vegetation. At the same time, it causes an increase in the amount of energy consumed for solar radiation absorption and cooling, negatively affecting the climate at local and regional scales in areas such as health problems, air pollution, and water shortage, causing the formation of urban heat island Dai et al. [13]; Lu et al. [14]; Sharma [4];

Highlights

- A systematic review on 33 literatures focused on the urban heat island effect and 3D modeling techniques.
- Buildings, green areas and sidewalks should be taken into account in the planning strategies to be created to reduce the urban heat island.
- The findings show the necessity of using advanced spatial techniques and 3D modeling techniques on the urban heat island.

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Yang et al. [15]; Yao et al. [16]; Yao et al. [17]; Akbari [18]; Akbari and Konopacki [19]; Akbari and Konopacki [20].

Urban and ecological problems experienced on a global scale affect people's quality of life at a high level Buyantuyev and Wu [21]; Dai et al. [13]; Oke [22]. Urban systems and the urban spaces formed by them must adapt to the climate change process, and planning and policy decisions must be made taking into account the effects of this change. For cities to be minimally affected by the climate change process and to adapt to this process, their spatial–temporal characteristics should be determined and planning decisions should be made accordingly Cobanyilmaz and Yuksel, [23]; Yüksel Duman and Yilmaz [24]. Therefore, for urban areas to be more resistant to the negative effects of climate change and to ensure urban sustainability, it is necessary to reduce the effects of UHI. In this context, determining, monitoring, and making planning decisions to reduce the formation of UHI has been one of the issues on the agenda in urban studies Howard, [25]; Deilami et al. [26]; Rizwan et al. [27]; Cao et al. [28]; Chen et al. [29]; Dorigon and Amorim [11]; El-Hattab et al. [30]. Especially in the field of planning, determining the UHI effect with 3D modeling is important in obtaining more effective and concrete results. Park et al. [31]; Akbari et al. [32]; Akbari et al. [33].

From past to present, UHI has been a subject of intense interest to researchers. While most of these studies focused on planning strategies to reduce the UHI effect Takebayashi and Mariyama, [34]; Krüger et al. [35]; Tian et al. [36], some of them focused on the built environments, green spaces, and outdoor thermal comfort of the UHI effect Bowler et al. [37]; Dai et al. [13]; Santamouris and Kolokotsa [38]; Sharmin et al. [39]; Yu and Hien [40]; Zhang et al. [41]. There are also review studies on the UHI effect and the planning strategies that need to be implemented to reduce this effect Kohler et al. [42]; Crawford and French [43]; Deilami et al. [26]; Santamouris and Kolokotsa [38]; Unger [44]; Santamouris, [38]; Santos [45]; Tian et al. [36]; Ulpiani [46]; Eliasson [47]; Fawzy et al. [48]; Hu et al. [49]; Zhou et al. [50].

Especially in recent years, as a result of the developments in geospatial analytics, studies in which 3D modeling techniques are used in the field of planning and design are increasing. Thanks to 3D modeling techniques, cities are better understood, and more effective results are obtained Chen and Hu [9]; Darbani [51]; Park et al. [52]; Park and Guldmann [31]; Gautier et al. [53]; Nakata-Osaki [54]; Rajasekar and Weng [55]; Wong et al. [56]. For this reason, it is important to understand the methods used in these studies, the criteria discussed, and the scales in which the applications were made. Based on determining effective planning strategies for UHI, many different features of the urban area should be considered as a whole. In this way, effective planning strategies will be determined in the long term and it will be easier to make successful climate plans. Therefore, for all these situations to be addressed in urban planning policies, a complete understanding of the issue of UHI is needed. In this context, it is aimed to fully understand the concept of UHI, to determine the basic planning strategies necessary to reduce the effect of UHI, and to show the importance of studies that reveal the effect of UHI with 3D modeling, especially in urban areas. In this study, studies using 3D modeling techniques focusing on the UHI effect and the factors necessary to reduce these effects were identified and systematically evaluated.*Especially in recent years, due to the development of 3D modeling techniques, only 33 studies were determined according to the criteria determined within the scope of the study.* As a result of the evaluations, it was determined from the perspective of 3D modeling what should be considered in the creation of planning strategies to reduce the UHI effect.

2 Methodology – Criteria Used to Select Literature on UHI

In this article, recent research focusing on planning strategies to reduce urban heat island formation and addressing these strategies within the scope of 3D modeling has been systematically evaluated. The methodology used for this assessment consists of the following steps:

1. Keywords were determined to select the most relevant articles in the field (Table 1).
2. The study population was limited by considering these criteria.
3. A wide-ranging discussion is presented, evaluating appropriate research.

Table 1 Criteria used to select the publications to be examined within the scope of the study

Databases where research is conducted	Web of Science Scopus Wiley ScienceDirect Sage
Keywords	3D modelling and urban heat island Simulation and urban heat island Heat island effect / characteristics / effective factors / consequences Strategies to reduce urban heat island formation LST (Land Surface Temperatures) Air temperatures Sustainable urban planning,
Document Type	Journal articles, conference proceedings, book chapters
Language	English
Publication date range	2005–2022

To find the relevant literature in the study, a search was made using the university's internet portal and related databases (Web of Science, Scopus, Wiley, ScienceDirect, etc.). The selection criteria of the articles have been defined appropriately according to the characteristics of the study. In line with the determined parameters, the abstracts of the articles were read and scanned to identify suitable studies. As a result of the scans of the heat island effect, its characteristics, consequences, effective factors, effects on cities and people, mitigation strategies, etc. a total of 33 publications that make comprehensive analyzes of their subjects were specified. In the review study, the research objectives of each article, applied or developed methods, research objectives, applied or developed strategies, and computer programs used were examined.

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3 Results

3.1 Parameters Used in Urban Heat Island and 3D Modeling Studies

The topic of UHI has been particularly important in urban climate and urban planning issues in recent years. There are many studies on this topic in the literature. Some of these studies are based on the factors affecting the formation of UHI and some of them are based on measures to reduce the effect of UHI. It has been found that 3D modeling techniques are also used to better understand these effects. Some of the parameters mainly used in the studies are green areas, Sky view factor (SVF), Lidar point cloud, building density, surface coating materials, land cover, and Land Surface Temperatures (LST) (Fig. 1).

3.2 Summary of Literature using UHI and 3D Modeling.

The criteria evaluated in studies using UHI and 3D modeling examined within the scope of the study were analyzed. According to the analysis results given in Table 2:

In studies where 3D modeling is used to reduce the UHI effect, the most used criteria are the form, type, floor heights, etc. of the building's properties (about 90%). Another criterion frequently used in studies is the temperature (about 72%). In these studies, the relationship between LST or air temperatures and UHI was evaluated by 3D modeling. On the other hand, there are also studies in which the relationship between surface materials, albedo values, and thermal properties (about 66%) in urban areas and UHI are evaluated with 3D modeling. Studies (about 57%) in which the shadows of trees, plants, and buildings are associated with the effect of UHI have increased especially in the last year. The most important reason for this situation is that the programs are made more useful thanks to the developments in 3D modeling techniques.

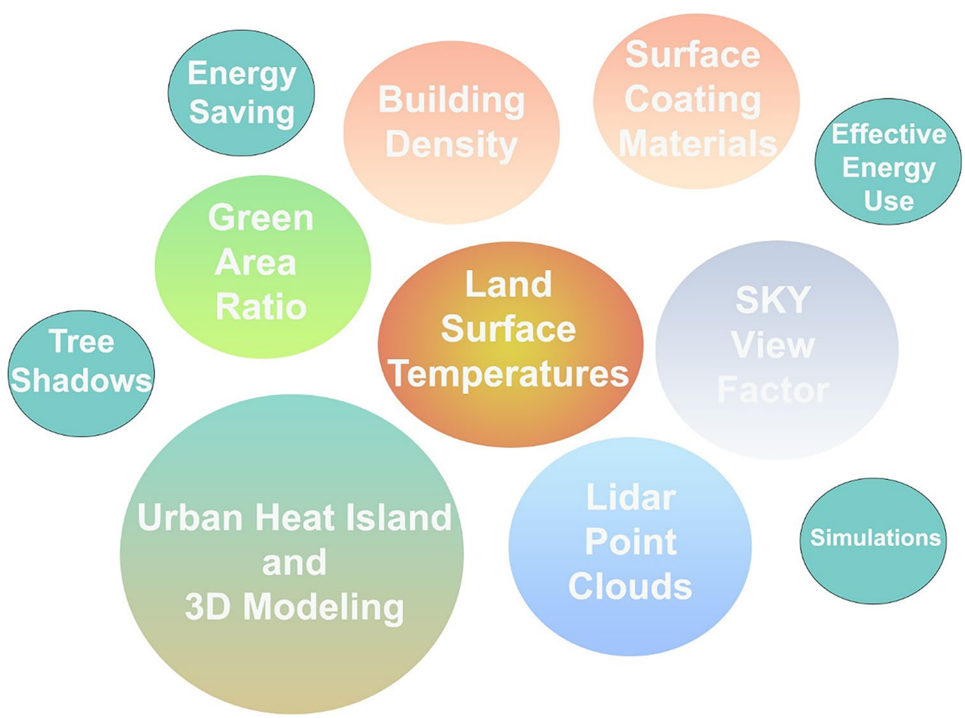

Fig. 1 Parameters used in urban heat island and 3D modeling studies

Table 2 Criteria used in UHI and 3D modeling studies

Literatures	Criteria's	Proportion in the reviewed literatures
Sato et al. [57]	Land use (Residential, commercial, urban and non-urban areas, etc.)	57.57%
Unger [58]		
Lindberg et al. [59]		
Sato et al. [60]		
Unger [61]		
Chen et al. [62]		
Chun and Guldmann [63]		
Chun and Guldmann [64]		
Touchaei and Wang [65]		
Hu et al. [66]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Chun and Guldmann [68]		
Park and Guldmann [31]		
Ma et al. [69]		
Park et al. [70]		
Park et al. [71]		
Chen and Hu [9]		
Darbani et al. [51]		
Sato et al. [57]	Building properties (form, type, etc.)	90.90%
Unger [58]		
Asawa et al. [72]		
Lindberg et al. [59]		
Sato et al. [60]		
Unger (Unger [61]		
Chun and Guldmann [63]		
Chen et al. [62]		
Chun and Guldmann [64]		
Ambrosini et al. [73]		
Touchaei and Wang [65]		
Nouvel et al. [74]		
Nakano et al. [75]		
Hu et al. [66]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Ujang et al. [76]		
Osaki et al. (2019)		
Alavipanah et al. [77]		
Chun and Guldmann [68]		
Park and Guldmann [31]		
Hu et al. [78]		
Equere et al. [79]		
Fahed et al. [80]		

Table 2 (continued)

Literatures	Criteria's	Proportion in the reviewed literatures
Asadi et al. [81]		
Ma et al. [69]		
Park et al. [70]		
Park et al. [71]		
Chen and Hu [9]		
Darbani et al. [51]		
Cortes et al. [82]	Green roofs	6.06%
Darbani et al. [51]		
Chun and Guldmann [63]	Water	21.21%
Chun and Guldmann [64]		
Chun and Guhathakurta [67]		
Hu et al. [78]		
Asadi et al. [81]		
Park et al. [70]		
Park et al. [71]		
Sato et al.[57]	Sky visibility	57.57%
Unger [58]		
Asawa et al. [72]		
Unger [61]		
Chen et al. [62]		
Chun and Guldmann [63]		
Gal and Unger [83]		
Touchaei and Wang [65]		
Hu et al. [66]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Chun and Guldmann [68]		
Alavipanah et al. [77]		
Hu et al. [78]		
Equere et al. [79]		
Asadi et al. [81]		
Chen and Hu [9]		
Fahed et al. [80]		
Darbani et al. [51]		
Sato et al. [57]	Park and green areas	51.51%
Unger [61]		
Chun and Guldmann [63]		
Chun and Guldmann [64]		
Gal and Unger [83]		
Touchaei and Wang [65]		
Hu et al. [66]		
Park et al. [52]		
Chun and Guhathakurta [67]		

Table 2 (continued)

Literatures	Criteria's	Proportion in the reviewed literatures
Chun and Guldmann [68]		
Alavipanah et al. [77]		
Hu et al. [78]		
Equere et al. [79]		
Asadi et al. [81]		
Park et al. [70]		
Park et al. [71]		
Chen and Hu [9]		
Sato et al. [57]	Shadow effect of trees and plants and building	57.57%
Asawa et al. [72]		
Unger [61]		
Chun and Guldmann [63]		
Chun and Guldmann [64]		
Ambrosini et al. [73]		
Gal and Unger [83]		
Touchaei and Wang [65]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Chun and Guldmann [68]		
Alavipanah et al. [77]		
Asadi et al. [81]		
Hu et al. [78]		
Equere et al. [79]		
Park et al. [70]		
Cortes et al. [82]		
Park et al. [71]		
Darbani et al. [51]		
Sato et al. [57]	Surface materials and Thermal properties	66.66%
Asawa et al. [72]		
Sato et al. [60]		
Unger [61]		
Chun and Guldmann [63]		
Chen et al. [62]		
Ambrosini et al. [73]		
Touchaei and Wang [65]		
Nouvel et al. [74]		
Nakano et al. [75]		
Hu et al. [66]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Ujang et al. [76]		
Chun and Guldmann [68]		
Osaki et al. (2018)		
Asadi et al. [81]		
Ma et al. [69]		
Fahed et al. [80]		
Park et al. [70]		
Chen and Hu [9]		
Darbani et al. [51]		

Table 2 (continued)

Literatures	Criteria's	Proportion in the reviewed literatures
Sato et al. [57]	Temperatures (Land surfade temperature-LST, air temperature)	72.72%
Unger [58]		
Asawa et al. [72]		
Lindberg [59]		
Sato et al. [60]		
Unger [61]		
Chun and Guldmann [63]		
Chen et al. [62]		
Chun and Guldmann [64]		
Ambrosini et al. [73]		
Touchaei and Wang [65]		
Nakano et al. [75]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Ujang et al. [76]		
Alavipanah et al. [77]		
Chun and Guldmann [68]		
Hu et al. [78]		
Equere et al. [79]		
Cortes et al. [82]		
Asadi et al. [81]		
Park et al. [70]		
Park et al. [71]		
Darbani et al. [51]		
Unger [58]	Heat island potential (HIP) or Urban heat island intensity (UHII)	24.24%
Chun and Guldmann [64]		
Touchaei and Wang [65]		
Nakano et al. [75]		
Hu et al. [66]		
Osaki et al. (2018)		
Ma et al. [69]		
Fahed et al. [80]		

Sky visibility (about 57%) is among the important criteria evaluated in the studies.

3.2.1 Urbanization and UHI

As a result of the analysis, UHI shows itself with high temperatures in areas where the effect of urbanization is intense. The size and characteristics of UHI are affected by many parameters in urban areas and are determined by these parameters. In the studies reviewed, UHI is mostly seen in regions or cities where urbanization is intense. It has been concluded that UHI, which is associated with the urban expansion process, differs between cities due to the differentiation of climatic conditions.

3.2.2 Urban Energy Consumption and UHI

It has been determined that UHI has a negative relationship with humidity, precipitation, wind speed, and cloud cover. Increasing urban temperature, which is an important consequence of the UHI effect, also affects the use of cooling energy, especially for buildings, through energy use and heat dissipation of air conditioners. The effect of UHI on building energy consumption varies according to building type. At the same time, the effects of UHI on the energy consumption of buildings in the city center and around the city also differ. The heating load indexes of buildings located in the city center are lower than those located around the city. Energy use, transportation, industry, residential areas, rapid urbanization, and the pressure of population growth on natural resources are the main factors causing the urban pollution problem. The UHI effect is also closely related to urban pollution. Climatic conditions such as high temperatures, low relative humidity, low wind speed, and cloudlessness cause both UHI and urban pollution. Low-level breezes negatively affect both local warming and air quality, especially at night.

3.2.3 LULC and UHI

The UHI effect also differs according to land use and land cover types. As a result of urban growth, the transformation of green areas into built environments causes a decrease in natural surfaces. Buildings, roads, and asphalt surfaces store heat during the day and cause heat release at night. Heat generation from vehicle traffic and industrial activities also increases the air and surface temperatures in the city. As an important result of this situation, the formation of UHI intensifies in cities. UHI affects the urban climate and energy use, as well as significantly affects the quality of urban life.

3.2.4 Quality of Life and UHI

Rising urban temperatures have a great impact on people's lives and the overall environmental quality of cities. Urban overheating causes a significant increase in energy consumption for cooling purposes. This situation affects the cities negatively on a local scale. As a result of the increase in harmful pollutants, besides environmental problems, many negative situations such as death and disability due to high temperatures occur. Studies have shown that the rate of death due to heat increases drastically. In addition, there is concern that this situation will increase.

3.2.5 Shadows Effect and UHI

To reduce the effect of UHI in urban areas; It is emphasized that materials that help to cool cold pavements, green areas, and surfaces, green roofs, and contributing to reducing energy consumption should be preferred. It is also a situation encountered in the studies that the shadows created by the trees are another effective factor in reducing the UHI effect. In addition to cooling by evaporation, the shade created by the trees not only blocks solar radiation but also has an effective role in cooling the atmosphere by preventing the ground surface from heating up.

Parks and green areas in the cities cause a significant decrease in temperatures with the effect of evaporation and shading, thus creating cool areas in cities. Some of the studies reviewed analyzed temperatures in park areas and the shade of trees. The general conclusion is that green and shaded areas are cooler than other areas and are particularly effective in reducing surface temperature. Some studies examine temperature changes not only in green areas but also in areas with different uses in their immediate surroundings. The results showed that green spaces are important in energy saving and they can reduce the cooling loads of buildings. In the evaluated studies, it was concluded that green areas and plant shadows help reduce the UHI effect, increase the cooling effect in summer, and save energy. At the same time, it has been determined that the preferred surface materials in these areas are also effective on temperature changes.

3.2.6 Sky Visibility and UHI

In urban areas, the heat felt from sunlight forms a mass in areas where heat accumulates, such as roofs, building surfaces, streets, and squares. This accumulated heat mass spreads to the environment as long-wave radiation over time, causing temperatures to increase. The intensity of this wave radiation varies depending on the characteristics of the grounds visible to the sky.

3.2.7 Green Surfaces and UHI

Studies are showing that green surfaces and building designs have a positive effect on energy saving and urban planning. In these studies, it was also determined that trees and vegetation can harm the urban microclimate in cold climates. The effect of vegetation on reducing sun rays and wind was analyzed using simulation programs. The results showed that trees and plants with dense shade in cold climates increase heating costs, but decrease cooling costs in hot climates. In this context, the necessity of conducting detailed studies on tree/plant forms and species has emerged, especially in studies examining the effect of UHI.

Green roof applications also contribute to reducing the UHI effect. In the studies examined, it has been found that green roofs help to make air temperatures lower during the day and higher at night, especially in summer, thanks to their thermal properties. In these researches, the result that green roofs, which are considered to be more suitable for high-rise buildings, detached residences, and commercial buildings, contribute to the energy saving of buildings, stands out.

3.2.8 Thermal Properties and UHI

The surface materials used on floors in urban areas also have a great influence on the UHI effect. The surfaces of these materials are exposed to sunlight, their thermal properties are of great importance. In the studies examined, rough, dark-colored surface coating materials (hot items), smooth, light-colored, and flat surface coating materials (cold materials) tend to confine it has been found that more solar radiation. For this reason, it has been concluded that cold materials should be used in cities with a hot climate and hot materials should be used in cities with a cold climate.

The distribution of structures in cities is one of the important parameters affecting the formation of UHI, as it affects the absorption of solar energy and the formation of wind currents. It is possible to control the occurrence of these situations with effective and efficient planning. In the studies examined, it has been concluded that a significant reduction in energy consumption can be achieved in response to the increase in urban density, especially by designing more compact urban spaces.

3.2.9 Buildings Features and UHI

Building forms, designs, and orientations are effective in the formation of UHI. It has been determined that high-rise buildings will provide less natural lighting than other buildings, so they will have more shaded facades and therefore will be unfavorable in terms of energy saving. The studies examined reveal that there is a positive relationship between designing building forms in harmony with the environment and increasing thermal comfort.

Some of the measures to be taken to reduce or eliminate the impact of UHI are evaluated within the scope of urban planning strategies, while others are evaluated depending on very different factors other than the controlled use of urban areas and their geometry. As a result, it was found that urban areas have more warming effects, while agricultural areas, forest areas, water edges, or areas near them have less warming effects.

3.3 3D Modeling Techniques in Urban Heat Island Studies

Especially in the last 10 years, thanks to the developments in the geospatial field, many studies have been published in which the UHI effect and the strategies to reduce this effect are 3D modeled through remote sensing and various software programs Chun and Guldmann, 2012; Gal and Unger, [83]; Chen and Hu [9]; Darbani [51]; Park et al. [52]; Park and Guldmann [31].

In this context, the methods that are mainly used in the studies examined have been determined. *Since similar methods were used in most of the studies and similar analyzes were made, the data obtained in this section are presented graphically.* According to these determinations given in Fig. 2:

In general, the relationship between building morphology and UHI has been evaluated. New modeling techniques have been developed by integrating building morphologies, urban surface temperatures, and 2D land cover data.

In the research, the city centers with the most intense UHI effect were chosen as the study area. In the evaluations, **building structure, building type, a footprint that defines the building, and the number of floors** were chosen as basic criteria. At the same time, **GIS-based analyzes and statistical analyzes** were carried out in almost all studies before 3D modeling. Thanks to these techniques, the temperature-reducing effect of green areas under the UHI effect was revealed by digital modeling using the 3D building and tree models.

Prominent methods have been identified in the studies examined within the scope of UHI and 3D modeling. From these methods given in Fig. 2; It is seen that GIS-based analysis (62%), and the SVF value (56%) and are used in 3D modeling.

3.3.1 Software Programs and UHI

Software programs are often preferred in studies where the UHI effect is revealed with 3D modeling techniques. In urban climate research, SVF is a frequently used method used to measure urban geometry based on the height, and width ratio of streets and street orientations. In studies, it has been found that SVF and temperature values are generally related. For the relationship between SVF and temperature to be established, it is emphasized that buildings and green areas should be taken into account in particular. In this context, the necessity of revealing this effect by using 3D urban geometry comes to the fore. Lidar data is a method used to determine the number of floors of buildings. In cities with lidar point cloud data, it takes less time to calculate the number of floors of buildings in GIS-based analysis. It is seen that SVF, which is an important factor, especially in areas where construction is intense, is frequently preferred in research. The data and programs used in the studies vary according to the purpose of the studies. However, during the transfer of 2D terrain information to 3D modeling, mainly GIS-based programs are preferred.

3.3.2 Statistical Models and UHI

Especially in recent years, in urban climate research, advanced statistical models applied in studies conducted at different scales to investigate the effects of urbanization dynamics, spatial structures, and 3D urban geometry on the formation of UHI; Random Forest Regression (RFR), support vector regression model (SVRM), artificial neural networks (ANN), ridge regression model (RRM), supervised machine learning-SML are used. In addition to these methods, the artificial neural networks-ANNs method, which has become widespread in remote sensing processes in recent years, is also used in UHI studies. Statistical methods allow the evaluation of the effects of 2 and 3-dimensional

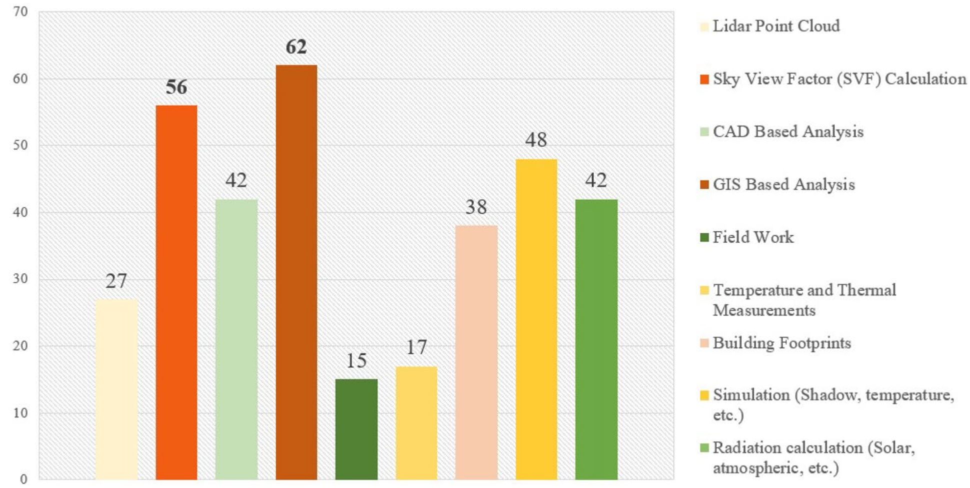

Fig. 2 Methods used in UHI and 3D modeling studies

components of urban texture on the formation of UHI in models based on the analysis of quantitative relationships between UHI and urban texture components. Various spatial statistical methods and models such as Ordinary least square-OLS, geographically weighted regression-GWR, or correlation are often preferred.

In addition to these methods, UH II (Urban Heat Island Intensity) was calculated in the studies. Formulas developed in the were used in the calculation of UHII. In general, meteorological or thermal observation methods have been preferred to examine UHII and its density in a city over a long period time.

3.3.3 Simulation Methods and UHI

Simulation methods are used to estimate different environmental parameters such as temperature and humidity in urban areas. The numerical weather prediction (NWP), computational fluid dynamics (CFD), models ENVI-met, building energy models (BEM), urban canopy models (UCMs), and statistical models are the preferred simulation tools for examining UHI at different spatial scales. The advantage of simulation studies in UHI research is preferred because of their potential to provide comparative analyzes based on different scenarios.

Satellite images or aerial photographs were used in the analysis of 17 of the 33 studies examined. In the studies, mainly Landsat satellite images were preferred (about 24%). Some studies prefer aerial photographs (about 18%). Satellite images or aerial photographs have generally been used in GIS-based analyses (Table 3).

Studies have found that remote sensing and GIS-based analyzes are more effective in understanding the effects of

Table 3 Satellite image or aerial photo used in UHI and 3D modeling studies

Literatures	Satellite image/Aerial photo	Proportion in the reviewed literatures
Sato et al. [57]	Aerial Photo	18.18%
Unger [58]		
Sato et al. [60]		
Unger [61]		
Ambrosini et al. [73]		
Touchaei and Wang [65]		
Chun and Guldmann [63]	Satellite Image (Landsat)	24.24%
Chun and Guldmann [64]		
Chun and Guldmann [68]		
Alavipanah et al. [77]		
Equere et al. [79]		
Asadi et al. [81]		
Park et al. [70]		
Chen and Hu [9]		
Chun and Guhathakurta [67]	Satellite Image (ASTER-Terra)	3.03%
Park et al. [71]	Satellite Image (MODIS)	3.03%
Hu et al. [78]	Satellite Image (Gaofen)	3.03%

UHI. In these analyses, satellite-based thermal images are used. Generally, images from Landsat TM/ETM + /OLI data sources are used. It has been determined that Landsat TM/ETM + /OLI data has a well-developed algorithm for determining land surface temperature (LST). In addition, it has been determined that MODIS LST data with high temporal resolution (temporal resolution twice a day) and wide coverage have been used worldwide in recent years to examine spatial, daily, and seasonal changes in UHI. Satellite images are also used to determine the effect of LULC on UHI. In general, satellite-based thermal data have been considered effective tools for describing the spatial model of the urban thermal environment, due to their good spatial coverage and open and easy access properties.

3.4 3D Modeling Software or Program in Urban Heat Island Studies

It has been determined that the researches mainly focus on the effects of reducing or increasing the UHI effect of urban elements and reveal these effects with the help of 3D spatial modeling. In this context, 3D modeling programs used in the research were identified and evaluated.

According to the data given in Table 4:

After the necessary evaluations and analyzes for UHI are completed in the studies, 3D modeling of the urban area is created by integrating 2D building information, land use information, trees, and greenery with a 3D database. In this way, it has been determined that more effective results are obtained.

ArcGIS programs or GIS-based applications (ArcView, ArcInfo, etc.) are mostly preferred in 3D modeling (about 63%). Especially in recent years, it is seen that GIS-based modeling programs have become widespread. The most important reason for this situation is that the new techniques developed in GIS applications and the studies carried out in this context give more effective results.

Table 4 Software/programs used in UHI and 3D modeling studies

Literatures	Software/Program	Proportion in the reviewed literatures
Sato et al. [57]	3D-CAD	9.09%
Asawa et al. [72]		
Sato et al. [60]		
Ambrosini et al. [73]	ENVI-met	15.5%
Touchaei and Wang [65]		
Fahed et al. [80]		
Cortes et al. [82]		
Darbani et al. [51]		
Hu et al. [66]	Rhino-Script	6.06%
Nakano et al. [75]		
Unger [58]	ERDAS Imagine	6.06%
Unger [61]		
Unger [61]	ArcGIS	63.63%
Chun and Guldmann [63]		
Chen et al. [62]		
Chun and Guldmann [64]		
Gal and Unger [83]		
Nouvel et al. [74]		
Park et al. [52]		
Chun and Guhathakurta [67]		
Alavipanah et al. [77]		
Ujang et al. [76]		
Chun and Guldmann [68]		
Nakata-Osaki et al. [84]		
Park and Guldmann [31]		
Hu et al. [78]		
Bulatov et al. [85]		
Equere et al. [79]		
Asadi et al. [81]		
Ma et al. [69]		
Park et al. [70]		
Park et al. [71]		
Chen and Hu [9]		
Lindberg et al.[59]	SOLWEIG	3.03%

4 Mitigation Strategies of Urban Heat Island Effect

As a result of urbanization, population growth, and global developments, urban areas consume more energy and have a higher temperature than rural areas due to their activities such as transportation, trade, and industry. This high energy consumption and temperatures affect the formation of UHI. To increase the combat forces of urban areas in the process of climate change, which is one of the biggest environmental problems on a global scale, it is necessary to create planning strategies that reduce the impact of UHI.

Based on the studies examined in this article, the things to consider when determining strategies are as follows:

4.1 LULC Detection

- Today, there is rapid urban growth, which causes a decrease in agricultural land, an increase in residential areas, and thus an irregular expansion of cities. With the expansion of cities, it is inevitable that different land uses will turn into urban use areas. For this reason, knowing the urban growth trend is important in terms of directing it in the desired direction (Rahmati et al. [86]). This situation is also important in determining the vulnerability levels of cities in the process of adaptation to climate change (Karimi et al. [87]; Guhathakurta and Gober [88];

House-Peters and Chang [89]; Jusuf et al. [90]; Shudo et al. [91]. There is always a need to realistically predict the future growth of cities and determine the impact of various planning scenarios on the urban growth process.

4.2 Buildings Features

- In the studies examined within the scope of the study, one of the important results is that in areas where built-up areas are dense, not only energy consumption but also temperatures are high. In line with this result, it has been revealed that if it is possible to design more compact cities, energy consumption in urban density and eco-efficiency can be increased accordingly (Gago et al. [92]; Eliasson [93]; Futcher et al. [94]; Grosso [95]; Kikegawa et al. [96]; Li et al. [97]; Liu et al. [98]; Mesa et al. [99]; Ratti et al. [100]; Svensson and Eliasson [101]; Wong et al.[102]; Yang et al. [103].
- Buildings, green areas, and sidewalks, which have a great influence on the temperature change at the local scale, are the main elements that should be taken into account in planning.
- The distribution of structures in cities affects the formation of UHI. Because this distribution determines the absorption of solar radiation and the flow of air.
- The combination of high-rise buildings and narrow streets that trap hot air, especially reducing airflow, leads to the formation of winds that do not disperse polluting gases. This situation also increases the formation of UHI. The use of SVF as an input when determining the density of built-up areas will help reduce the formation of UHI.
- To reduce the impact of UHI, it is necessary to apply measures primarily to the elements that affect temperatures in urban areas.
- In the creation of planning strategies, the use, and geometry of the areas must be excluded from the scope. This is because it is not possible to make changes in these areas. But for these areas, it is also necessary to take feasible measures to reduce the temperature.

4.3 Green Vegetation

- It is known that green vegetation is one of the most important factors determining the comfort and quality of urban space Afsharzadeh et al. [104]; Mohammad et al. [105]. Vegetation has many effects that improve the quality of urban life, such as reducing noise levels and stress levels, improving air quality, and cooling the urban environment Karimi et al. [106]. At the same time, green vegetation is also effective in reducing the impact of UHI Gago et al. [92]; Gunawardena et al. [107]; Bourbia and Boucheriba [18]; Bouyer et al. [108]. In this context, the inclusion of green infrastructure in city planning emerges as an important necessity Bretz and Akbari [109]; Ca et al.[110]; Robitu et al. [111]; Shashua-Bar and Hoffman [112].
- Vegetation has a strong role in improving the energy performance and environmental conditions of buildings Balany et al. [113]; Karimi et al. [106]; Dimoudi and Nikolopoulou [114]; McPherson et al. [115]; Niachou et al. [116]; Ong [117]; Onishi et al. [118]. It has been determined that trees can reduce air temperatures by up to 2 °C on average Balany et al. [113]; Renou [119]; Shashua-Bar et al. [120]. In addition to their positive effect on microclimate and thermal comfort, trees also reduce wind speed by acting as a barrier. Increasing wind speed will also reduce temperatures, mitigating the UHI effect.
- Planting trees and increasing greenery in urban areas increase local breezes. Large parking areas should be integrated into the urban fabric as they provide higher volumetric heat capacity.
- In urban planning applications, to increase the cooling effect of water surfaces and to affect the heat flow to larger urban areas, especially large water bodies should be surrounded by low-rise buildings.

4.4 Thermal Comfort

- While the issues related to the adaptation of the population to UHI, especially to high temperatures, are of great importance, there is limited research on the impact of increasing urbanization on health. In parallel with this situation, the issues of urbanization, population, increasing ambient temperature, the combined effect of humidity and air pollution, hot humidity, and pollution in cities need to be evaluated by further research.
- The UHI impact varies with many different factors, including urban development and structural features. The impact of this effect on human health and urban quality of life is important. Thermal comfort, which stands out as people's evaluation of their satisfaction with the outdoor temperature and environment, depends on many factors such as outdoor air temperature, humidity, wind speed, and environmental factors Karimi et al. [121]; Karimi et al. [87]; Compagnon [122]; Hoyano [123]; Mindali et al. [124]; Nabil and Mardaljevic [125]; Ratti et al. [126]; Taha [127]. Therefore, assessing thermal comfort correctly will be effective in determining it accurately and effectively by taking into account both microclimate conditions and the physical and behavioral characteristics of people at the local scale.

4.5 Sustainability

- Recently, sustainability has been evaluated as a whole with the concept of flexibility. It is a policy that should be adopted so that cities can be resilient in the process of climate change and maintain this situation in the future. Against environmental degradation, which is a negative effect of climate change, sustainable strategies to be determined today should be ensured to maintain their intended benefits in the future.
- In the studies reviewed, it is emphasized that UHI has many negative effects not only on cities but also on people's health. It is therefore important to have a clear understanding of the relationship between urbanization and UHI, taking into account the impact of UHI on human health and also to promote sustainable urban management Isinkaralar [128]; Cheung and Jim [129]; Givoni [130]; Lai and Cheng [131]; Lai and Ahern [132]; Rosales [133]; Schwanen et al. [134].
- The prediction that urbanization and population growth will continue shows the necessity of ensuring sustainability in the twenty-first century. The prediction that urbanization and population growth will continue shows the necessity of ensuring sustainability in the twenty-first century. It is known that this increase will continue to increase Karimi et al. [121]; Leveratto [135]. Therefore, it is important to accurately determine energy consumption, especially in regions with dense built-up areas, and to predict it accurately for the coming years, in order to accelerate the transition to sustainable cities Yamaguchi et al. [136].
- Another important factor in ensuring urban sustainability is that the strategies and actions required to reduce UHI should be included in urban development policies. In this context, it is important for researchers, politicians, architects, and planners to act in cooperation. In this way, it will be easier to create sustainable and healthy urban environments and it will be possible to offer people better quality living spaces. This will also make it easier for cities to act more harmoniously during the climate change process, ensuring that they are less affected by the negative effects of climate change.

4.6 Practical Action Steps

The UHI effect is inevitable in cities because cities consist of a mixture of permeable and impermeable materials. The main problem to focus on is how to reduce the UHI effect. The study identified several spatial factors that contribute to increasing or decreasing the UHI effect. It is thought that these factors and relationships will be a guide for researchers, urban planners and policymakers. In this context, city planners and architects can take climatic scenarios into account when determining suitable residential areas for cities. Temporal and spatial detection of LULC and the results of simulation studies will also be useful for decision-makers in this context. By predicting the future LULC growth direction and pattern, it will be easier to take the necessary steps to ensure energy consumption and urban development in cities. Once the most suitable residential areas are determined, architects can use the research results to determine the ideal building height by choosing suitable materials in terms of thermal properties in design applications. SVF is an ideal method that can be preferred at this point. High sky visibility not only increases the thermal comfort level, but also reduces the UHI effect. In order to increase the level of thermal comfort in urban spaces, studies providing information on which types of plants can be used in urban open spaces by landscape architects and which forms of plants have a more positive effect on the level of thermal comfort will be guiding Mohammad et al. [105]; Zadeh [137]; Canan [138]; Wong and Steve [139]; Yuan and Chen [140].

5 Conclusions

The study of the spatial–temporal factors of the studies evaluating the subject of UHI is important in terms of understanding how UHI is formed and at the same time how it affects areas with different characteristics. This study aims to compile the existing knowledge base on this topic and guide both managers and researchers in this regard. The study presents an analysis of the planning strategies that are effective in reducing the occurrence of UHI and especially the 3D modeling techniques that have gained importance in recent years. A total of 33 studies were determined in this context.

In the studies examined, it has been shown that impermeable surfaces such as buildings, roads, and parking lots increase the temperature, while permeable surfaces such as grass, shrubs, trees, and water bodies reduce the temperature. In addition to land cover assessments, the developments in geospatial analytics, especially in recent years, have enabled the creation of digital 3D representations of complex urban geometries. Studies conducted in this context show that building morphology and temperature are in a strong relationship, and 3D indicators, especially building height and shade, have about 2 times more effect on temperature than 2D land cover variables. The studies examined in this context show the necessity of using advanced spatial statistical techniques in UHI research. In these studies, lidar point data, sky visibility factor (SVF), GIS-based analysis, and modeling are particularly prominent. Due to the developments in geospatial analytics in recent years, there are a limited number of studies focusing on the UHI effect and 3D modeling.

In the process of global climate change, it is extremely important to develop feasible mitigation and adaptation policies. To reduce the negative effects of UHI, one of the biggest environmental problems of climate change, it is necessary to create planning strategies. These strategies directly affect the temperature at the local scale. Therefore, they must be applied in the field of planning. Elaborating effective mitigation strategies within the scope of UHI is an important requirement for urban design, planning, and policy-making. Effectively reducing the occurrence of UHI is equivalent to ameliorating the harmful effects of urban heat on human health and solving the problem of global warming. In the study, research on UHI measurement, evaluation, causes, effects, and spatial–temporal changes of these effects were evaluated. Within the scope of these studies, UHI causes, effects, and spatial–temporal changes were examined. At the same time, state-of-the-art methods to reduce the occurrence of UHI are also systematically presented. Addressing the harmful effects of UHI and adopting effective mitigation strategies that can improve the environmental, social, and economic sustainability of urban structures and landscapes is an important requirement on a global scale. With these aspects of the study, it is thought to be a guide for planners, politicians, and researchers who will work on similar subjects.

6 Limitations of the Research

In line with the researches examined within the scope of the study, it is proposed to develop future researches in three directions. (1) An appropriate and comprehensive design protocol for UHI research needs to be developed. (2) To create models and units in which the relevant features of LULC and urban geometry parameters can be reflected in UHI studies. (3) To develop indices in which UHI impacts can be addressed from many aspects such as environmental, social, health and economic.

Research related to these three objectives will contribute to the development of more comprehensive and effective UHI studies.

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Author Contribution 1. Author Dilara YILMAZ: Conceptualization, data curation, methodology, resources, visualization, writing-original draft, and prepared figures. 2. Author Sevgi OZTURK: Conceptualization, methodology, visualization, writing-review&editing.

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Declarations

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