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Research on strategies to mitigate the impact of Urban Heat Islands using the ENVI-met Model applied to the Van Phu urban area, Hanoi.

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Abstract

Under the extreme development of climate change, the issue of urban heat islands (UHI) is an increasingly widespread concern in many countries worldwide, including Vietnam. In sustainable urban development, climate and environmental information are the most important factors, helping forecast climate change according to planning scenarios and providing recommendations and strategic directions in adjusting planning to minimize climate change. A practical method to study the complex mechanisms of urban climate formation at the urban planning stage is numerical simulation modeling, which assesses the impact of the UHI in relation to the area and evaluates the effectiveness of mitigation measures under different scenarios for that area. In this study, the authors evaluated the effectiveness of measures to minimize the impact of UHI, applied to the Van Phu urban area, Ha Dong Disc., using scenarios of positive change of green infrastructure improvement and increase in greenery in the area. Recommendations have been made to mitigate the UHI. Based on the heat regime simulation results, the solution of changing infrastructure and increasing green areas effectively minimizes the UHI phenomenon and ensures human thermal comfort in urban environments. Future research will focus on developing multivariate correlation regression models to evaluate the effectiveness of UHI mitigation through green infrastructure improvements.

Keywords: *Urban planning; urban heat island; green space; thermal comfort; microclimate;*

1. Introduce

The urban environment is where the radiative, thermal, dynamic, and hydraulic processes change climate. One characteristic distinguishing urban areas from rural areas is their ability to dissipate heat less well at night. Cities accumulate heat energy during the day and only partially release it into the surrounding space at night [1], [2]. The structure of the urban environment is characterized by high-rise buildings with high construction density combined with a large thermal mass of construction materials, leading to reduced wind speeds [3]. In current conditions, when there is a need to minimize the consequences of urbanization, knowledge of modeling various physical phenomena in the city becomes important. Monitoring urban energy consumption, characterizing and quantifying the impact of urban heat islands (UHI), and studying thermal comfort inside and outside the homes of urban residents are widely relevant to the development of knowledge of the interactions between planning, climate, and energy. Urban surface heating is one of the most discussed phenomena in the scientific literature in recent years, contributing to global warming and leading to the need to reconsider planning policies for sustainable urban areas [4]. In addition to the urban heat island problem, climatic conditions and air quality in urban areas are also important for human health and are factors that affect flora and fauna as well as agricultural systems. Urban climate can be described at the micro, meso, and macro levels to identify and analyze relevant climate information. Microclimate can refer to areas or structures with detailed image resolution over distances of up to several meters (e.g., building complexes or trees). Microclimate mainly affects the health of humans, as well as plants and animals. The relevant meteorological indices are (i) temperature, (ii) wind direction and speed, (iii) evaporation, relative humidity, and (iv) solar radiation. For example, impermeable surfaces in urban areas have a negative impact on the microclimate, having scorching heat during the day and gradually cooling down at night [5]. Additionally, these surfaces have little to no filtering ability for air pollutants and dust particles. Negative impacts on the microclimate are mainly due to emissions as well as obstacles to air exchange (such as construction sites), and a reduction in the number of open areas and green spaces is essential for a healthy microclimate [6].

Vietnam is a country strongly affected by climate change, with a significant increase in extreme heat. Vietnam's urban areas are all in the process of expansion and development, making the heat island phenomenon in large cities in Vietnam increasingly severe. One of the most effective ways to improve the comfort and safety of the city environment is to improve green infrastructure. Developing green infrastructure is important in forming urban planning strategies to reduce the urban heat island effect and improve the urban ecosystem. Proposed measures include green spaces, fountains, artificial water surfaces, the greening of roofs, and building facades. Research has proven that the total amount of heat transferred into a building with a green roof can be reduced by 50-60% compared to a conventional roof [10]. In hot, dry climates, increasing air humidity through landscaping can reduce temperatures by up to 5 degrees, thereby increasing thermal comfort in summer [11]. Trees and vegetation are most effective at climate mitigation when planted in "strategic" locations around buildings or to shade sidewalks or streets. These measures are becoming increasingly popular in the fight against rising temperatures in megacities in summer [7]. The connection between ecosystems and urban areas must be the foundation for the sustainable development of urban areas. On the other hand, the lack of open and green spaces, high construction density, urban compaction, poor air quality, and constant traffic congestion can lead to urban environmental degradation [8][9].

In management, urban environmental monitoring using meteorological monitoring data does not always provide the ability to find urban heat islands quickly. Numerical modeling is an effective method to study the complex mechanisms of urban climate formation at the urban planning stage. Over the past two decades, numerical modeling methods have received strong development. They are implemented in modern computer systems and software. Numerical models help to study complex nonlinear heat and mass transfer processes in heterogeneous media, which is especially important when studying urban climate problems. Thanks to the advent of new information technology, digital models are constantly being improved. Through the application of numerical modeling, it is possible to evaluate the effectiveness of urban climate mitigation strategies using different experimental forecasting scenarios. Thus, it is definitely effective in solving and resolving planning issues to ensure the sustainable development of territories.

Energy balance methods (Energy Balance Model, EBM) and computational fluid dynamics (Computational et al.) are used to model heat and thermal mass transfer processes in urban environments. Among them, the CFD method is a powerful tool for modeling the microclimate of the urban environment, allowing the calculation of heat fields, velocities, and radiation, as well as in the assessment of external thermal comfort [12].

The ability to create three-dimensional computer models that simulate urban environments, taking into account climatic influences at different scales, both within the city and within the boundaries of the surrounding area, is a significant advantage of the software and computing complex under consideration. ENVI-met allows for calculating the dynamic characteristics of the air environment, thermodynamic properties, and radiation flows, considering heat transfer processes and thermal mass occurring on the ground surface, walls, and roofs of buildings. Houses as well as green areas. ENVI-met is a 3D microclimate model designed to simulate the interaction of surfaces, vegetation, and air in urban environments based on the fundamental laws of thermodynamics and dynamics liquid. By modeling, it is possible to identify and analyze shortwave and longwave radiation fluxes, considering shading, reflection, and re-radiation from a combination of buildings and vegetation. The main variables the ENVI program responds to are air temperature, humidity, wind speed and direction, environmental turbulence and dispersion levels, radiation fluxes, bioclimatic characteristics, etc. [13]. In this study, the authors used the climate model in the Envi-met program to simulate and calculate the intensity of thermal radiation to evaluate the effectiveness of different mitigation measures, thereby helping to provide a vision. Recognition and decisions related to urban space design, such as the Van Phu urban area and Ha Dong district, were chosen for the case study. This study aims to evaluate the urban heat island phenomenon for urban areas in Hanoi city and determine the effectiveness of mitigation measures on air temperature and thermal comfort of residents.

2. Research data and methods

2.1. Research and data collection area

This study aims to evaluate the influence of high-density urban construction areas on urban microclimate. To achieve this goal, the study considers changing temperature conditions depending on the density of trees in residential areas, thereby evaluating the impact on the thermal comfort of residents in the area. Van Phu urban area in central Ha Dong was studied with a population of 20.000 people and an area of 94,1 hectares and was designed considering the requirements for modern architectural space and infrastructure. The road network accounts for 34,4% of the total area. The Van Phu urban area was chosen because it has the characteristics of a typical metropolitan area with a busy street system and many types of establishments: office buildings with 36-40 floors, adjacent villas, and residential areas with low-rise housing with 4-5 floors. In general, this area is characterized by little vegetation and narrow streets adjacent to high-density highways - sources of pollution.

Microclimate data from the nearest weather station in Ha Dong (VNM_NVN_Ha.Dong.488250) were used for modeling. The purpose of the model is to study how urban microclimate develops from existing environmental conditions and how vegetation and trees influence thermal comfort. Based on climate data from Climate.onebuilding.org, the analysis considered relevant meteorological parameters: temperature variation over time, relative humidity, wind speed, and direction on a sunny day typical hot.

2.2. Urban microclimate modeling

ENVI-met software uses parameters of the building, vegetation, ground, climate, and soil conditions to simulate microclimate changes depending on the shape of the building and additional shading. , etc. ENVI-met is a three-dimensional computer model that analyzes microscopic-scale thermal interactions in urban environments.

ENVI-met models the dynamic changes of several thermodynamic parameters at the macroscopic level, creating a three-dimensional (2×2×2 meter grid), building-air interaction model atmosphere - vegetation - water surface [14]. With a foundation based on the principles of fluid mechanics, thermodynamics, and the laws of atmospheric physics, ENVI-met is capable of calculating three-dimensional fields of wind, turbulence, temperature, and air humidity. Gases, radiation fluxes, and pollutant dispersion[13]. High-resolution spatial model data, combined with detailed vegetation models, can help calculate photosynthetic rates, air temperature and humidity, wind speed, CO2 concentration, and many other information. Others [13].

There are two main steps to take before modeling in ENVI-met:

- Edit input data of the urban area that needs to be checked. This task requires the built environment's geometric dimensions and the urban infrastructure's specific design characteristics, such as land cover lines, vegetation size, and area. The model is designed in a three-dimensional space where buildings, trees/vegetation, and various surfaces are present. These elements are represented by grid cells of different sizes. The smaller the cell, the better the resolution.

- The second step is to edit the urban climate configuration file, which contains information about the object's location, temperature, wind speed, humidity, and PMV parameters, as well as a database of soil types and vegetation. The simulation is then computed using both the input file and the configuration file.

Visualizations are customized to show the urban environment at the desired data layer: horizontally (plan view), vertically (section view), or in 3D axonometric view. This data separation allows for the analysis of small-scale interactions between buildings, surfaces, and individual sources for different scenarios over a 24-hour period.

Through typical meteorological data during the period 2007-2021, one of the hottest days was selected to simulate microclimatic conditions in the region and evaluate scenarios to minimize the recorded impacts. Received on July 3 was 40,4 °C at 17:00 hours in summer (Table 1).

Table 1. Initial data of the study area in ENVI-met

Simulation model size (m)	1440 × 1488 ×240
Model size (number of grid points in xyz direction)	181×187×31
Grid size (meters) dx, dy, dz	8×8×8
Geographic location (latitude, longitude)	20,96 –N; 105,76 -E
Nested grid	8
Method for creating a vertical grid	Equidistant
Time zone	GMT +7
Main parameters of the model	
Simulation date	July 3
Simulation start time	00:00, continuous 24 hours
Wind speed at 10 м	2,26
Wind direction	Southeast

Initial air temperature	33,17 ℃ = 306,17°K
Minimum temperature (simulated day)	31,25℃
Maximum temperature (simulated day)	40,4℃
Average daily specific humidity (g/kg)	19,78
Minimum humidity (simulated day) (g/kg)	17,97 at 5:00 p.m
Maximum humidity (simulated day) (g/kg)	22,5 at 2h

Scenario	**Characteristics**
Scenario 1	Current status of the urban area Van Phu
Scenario 2	The amount of green trees has increased by 30%, increasing lawns, and renovating roofs and walls in the area into green wall and green roof systems for building, accounting for about 70% of the area.
Scenario 3	The amount of new trees in urban areas increased by 50%

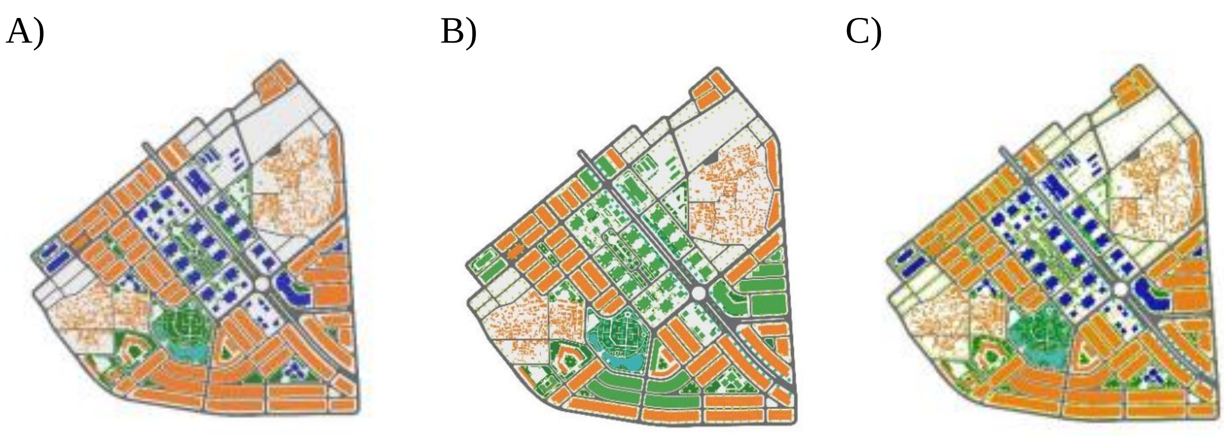

Figure 1. Simulation scenario for Van Phu urban area according to: (A) Scenario 1*; (*B) Scenario and (C) Scenario 3.

Table 2. Scenarios for Van Phu area

3. Results

The results obtained from the simulation show that the air temperature in the area in the scenarios has similar day-night changes and is consistent with the observed temperature changes. Air temperature tends to be lowest in the morning at 4-5 a.m. and maximum at 4-5 p.m. during the day and then gradually decrease. Examination and evaluation of the simulation results obtained show that the mitigation strategies proposed in scenario two and scenario three both help reduce air temperature in urban areas and improve thermal comfort.

Specifically, at 12:00 a.m. during the simulation day, the air temperature in the area calculated according to scenario one ranges from 36,55 – 38,83 °C; however, if the amount of greenery is increased by 50%. In the region, the temperature in the area will decrease from 0,21 – 2,42 ^{0}C, fluctuating between 34,13 – 38,62 ^{0}C, shown in Figure 2.

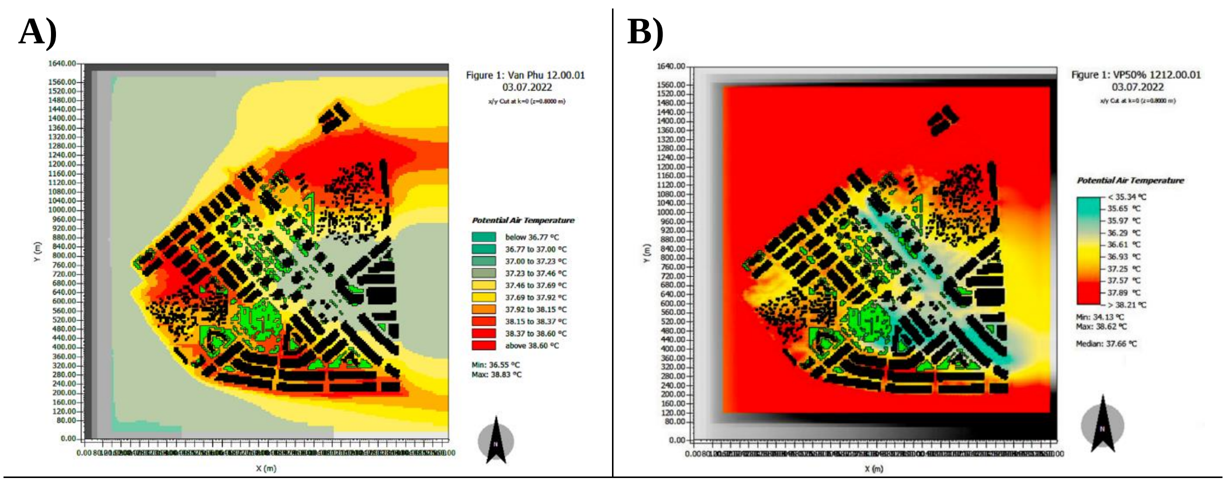

Figure 2. Evolution of air temperature in the Van Phu urban area at 12:00 on July 3, 2022, according to (A) Scenario 1 and (B) Scenario 3

Comparative results of the difference in air temperature during the hottest time of the day at 16:00 between scenarios show that, if don't have any mitigation methods, the temperature recorded in the Van Phu urban area of Scenario 1 is from 39,54 to 40,97 °C.

When implementing the mitigation methods proposed under Scenario 2 and Scenario 3, there is a significant decrease in air temperature in the Van Phu urban area. In particular, on the central road in the area, the temperature is improved and reduced by 1,5 – 4,36 °C in scenario 2 and decreased from 1,34 – 3,8 °C in scenario

3 when compared to the temperature in the same location in scenario 1. The calculation results also show that there is a difference. There is a slight difference in air temperature between Scenario 2 and 3 methods, a maximum of about 0,43 °C, in which the deployment of green infrastructure combined with planting more trees is effective in reducing air temperature.

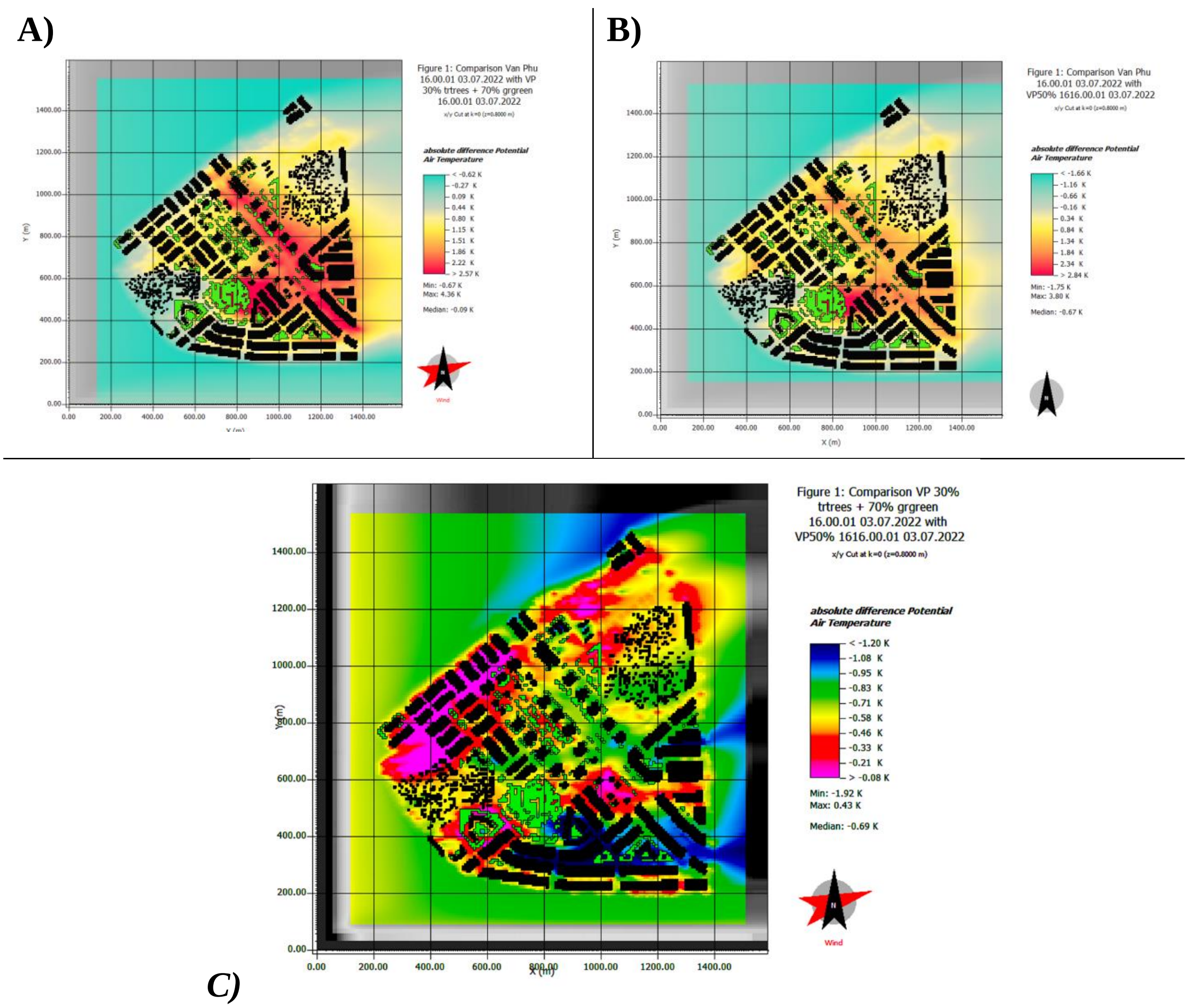

Figure 3. Zoning of air temperature difference (°C) in the Van Phu urban area between: (A) Scenario 1 and Scenario 2; (B) Scenario 1 with Scenario 3 and (C) Scenario 2 with Scenario 3.

In order to evaluate the impact on people's urban thermal comfort level, the study used the calculated thermal indices T core static (static base temperature), T skin static (static skin temperature), and T cloths statics to characterize the thermal environment influences on human thermal comfort perception. Human response to environmental temperature in the area is an increase in body and skin temperature, especially from 6:00 a.m. to 5:00 p.m. The simulation results for the crossroads in the Van Phu urban area in Figure 4 show that the proposed mitigation scenarios, which include changing the area's landscape, all help reduce heat values. Especially during the day, thereby increasing human comfort due to the shading effect and moisture evaporation from trees' leaves and soil surfaces.

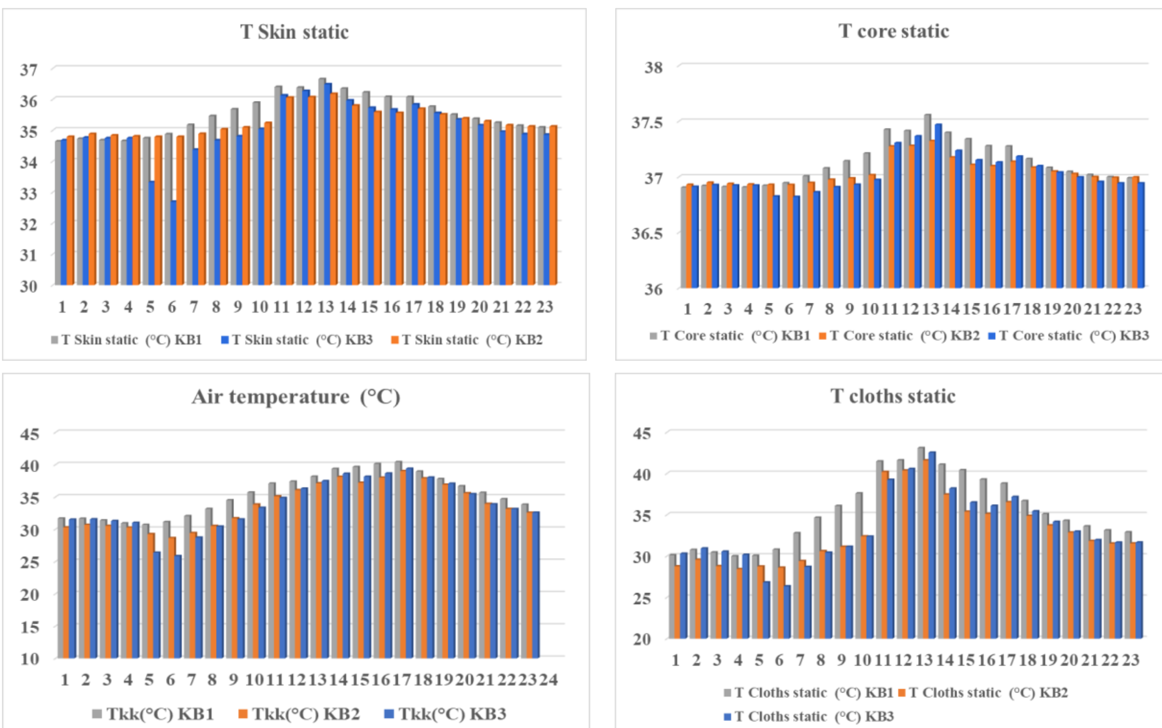

Figure 4. Evolution of temperature parameters in assessing human comfort

Core static temperature refers to the human body's internal temperature and is maintained within a narrow range, approximately 36,5 to 37,5 °C, under normal conditions. It can be seen that in scenario 1, the Core static temperature value at 13:00 exceeds 37,5°C, which can make the body feel hot and uncomfortable. The mitigation scenarios all show that this value fluctuates within the allowable range, bringing comfort to people.

The figure shows the temperature of clothes for three different scenarios. The temperature of all three scenarios values range from 25 to 45 °C and exhibit a similar trend:

initial increase in temperature, peaking at 13:00, followed by a decline. Scenario 1 generally shows that the highest temperature values and variability (over 40 °C) are likely to exceed comfort thresholds, leading to overheating, sweating, and discomfort. Such conditions may compromise thermoregulation and result in thermal stress. Scenario 3 consistently shows the intermediate values suggest a moderate level of comfort, though still prone to slight discomfort during peak times. Scenario 2 shows the lower values and more stable temperatures, which are expected to maintain conditions closer to the thermal comfort zone, minimizing stress and enhancing comfort.

The analysis of Temperature Clothes Static values across the three scenarios reveals significant differences in thermal conditions, impacting human thermal comfort. Scenario 1 exhibits the highest variability and peak temperatures, potentially leading to discomfort and thermal stress. In contrast, Scenario 2 maintains lower and more stable temperatures, promoting better thermal comfort. Scenario 3 presents intermediate conditions, balancing between the extremes of Scenario 1 and Scenario 2.

4. Discussion

Rapid urbanization has increased the level of microclimate extremes between urban areas and neighboring natural areas, as well as aggravated ecological safety issues such as:

- The decline in agricultural land area used for urban development, entertainment areas, and industrial facilities;

- The use of energy sources is increasing due to increased living needs, the intensive operation of means of heating buildings and structures, household and industrial energy consumption;

- Degradation of the air environment in cities, the amount of pollutants released into the atmosphere is increasing due to traffic, industrial and thermal power facilities;

- Degradation of water resources due to air pollution of water bodies and discharge of untreated or untreated wastewater;

- Microclimate changes in cities due to uncontrolled heat loss, etc.

The urban environment significantly impacts soil, water resources, air basins, and vegetation cover, leading to the occurrence of UHI, which negatively affects the quality of life of city residents. Considering the specific characteristics of UHI for the Van Phu Ha Dong area, the study proposed various modifications to the current design of the built-up areas. Enhancing vegetation, thereby increasing the vegetation index, is a popular method due to trees' cooling and shading effects. Another option is to transform urban surfaces, such as renovating wall surfaces and green roofs, to help effectively reduce air temperature through changes in solar radiation and emitted radiation. Environment. Simulation results for the Van Phu urban area show that measures to reduce UHI in the area through increasing greenery or combining measures between green infrastructure, trees, and grass all contribute to significant reduction. Includes air and surface temperatures in the area. The combination of renovating green infrastructure and increasing greenery in the area helps mitigate more effectively. However, the rate of renovating buildings also accounts for a large proportion of the area and has a large surface area. Much more extensive than the number of trees added to reduce the temperature accordingly. It can be seen that urban landscape planning design is essential in minimizing environmental problems. The organization of green space in the Van Phu area is proposed to be implemented according to the following principles:

− To effectively regulate the microclimate, trees must be placed close together to form green corridors to optimize natural urban ventilation;

− The standard area of green space must meet the standards, at least 7 m2/person;

− Green space must create maximum conditions for human culture, life, and social activities. Landscaping should meet requirements and take into account efficiency with minimal costs;

− Encourage construction to increase the use of environmentally friendly materials and green materials, take measures to minimize impacts, and protect green spaces.

5. Conclusion

The study has clarified the impact of trees on reducing the UHI phenomenon by using the ENVI-met model combined with simulation scenarios with changes in the number of trees in the area, evaluating the impact on parameters such as air temperature, relative humidity, surface temperature, and thermal comfort index. The results have shown that adding trees in the area combined with improving green infrastructure will help reduce the air temperature in the area at the hottest time of the day from 1.5 - 4.36 °C at the same time. Also provides better thermal comfort for humans, especially during the day.

The above results of the study show that it is possible to reduce the UHI phenomenon in urban areas with simple approaches, such as changing vegetation in the area or improving green infrastructure. This is the basis for further strengthening the need for greening in urban design and planning because it is effective in cooling and brings benefits, such as the potential to reduce carbon and greenhouse gas emissions and bring thermal comfort to people in urban areas.

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