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SIMULATION MODEL OF GREEN OPEN SPACE ON MICROCLIMATE PERFORMANCE IN TROPICAL COASTAL AREA

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Abstract

This research aimed to simulate scenario of green open space to mitigate heating within microclimate performance. It also optimized the composition of the built environment's surface to reduce urban heating. A numerical model was simulated using ENVI-met, and spatial analysis was conducted with ArcGIS software. Three different scenarios were established to propose solutions for heating reduction. Simulation showed that a balanced composition between buildings and vegetation resulted in air temperature decrease of 2.45°C to 3.31°C compared to no-greenery simulation. Meanwhile, when compared to the existing situation, hybrid greenery achieved a 3.50°C air temperature decrease. This research offered valuable insights into the urban environment by prioritizing landscape design, focusing on buildings and the composition of green open space in surrounding areas

Keywords: Green open space, scenario simulation, air temperature, spatial analysis.

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INTRODUCTION

Urban heat island (UHI) is a phenomenon that originates from land cover changes and rapid urbanization, specifically affecting urban ecosystem (Oxoli et al, 2018; Mutani et al, 2019). Due to the consequences of urban landscape and anthropogenic heat release, cities experienced higher surface air temperature that influenced local climate. Therefore, green open space is an effective nature-based solution to improve the quality of the natural environment and mitigate UHI. This approach can reduce heat by modifying the proportion of green vegetation and surface geometrical features, such as building height, density, as well as city design and shape (De Abreu et al, 2015; Ragheb et al, 2016).

Urban ecosystem comprises three different elements, namely impermeable surfaces, vegetated surfaces, and water bodies. These elements are closely related to the actual properties of the urban morphological surface, subsequently influencing both the microclimate of urban area and heat intensity (Chatzidimitriou et al, 2015; Broadbent, 2020; Krayenhoff et al, 2020). Microclimates are governed by the localized outdoor thermal environment, which includes parameters like air temperature, air pressure, wind speed, and direction (Eni et al, 2015; Galagoda et al, 2018). To minimize the high intensity of microclimate, new construction and urban planning using various technologies and strategies can be implemented.

Dense buildings can increase thermal capacity and reduce wind speed in an environment. During the day, building materials and density trap heat, while at night, the heat is released, affecting diurnal air temperature (Krehbiel, 2017). This also applies to other man-made features, such as roads, asphalts, and pavements, which increase anthropogenic heat emission to the atmosphere (Oke et al, 2017; Arifwidodo, 2019). Simulating landscape elements can alter both wind and radiation, as well as atmospheric temperature and humidity at the neighbourhood or community level. Research have shown that a balanced composition of vegetation space among buildings can significantly reduce heat stress but may have a negative impact on wind ventilation (Yahia, 2018; Zhang, 2022). Only a few research focused on local or small-scale modeling of green open spaces, as large amounts of air temperature and land surface temperature are investigated using large-scale remote sensing observations (Peng, 2019). Therefore, to investigate the spatial air temperature variation under microclimate behaviour, scenario simulation of green open space in a specific area was conducted. An urban university campus environment in Semarang, Indonesia, was selected to model simulation. Furthermore, a geographic information system (GIS) was used to generate spatial data and ENVI-met as well as green open space scenario for heat mitigation strategies.

METHODS

Research area

Universitas Islam Sultan Agung in Semarang, northern central Java coastal area, was selected for the research simulation. This area is located at the coordinates 110°27'22.44" – 110°27'36.93" E and 6°57'6.82" – 6°57'23.35" S. The campus environment had high air pollutant and emission levels due to its proximity to an industrial area, settlement, and Java national roads (Figure 1). The campus covered area of 20.7 hectares, comprising building areas (3.88 hectares or 19%), ponds (3.82 hectares or 18%), green open space (4.76 or 23%), and non-vegetation surfaces, such as parking area, pavements, courts (8.19 or 40%). The heights of low-rise buildings were between 4 m - 10 m and medium rise buildings ranged between 10 m - 30 m. Measurements were conducted during the dry season from 19 to 25 September 2022 for 24 hours at 15-minute intervals using a temperature and humidity automatic recorder (Tables 1 and 2). Air temperature data from the meteorological agency were used to validate the ground measurement. Missing data were interpolated and erroneous data for further analysis.

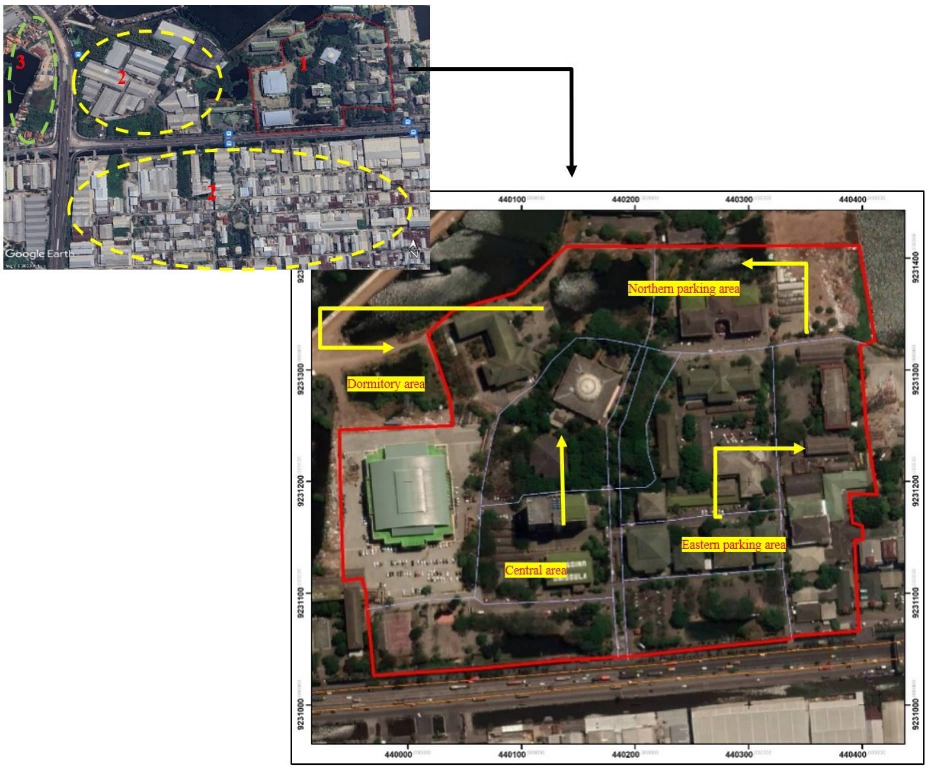

Figure 1: The research location and surrounding area: (1) campus area selected as the research area, (2) industrial area, and (3) settlement.

Table 1: Field measurement from 19 - 22 September 2022

Date	19-Sep-22		20-Sep-22		21-Sep-22		22-Sep-22	
Location	Outdoor air temp [ºC]	RH [%]	Outdoor air temp [ºC]	RH [%]	Outdoor air temp [ºC]	RH [%]	Outdoor air temp [ºC]	RH [%]
Auditorium area (DA)	31	61	31	57	31	55	31	48
Northern parking area (NP)	32	57	32	54	31	52	31	46
Eastern parking area (EP)	33	54	32	54	32	51	32	45
Central area (CA)	33	55	31	58	32	50	32	46

Table 2: Field measurement from 23 - 25 September 2022

Date	23-Sep-22		24-Sep-22		25-Sep-22	
Location	Outdoor air temp [ºC]	RH [%]	Outdoor air temp [ºC]	RH [%]	Outdoor air temp [ºC]	RH [%]
Auditorium area (DA)	30	46	31	49	33	55
Northern parking area (NP)	31	43	31	45	33	53
Eastern parking area (EP)	32	42	32	43	33	52
Central area (CA)	33	44	32	45	33	55

Simulation Setup

The research framework is presented in Figure 2, and model was simulated using ENVI-met software to calculate climatic factor parameters (air temperature) in the research area. ENVI-met is a 3D simulation software designed to analyze surface-plant-air interaction in urban neighborhoods ranging from 0.5 to 10 meters. The software used the principle of thermodynamics and fluid dynamics to calculate urban microclimate such as air temperature, turbulence, and humidity (Zhao et al., 2017).

The following was carried out to set up simulation. Firstly, the map was prepared by digitizing each building and vegetation features, represented in the grid cells of 40 x 40 x 20 m, with a vertical and horizontal grid resolution of 2 m. Secondly, simulation period ran for 24 hours starting at 7 pm, with model output generated every 60 minutes. Thirdly, meteorological settings were configured by inputting wind speed at 10 m height (m/s), wind direction (in degree), roughness length at the measurement site, temperature, and humidity.

Regarding the greening scenario simulation, three scenario models were prepared based on the greenery status to be planted in the selected area, reflecting the current situation (Figure 3). The three scenario simulations, as presented in Figure 4, included base case (zero green open space or no greenery), greenery (a balanced composition between buildings and green open space), and hybrid greenery (80% green open space and 20% buildings). All buildings had a height of approximately 20 m, while the trees reached 10 m. To evaluate the general model accuracy, the base model was compared to observations using R^2. Meanwhile, the root mean squared error (RMSE) was calculated to assess the performance of simulation scenario (Willmott, 2005; Pichierri, 2012).

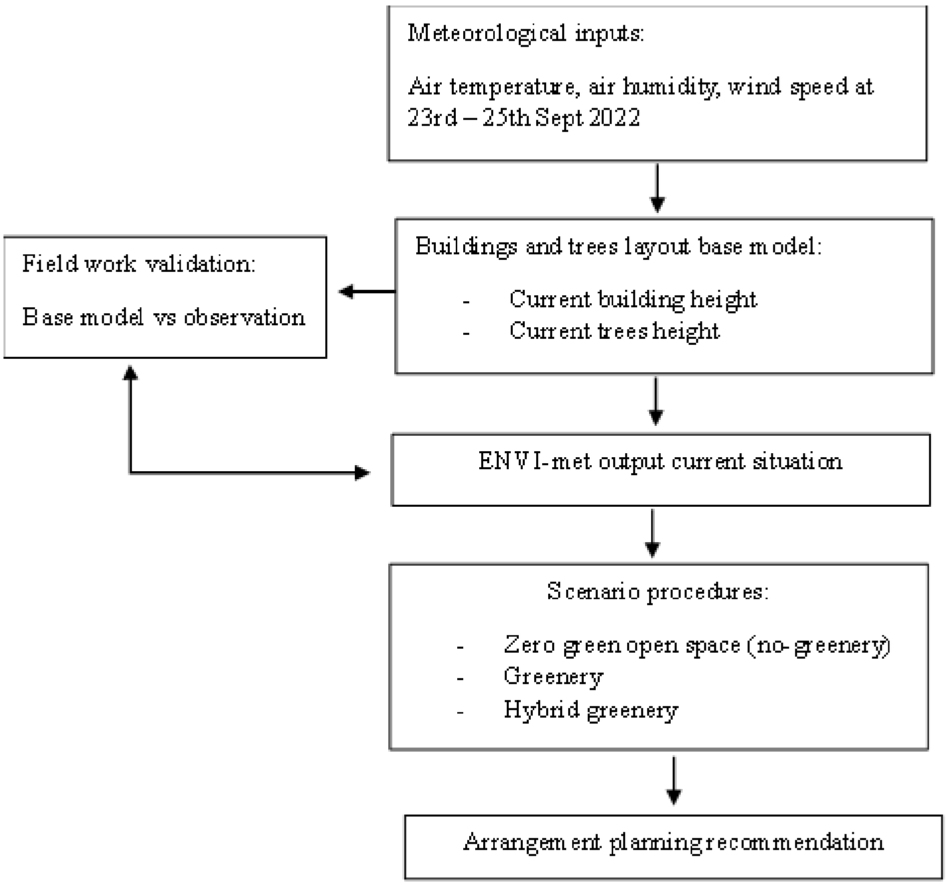

Figure 2: Methodology framework

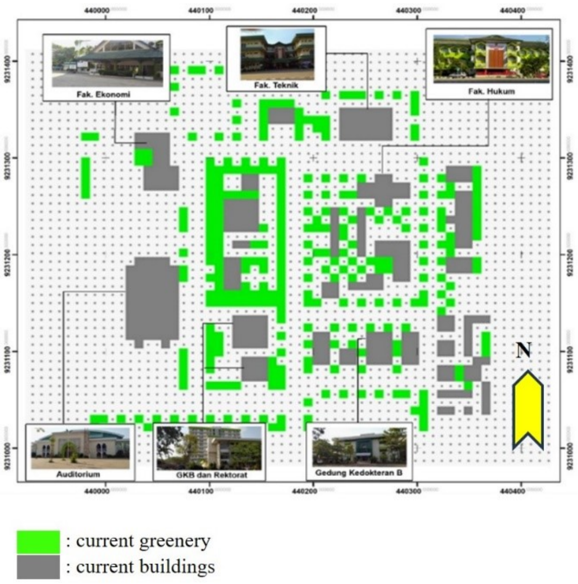

Figure 3: Current site situation as simulation baseline

Figure 4: Proposed scenario of green open space in the focus area: (a) no greenery, (b) greenery, and (c) hybrid greenery.

RESULTS AND DISCUSSION

Model validation

A comparison of air temperature measurements without any scenario and simulation data for the observation period was conducted to validate simulation (Figure 4). Figure 5 shows the scatter plot between air temperature measurements and simulation, with both showing good performance ($R^2 = 0.9$). The results showed that air temperature performance, on average, increased during the day, starting in the morning, and gradually decreased from the late afternoon to evening. To calibrate the modeled measurements with field location, data from the nearest meteorological agency weather station were used, which showed irregular heating patterns. Considering the entire day, this irregularity might be attributed to the broader coverage area of the nearest weather station instead of fixed-point measurement in the focus area. The fixed-point measurement is a localized measurement that can provide a more detailed representation of air temperature behavior. This measurement showed higher temperature intensities from 10 am to 2 pm, with an average value of 33.1°C, while the control temperature was 27.3°C.

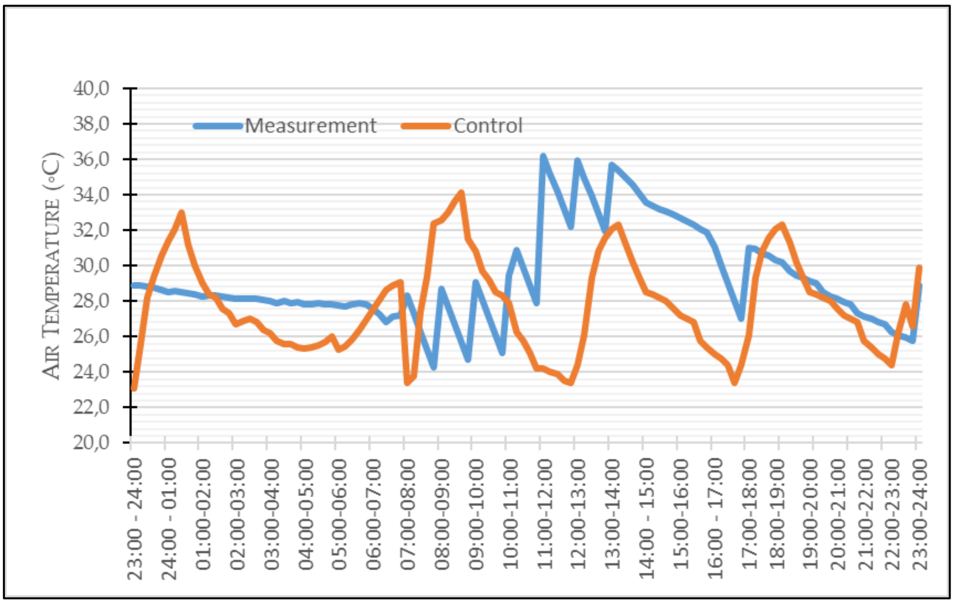

Figure 5: Hourly measured air temperature and control point air temperature.

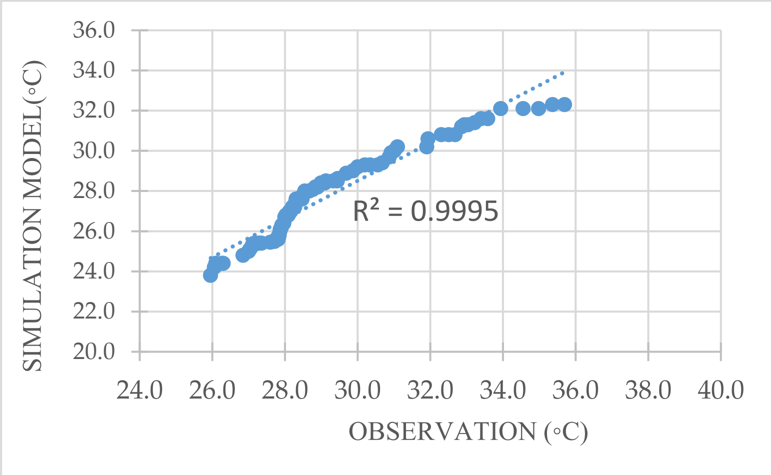

Figure 6: Scatter plot of air temperature measurement and control point.

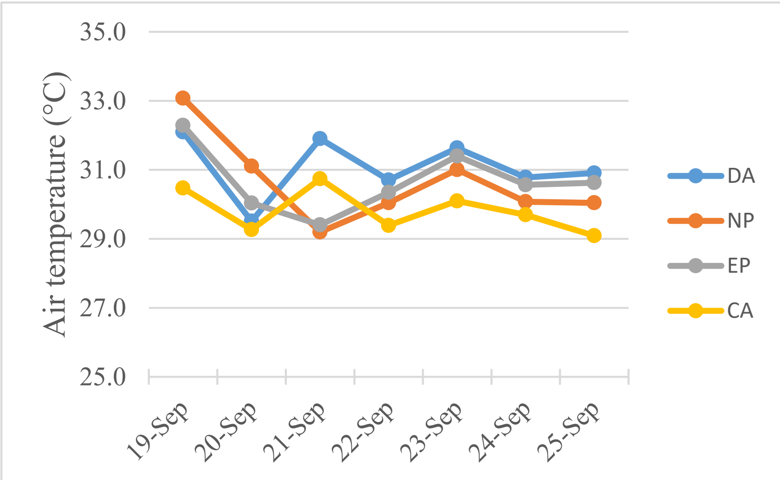

Figure 7: Air temperature measurement points in focus areas.

Figure 6 shows the average daily air temperature in four in situ points from 19 to 25 September 2022. The highest average air temperature was 33.1°C in the northern parking area (NP) on 19 September, and the lowest average was 29.1°C in the CA on 25 September. The variation in air temperature at each in situ measurement point was influenced by the surrounding physical environment, such as shadowing, building density, and local landscape. Generally, the highest air temperature was recorded in open impervious area (Willmott et al., 2005). Interpolation was conducted using GIS based on the in-situ measurement points on two selected days (19 and 23 September) to understand the distribution of daily average air temperature.

The results showed that the daily average air temperature on 19 September 2022 ranged from 32.8°C to 39.4°C (Figure 7a), and ranged from 29.5°C to 32.2°C on 23 September 2022 (Figure 7b). The red gradient mark showed the highest average air temperature, while green gradient mark showed the lowest. According to the map, there was variation in heat distribution corresponding to the different average ranges of air temperature. On the left side (Figure 7a), the cold area was localized in the CA, while on the right side (Figure 7b), the CA was dominated by higher air temperature. Therefore, heat was closely related to extensive sun radiation exposure and atmospheric conditions during the days.

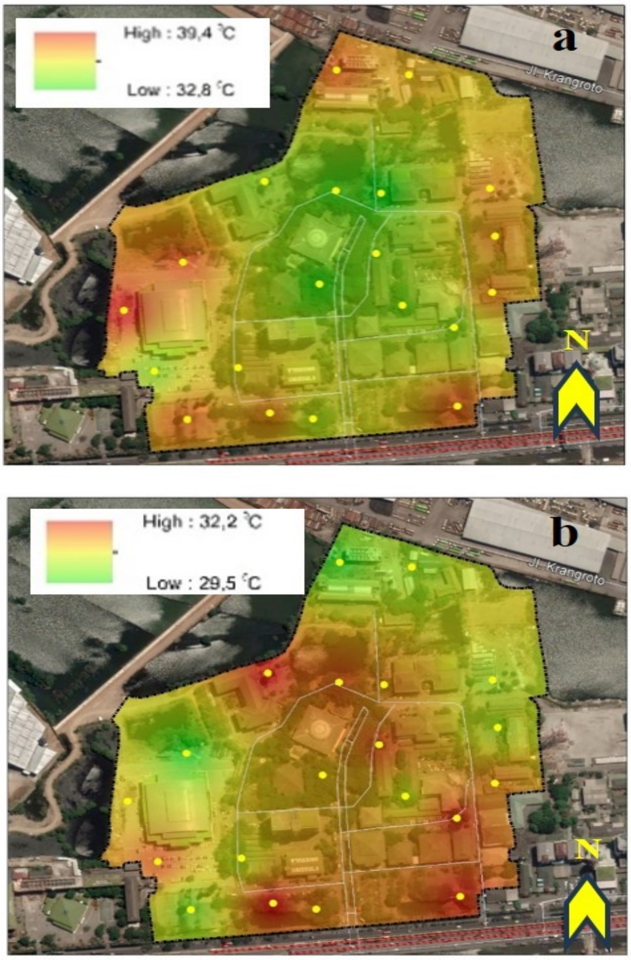

Figure 8: Distribution of air temperature in the selected days, namely (a) 19 and (b) 23 September 2022

Simulation Scenario

Model simulation scenario for green open space under microclimate performance was developed by interpolating the weekly average air temperature using GIS. Figure 8 showed air temperature in three different simulations, namely simulation 1, representing the absence of greenery; simulation 2, a balanced composition between buildings and vegetation; and simulation 3, hybrid greenery (80% vegetation and 20% buildings). The Root Mean Square Error (RMSE), showing the variation of calibration process result, is presented in Table 3. Simulation 2 obtained the lowest RMSE value (2.7). Figures 9 - 11 show the variation in air temperature for green open space scenario under microclimate performance, with air temperature measured at 1.5 m above the ground. The results showed that simulation 1 (Figure 9) had high heat intensity in the absence of greenery, with cooling effects only produced by shadowing. The highest recorded air temperature was 39.5°C, while the lowest was 37.67°C.

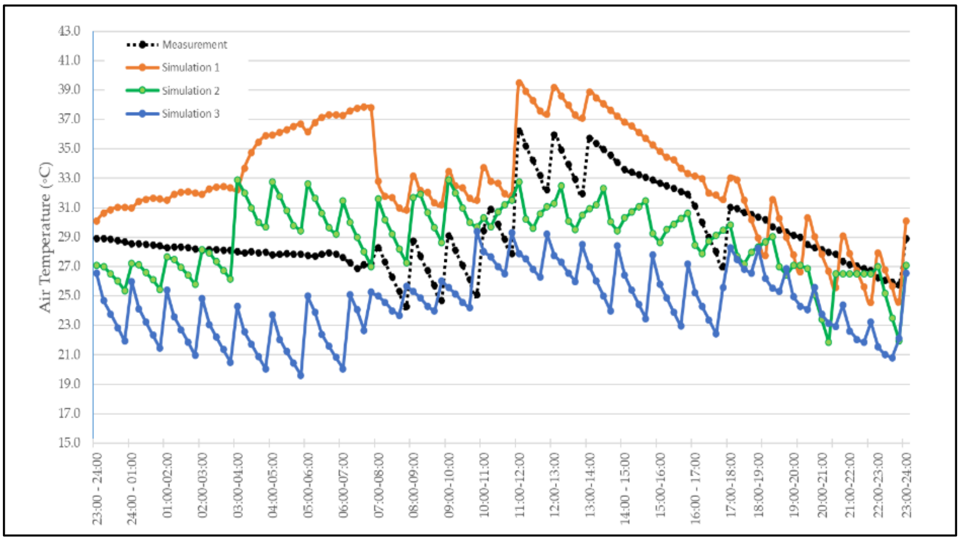

Figure 9: Comparison between air temperature measurement and simulation.

Table 3: Root Mean Square Error (RMSE)

Simulation Scenario	RMSE
1	4.7
2	2.7
3	5.0

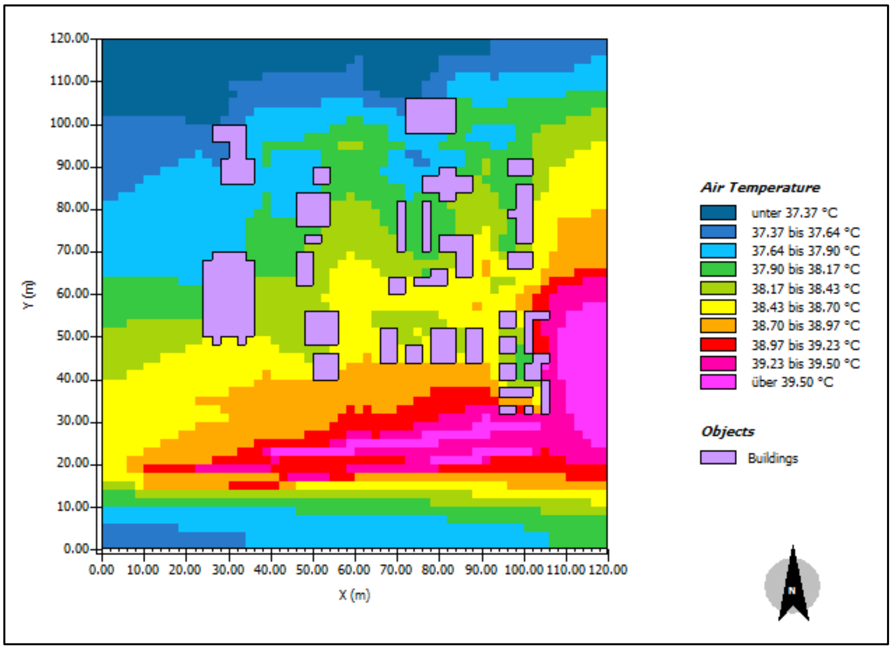

Figure 10: Simulation 1 (no greenery).

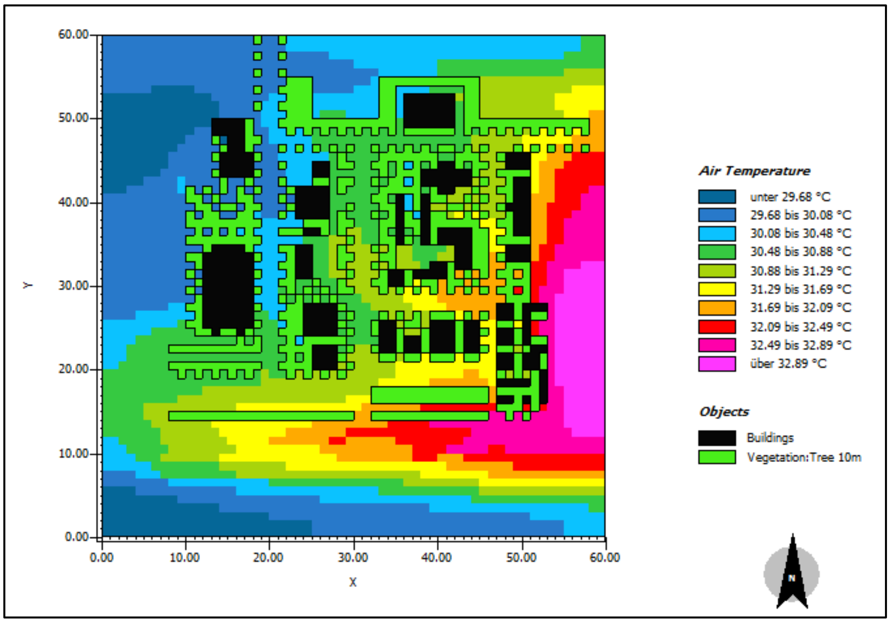

Figure 11: Simulation 2 (a balanced composition between buildings and vegetation).

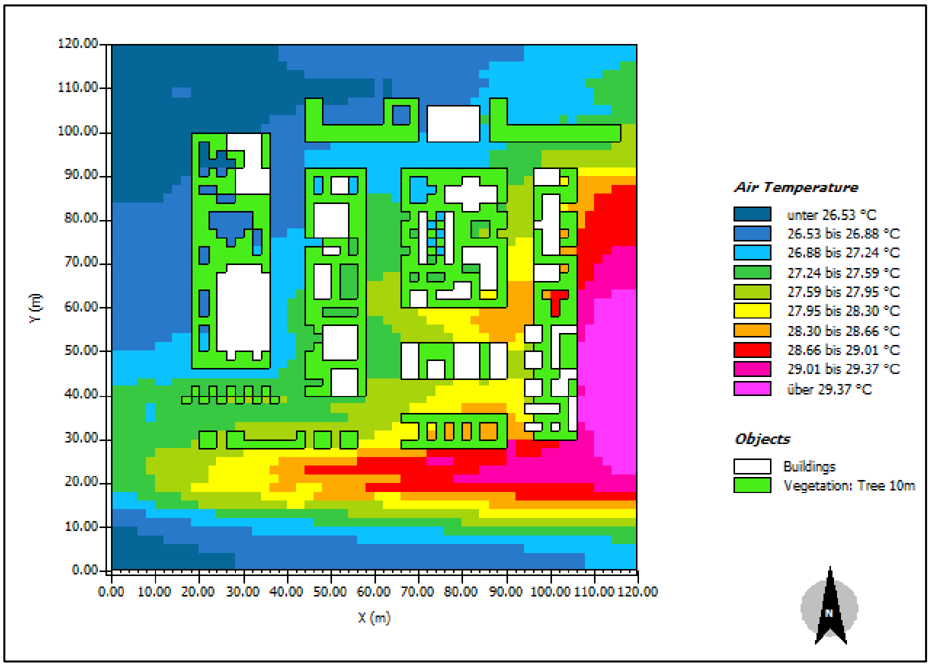

Figure 12: Simulation 3 (hybrid greenery).

Figure 10 shows the spatial variation of air temperature in simulation 2, which was set up with a balanced composition between buildings and vegetation. The results showed this scenario had a better cooling effect on the focus research. The highest air temperature recorded was 32.89°C, and the lowest was 30.06°C. Figure 11 shows the results of air temperature spatial variation in simulation 3, which was set up with hybrid greenery, consisting of 80% vegetation and 20% buildings. Simulation showed that hybrid greenery decreased the heat intensity of air temperature compared to simulations 1 and 2. The highest air temperature was 29.37°C, and the lowest was 26.68°C. The results showed that the distribution of air temperature was significantly influenced by the surrounding landscape environment. The intensity of the cooling effect was consistent with the greenery composition and controlled by different factors, such as artificial surfaces, building shading, solar radiation, and specific periods of solar intensity.

Table 4: Average, minimum, and maximum difference air temperature (°C) between the current situation and simulation scenario

	Simulation 1	Simulation 2	Simulation 3
Average difference	2.47	1.70	-3.50
Minimum difference	1.00	-2.80	-6.90
Maximum difference	3.30	0.01	-0.03

Table 5: Average, minimum, and maximum differences in spatial variation of air temperature (°C) between the current measured situation and simulation scenario

	Scenario 1	Scenario 2	Scenario 3
Average difference	3.67	-0.43	-4.81
Minimum difference	0.24	-2.45	-4.69
Maximum difference	3.30	-3.31	-6.83

Table 5 shows the observed spatial variation in air temperature difference between the current measured situation and simulation. In simulation 1, where there was no greenery, air temperature increased by a range of 0.24°C to 3.30°C. Meanwhile, in simulations 2 and 3, where greenery was introduced, air temperature cooled down from -2.45°C to -0.43°C. Furthermore, trees ranging from 5 m to 15 m in height reduced the heating compared to open pavements or canopies in parking areas.

CONCLUSION

In conclusion, air temperature was selected as the microclimatic parameter, collected at four measurement points, interpolated to investigate spatial variation, and subsequently simulated using ENVI-met scenario output. Three different scenarios were simulated by mitigating heat in the focus area. During sunny days, trees ranging from 5 to 15 m in height reduced air temperature by distributing the wind and providing shade. The best RMSE was observed in simulation 2, which had a balanced composition of buildings and vegetation, while the worst was observed in simulation 3, featuring hybrid greenery. Therefore, a balanced composition of buildings and vegetation in simulation 2 showed a better performance in mitigating heat since high building density, trees, and surrounding built surfaces could influence outdoor air temperature.

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