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The Effect of Urban Farming Module on Urban Heat Island in Yogyakarta (A Case Study of Ngampilan Urban Village)

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ABSTRACT

Ngampilan, the most densely populated sub-district in Yogyakarta City, experiences a significant Urban Heat Island (UHI) effect, as revealed through land surface temperature mapping. This issue is intensified by high residential density and heat-absorbing surface materials with low albedo values. To mitigate this phenomenon, the study explores the introduction of urban farming modules tailored to the area's morphology within the LCZ 3 zone. The research addresses the effectiveness of urban farming modules in reducing mean radiant temperature (MRT) in densely populated areas and the optimal module placement for maximum temperature reduction. The 3D model of the urban farming module was developed using Sketchup, reflecting site-specific characteristics. Envi-met software was then employed to analyze the area, incorporating the module at predetermined points. The module's impact on MRT was evaluated at four distinct stages, corresponding to different proportions of module coverage in Ngampilan Urban Village. This analysis spans three location points and four time periods, with results presented through comprehensive mapping, longitudinal-transverse sections, and micro impacts at each module point. Findings indicate that urban farming modules contribute to a reduction in MRT temperatures by up to 3.9 degrees Celsius, highlighting their potential benefits in mitigating UHI effects and improving urban microclimates.

Keywords: urban farming, urban heat island

1. Introduction

As the fourth most populous province in Indonesia [1], Special Region of Yogyakarta or "*Daerah Istimewa Yogyakarta* (DIY)" faces numerous challenges and issues. While the region experiences rapid economic growth, supported by the education and tourism sectors, and a burgeoning population, there is a concurrent decline in environmental quality. This uncontrolled population growth, increasing needs, and ongoing development, often termed as urban sprawl [2], lead to various negative impacts on cities. These impacts include decreased groundwater availability and green open spaces, rising temperature and pollution levels, climate uncertainties, diminished health and well-being of urban residents, and urban area expansion [2] [3]. These trends are particularly evident and can be measured in Yogyakarta City, DIY's capital, where the Land Surface Temperature (LST) map indicates significantly higher temperatures in the city center compared to surrounding areas (Figure 1). This situation is further exacerbated by the inadequate green space in Yogyakarta, with a Green Base Coefficient of only 23%, falling short of the 30% minimum standard required by Indonesian Law Number 26/2007 on Spatial Planning [4].

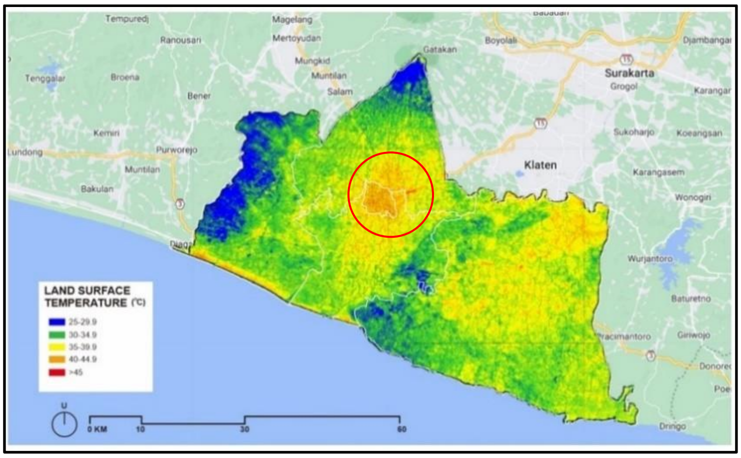


Figure 1. DIY's LST Map
Source: Author, 2023 [5]

1.1. Urban Heat Island

The Urban Heat Island (UHI) effect is a condition in where urban areas experience higher air temperatures than their rural counterparts, both during the day and at night [6]. This phenomenon arises from several factors, including the replacement of natural landscapes with heat-absorbing materials like buildings, roads, and parking lots; geographical aspects such as the shape and arrangement of structures obstructing wind flow and trapping heat; and human activities that increase heat production, such as the use of private vehicles, air conditioning, and industrial operations [7].

Addressing UHI is challenging due to the continuous growth in population and urban demands, making it difficult to replicate rural conditions in urban settings. However, various strategies can mitigate UHI's negative effects. Technological and scientific advancements offer the potential to replace traditional materials with cooler, lower-albedo alternatives for roofs and pavements [8]. Albedo, the measure of surface reflectivity, ranges from 0 (absorbing all radiation) to 1 (perfect reflector) as shown in Table 1, plays a critical role in the Earth's surface energy balance [9, 10]. Another effective strategy is increasing urban vegetation, as plants can significantly reduce air temperatures through evapotranspiration [11].

Table 1. Albedo for Urban Surfaces

Material	Albedo
Highly reflective roof	0.60–0.70
White paint	0.50–0.90
Grass	0.25–0.30
Brick and stone	0.20–0.40
Trees	0.15–0.18
Red or brown tile	0.10–0.13
Concrete	0.10–0.35
Corrugated roof	0.10–0.16
Tar and gravel	0.08–0.20
Asphalt	0.05–0.20

Source: US EPA, 1992.

Source: [8]

1.2. Urban Farming

Previous studies have demonstrated the effectiveness of green strategies in mitigating the UHI effect and enhancing urban ecological benefits, such as improving atmospheric conditions through O2 and CO2 exchange, serving as sound insulators, and cooling the environment [12, 13, 14]. However, creating green spaces in urban areas faces challenges due to high population density, limited available land, and rising land prices [15]. Greening solutions like green roofs, green walls, and vertical farming can address these issues [16, 17]. Vertical farming, or urban farming, goes beyond being an environmental solution; it also supports urban food security by efficiently producing agricultural goods, particularly vegetables and fruits, using hydroponic methods [18].

1.3. Modular System

This study introduces an innovative urban farming approach using a modular system, where building structures are manufactured off-site and assembled on-site. Although less flexible than traditional designs, this method offers several advantages, including cost-effectiveness, faster construction, higher construction accuracy and quality, and easier maintenance due to its disassembly capabilities [19]. Thus, this research builds on previous research by exploring the implementation of urban farming modules in mitigating the UHI effect and enhancing environmental quality in densely populated urban settings. The hypothesis is that urban farming modules, when strategically placed, can significantly reduce the Mean Radiant Temperature (MRT) and improve urban microclimates.

The purpose of this study is to evaluate the effectiveness of urban farming modules in reducing the UHI effect in Yogyakarta. By analyzing the impact of these modules on MRT and overall environmental quality, the research seeks to provide viable solutions for improving urban sustainability and resilience.

2. Method

This paper uses a mixed-methods approach, combining descriptive and experimental-analytic research [20].

2.1 Data Collection

Preliminary Research: The research begins with an extensive desktop study aimed at understanding the location and pinpointing relevant research issues. This phase involves a descriptive analysis to elaborate on the findings from the literature review and secondary research using regional data. The literature review focuses on theories of UHI and urban farming. UHI research aims to define the concept, establish minimum standards, and identify influential factors, providing the foundational data for simulation, while urban farming theory is investigated as a potential hypothesis, representing an effective design solution for urban areas.

Satellite Imagery Acquisition: Using existing designs, research continues with the mapping of Ngampilan District using satellite imagery from Google Maps. Key aspects extracted from the satellite imagery included building distribution and height, vegetation distribution and types, and the conditions of roads and open areas. The images were captured within the defined boundaries of the area intended for the simulation model.

Weather Data Collection: Climate data used for the simulation were sourced from the official MERRA-2 weather station website. Data recording was performed over 24 hours on December 4, 2023, capturing air temperature, humidity, wind speed and direction, and cloud cover percentage.

ENVI-met Simulation: ENVI-met is a software that processes climate data using fluid dynamics calculations in open and built environments that capable of calculating detailed and complex microclimatic conditions in urban areas [21, 22]. The experimental method with ENVI-met produced maps of microclimate distribution and values. The tested models included existing conditions and the distribution of urban farming modules with scenario of the module coverage of 5%, 10%, and 15% (based on Green Base Coefficient scenarios) over open areas such as streets, buildings, and open spaces.

2.2 Data Analysis

Comparative Study: Data for the comparative study were based on the distribution of MRT as an indicator. MRT serves as a computational model for urban microclimates, enabling the mapping of heat exposure distribution across urban areas [22]. MRT values were extracted from the simulations of existing conditions and module distributions in different characteristic areas such as black asphalt roads, open soil fields, and rooftops. MRT data were extracted from cross-sections at a height of 0.5 meters and from the y-axis plane. The comparison of distribution maps and extracted MRT values from the existing simulation and module scenarios provided insights into the impact of urban farming modules on the microclimate conditions of Ngampilan District.

3. Result and Discussion

3.1 Selected Location: Ngampilan District

Due to urban development and population growth, Yogyakarta is categorized into Local Climate Zone (LCZ) 3 (compact low-rise), 5 (open midrise), and 6 (open low-rise) [23]. LCZs classify land surface cover adapted to the local climate, affecting environmental phenomena, including the UHI effect [24]. Yogyakarta's temperature profile includes an average yearly temperature of 25.3 to 26.9°C, average humidity between 79.74% and 87.31%, 22.5 and 575.5 mm³, and an elevation ranging from 96 to 156 meters above sea level. The city has a population of 378,913 and a density of 11,659 people per square kilometer [25].

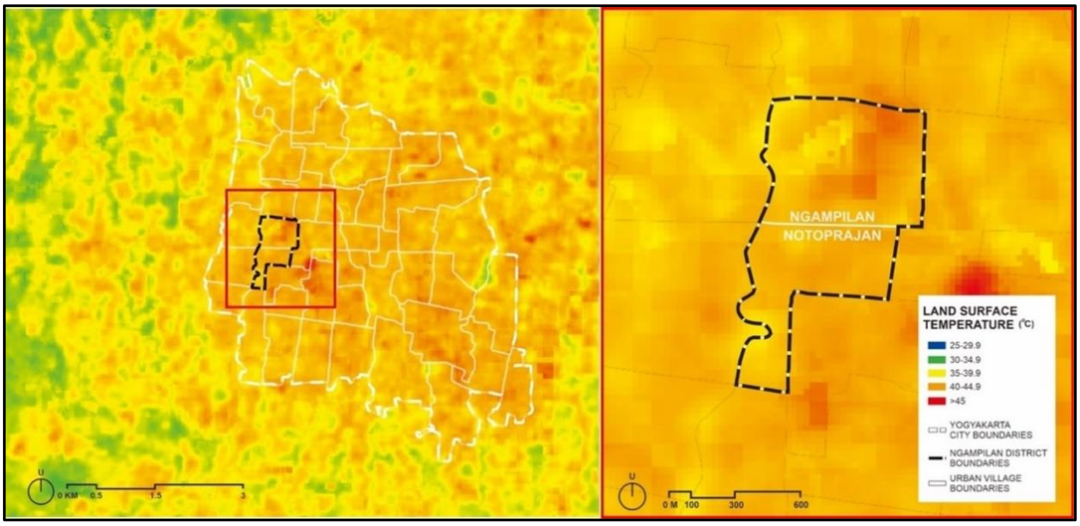


Figure 2. Yogyakarta's LST Map
Source: Author, 2023 [5]

This research identified areas with the highest UHI values using the LST map (Figure 2). Several districts have high UHI values, with temperatures exceeding 45 degrees Celsius (data from December 4, 2023). The study focuses on Ngampilan District, selected for its proximity to the city center (within 500 meters) and its high population density, reaching 18,841 individuals per km² – the highest in Yogyakarta (Figure 3). Ngampilan District covers 0.82 km², includes two sub-districts (Notoprajan and Ngampilan Urban Villages), and has a population of 15,450 with an annual growth rate of 0.81% [26].

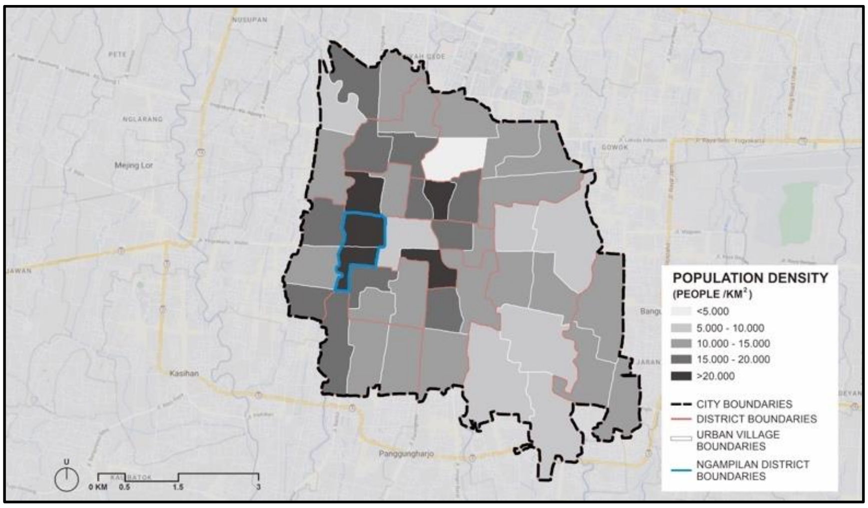


Figure 3. Yogyakarta's Population Density Map
Source: Visualized by Author, 2023 [26]

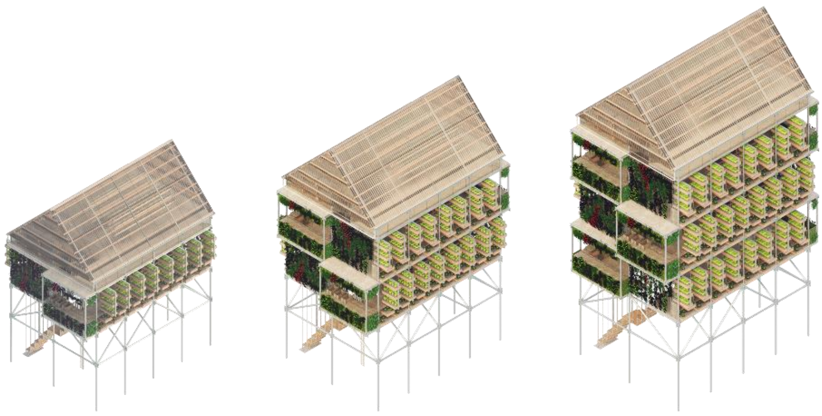
3.2 Building Modelling

The research focused on Ngampilan Urban Village, the highest LST number and density area in Yogyakarta. Characterized by permanent residential, office, and commercial structures, it spans 0.45 km² of paved or dry land [27]. The Winongo River runs through the sub-district, leading to informal settlements along its banks, marking it as a slum zone with a priority area of 7.45 hectares [28]. Considering the population density, we initiated the modeling process using the exisiting site (Figure 4.a), followed by the urban farming structure (Figure 4.b), and finally replicated the module multiple times within the area for simulation (Figure 4.c).

(a) (b) (c)

Figure 4. Development Phase
(a) Current condition, (b) Project plan, (c) Future plan
Source: Author, 2020

Modular System: The urban farming module, based on the "*Rumah Tumbuh*" concept, is designed to be constructed in three phases according to specific requirements (Figure 5). Adaptable in size and height to site conditions and productivity needs, the structure can expand vertically or horizontally. The typical design measures 6 x 8 meters with three levels (Figure 6), using materials such as polycarbonate for the roof, a wooden and hollow iron roof frame, and iron pipes of scaffolding form modules, each measuring 2 x 3 meters in length. The enclosure integrates a vertical garden and planting media as windows (Figure 7). Using a hydroponic wick system, the module can yield 3 kg/m² per harvest (excluding any crop failure costs), with a harvest period of one to four months.



(a) (b) (c)

Figure 5. Urban Farming Modular System
(a) Phase 1, (b) Phase 2, (c) Phase 3
Source: Author, 2020

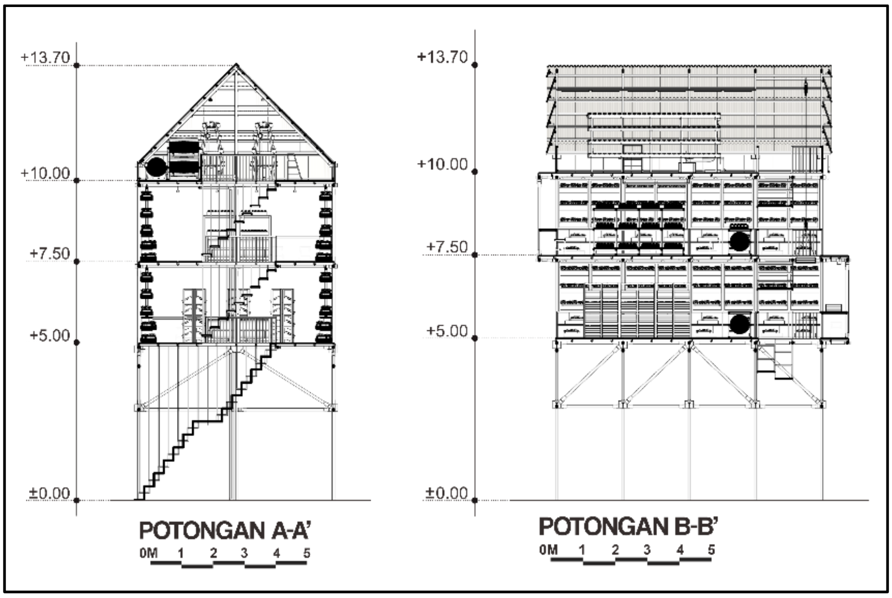


Figure 6. Urban Farming – Section
Source: Author, 2020

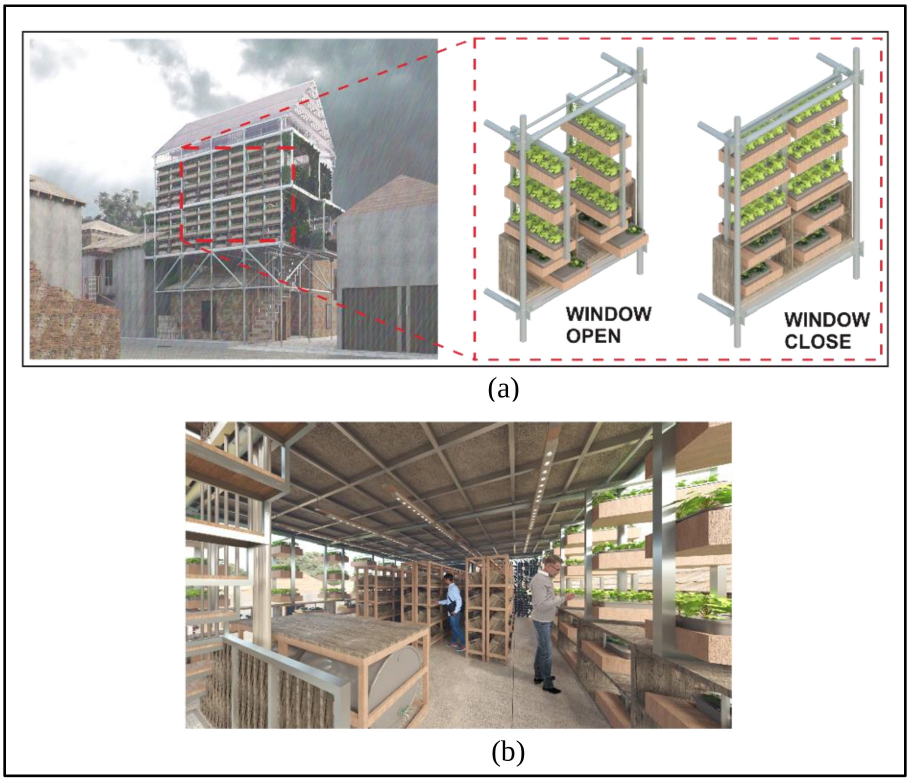


Figure 7. Urban Farming – Enclosure Design
(a) Wick System Window, (b) Vertical Garden
Source: Author, 2020

3.3 MRT Simulation

The placement of the modules varies based on their characteristics, adapting to the availability of space in the existing conditions of the Ngampilan Urban Village area. The selected sample locations represent the most effective module results in reducing temperature within their existing environment (Figure 8). Placement of these samples includes public streets (module type 1), building rooftops (module type 2), and open spaces (module type 3).

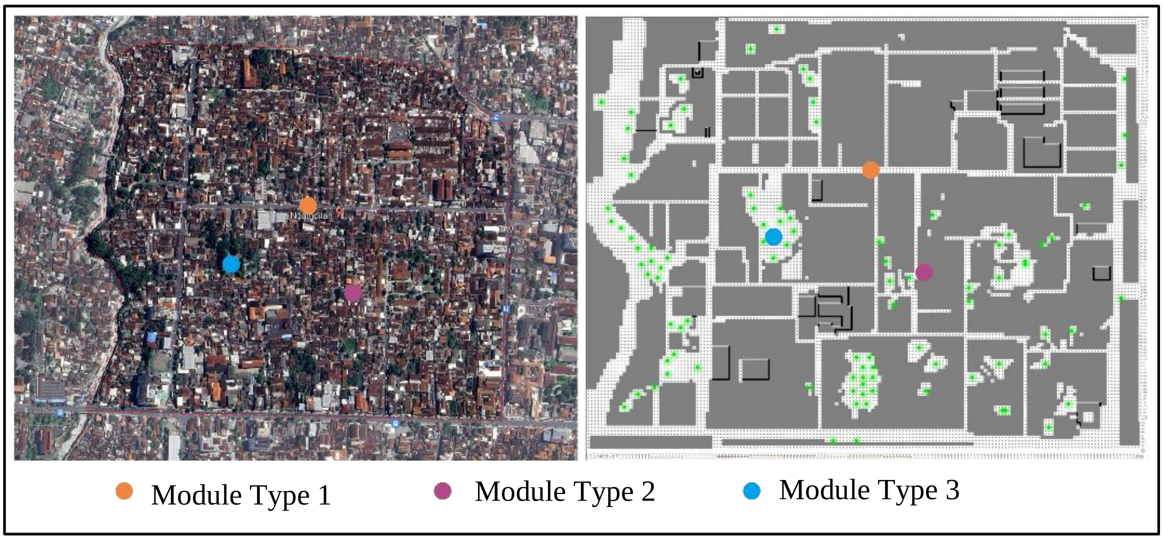


Figure 8. Map of Ngampilan Urban Village
(Left) Existing Map; (Right) ENVI-met Model
Source: (Left) Google Earth, 2023; (Right) Author, 2023

1. Existing Location Analysis (without Urban Farming Module)

The macro analysis began with a simulation of the chosen location under real conditions before adding the urban farming module. Using ENVI-met software, the study assessed the quantity and distribution of MRT. According to Table 2, the analysis identified key time variables for further comparison: 08:00 (most effective UV Index time), 13:00 (peak temperature), 17:00 (last UV Index appearance), and 23:00 (when the surface releases heat).

Table 2. Analysis of Existing Location (without Urban Farming Module)

NO	WAKTU	TEMPERATURE (C)	WIND GUST (KM/H)	WIND (KM/H)		UV INDEX	HUMIDITY	DEW POINT (C)	CLOUD COVER	PRESSURE (MILIBAR)
1	12:00:00 AM	25	11	0		0	86%	23	100%	1010
2	1:00:00 AM	25	10	0		0	89%	23	100%	1010
3	2:00:00 AM	25	9	0		0	91%	23	100%	1011
4	3:00:00 AM	25	4	0		0	90%	23	91%	1012
5	4:00:00 AM	25	5	0		0	89%	23	100%	1012
6	5:00:00 AM	25	6	0		0	88%	23	100%	1013
7	6:00:00 AM	25	8	5	NNW	0	89%	23	100%	1013
8	7:00:00 AM	25	10	6	NNW	0	91%	23	100%	1013
9	8:00:00 AM	25	12	7	NW	1	90%	24	100%	1012
10	9:00:00 AM	27	11	8	WNW	1	85%	24	99%	1012
11	10:00:00 AM	28	16	8	WSW	1	80%	24	99%	1012
12	11:00:00 AM	29	19	8	S	3	75%	24	99%	1011
13	12:00:00 PM	29	24	10	S	5	74%	24	99%	1011
14	1:00:00 PM	30	24	10	S	3	70%	24	99%	1012
15	2:00:00 PM	30	29	17	SSW	2	76%	25	94%	1013
16	3:00:00 PM	30	25	17	S	2	72%	25	96%	1013
17	4:00:00 PM	29	22	15	S	1	77%	25	98%	1013
18	5:00:00 PM	29	23	13	S	1	76%	24	100%	1013
19	6:00:00 PM	28	22	0		0	80%	24	99%	1013
20	7:00:00 PM	27	20	0		0	85%	24	99%	1012
21	8:00:00 PM	26	15	0		0	86%	24	99%	1011
22	9:00:00 PM	26	11	0		0	90%	24	94%	1010
23	10:00:00 PM	25	11	0		0	92%	24	88%	1010
24	11:00:00 PM	25	11	0		0	91%	24	83%	1011

Source: AccuWeather, 2023 [29]

2. Existing Location Analysis (with Urban Farming Module)

The study continued by integrating urban farming modules into ENVI-met, simulating scenarios of 5%, 10%, and 15% coverage (Figure 9), aligning with the standard Green Base Coefficient numbers at the location [30]. The simulation included the same analytical aspects and time variables, with the following results:

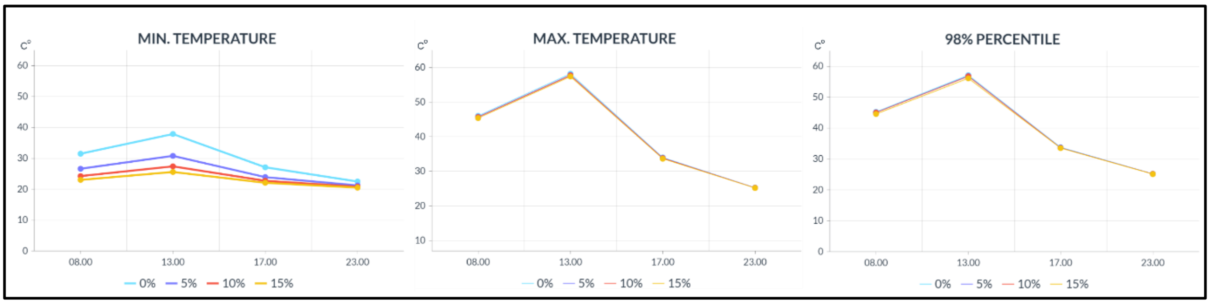


Figure 9. Comparison of Ngampilan MRT Data Analysis using ENVI-met (Data: 4/12/23)
Source: Author (processed using Visme (https://www.visme.co/)), 2023

The results showed a reduction in MRT corresponding to the percentage of module coverage, with higher coverage leading to more significant decreases (Figure 10). However, due to regulatory restrictions, modules could not be installed on protocol roads, limiting the overall MRT reduction. Despite this, the cross-sectional analysis revealed that urban farming modules could lower surrounding temperatures by up to 14.31 degrees (Figure 11).

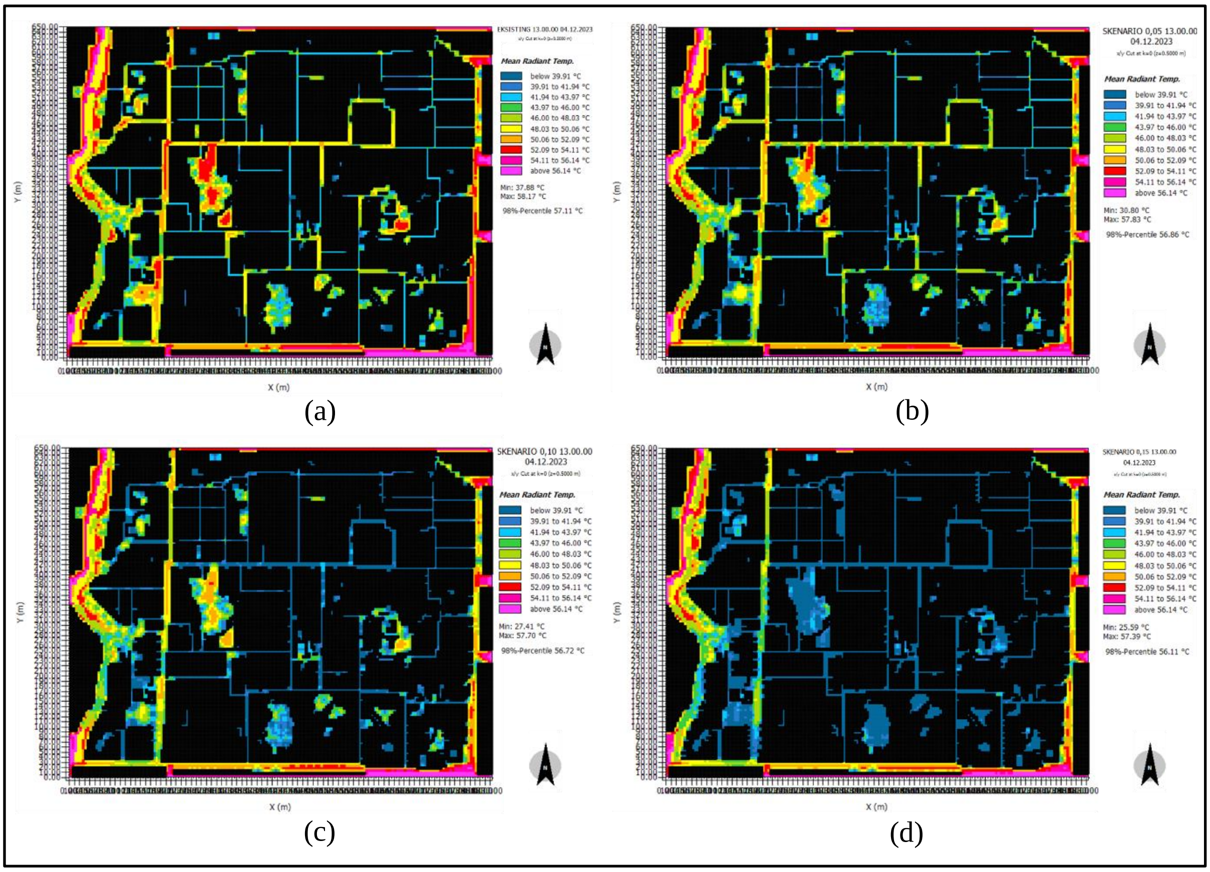


Figure 10. Map of Ngampilan MRT Analysis Results using ENVI-met (Data: 4/12/23 | 13:00)
(a) Existing Site; Providing (b) 5% Module, (c) 10% Module, (d) 15% Module
Source: Author, 2023

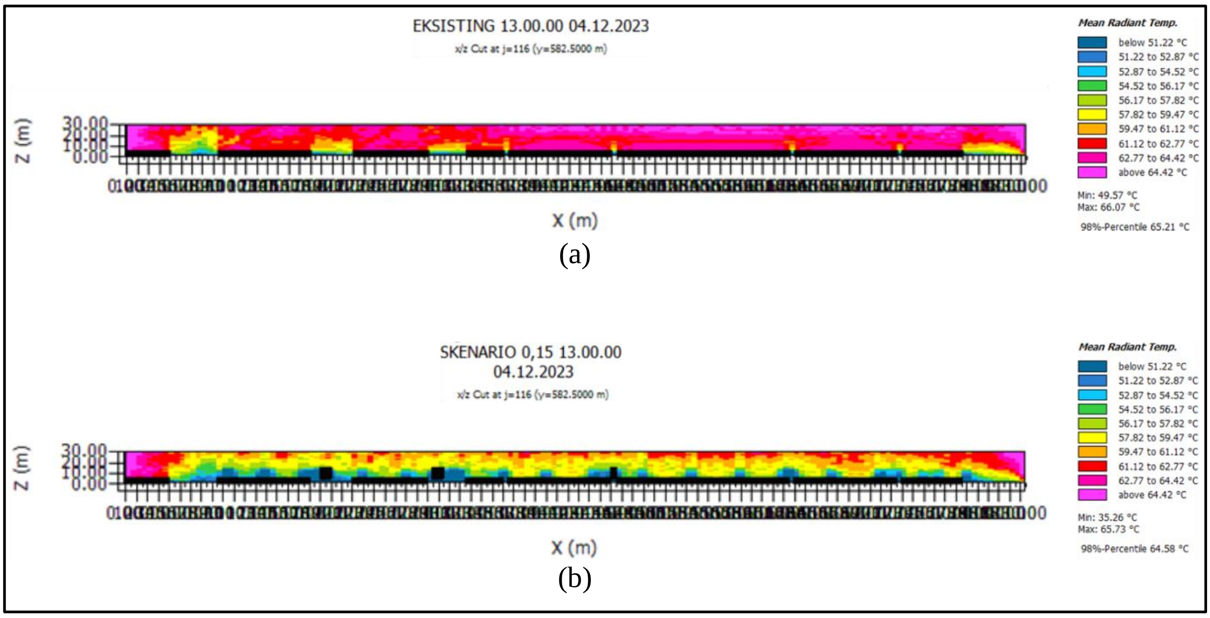
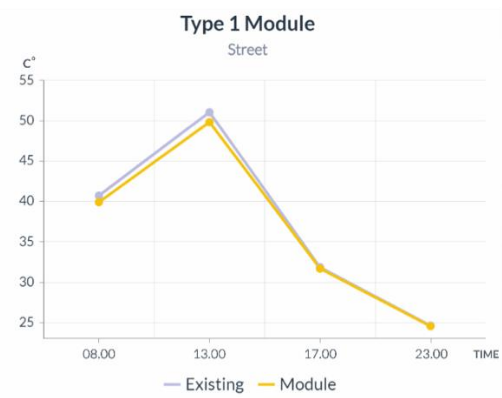


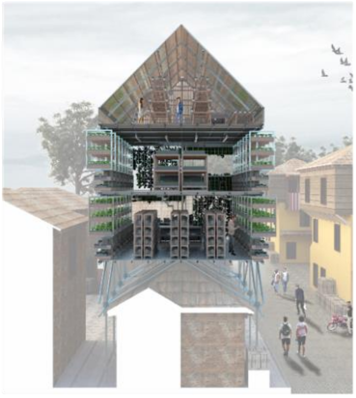
Figure 11. Cross Section of Grid Number 116, Ngampilan MRT Analysis Results using ENVI-met (a) Existing Site; (b) Scenario of 15% Module – (Data: 4/12/23 | 13:00)
Source: Author, 2023

Figure 11 illustrates that the urban farming module affects MRT values both below and above the building roof level (10-30 meters high), influencing heat reflection and absorption. After incorporating the modules and various placement scenarios, a more detailed analysis was conducted. This included simulating different scenarios with various typologies with distinct albedo values: streets (asphalt and concrete pavement, albedo 0.05 – 0.35), buildings (clay tile roofs, albedo 0.1 – 0.35), and open spaces (grass cover, albedo 0.25 – 0.3). Coordinate points matching the existing location were used for the simulations, and the analysis was conducted with consistent variables and scenarios with the following results:

Table 3. Summary of Module Simulations

Module Installation Scenarios	MRT Values (before and after)	Descriptions
1. Module Type 1: Street 		Streets with asphalt and concrete pavement (albedo 0.05-0.35) saw the MRT value drop by up to 1.2 degrees at 13:00 after introducing urban farming modules with an albedo of 0.2 (*Amaranthus*).

<table>
<tr><th>Module Installation Scenarios</th><th>MRT Values (before and after)</th><th>Descriptions</th></tr>
<tr><td>2. Module Type 2: Building


</td><td>


</td><td>For buildings with clay tile roofs (albedo 0.1-0.35), the modules reduced MRT by up to 3.4 degrees at 13:00.</td></tr>
<tr><td>3. Module Type 3: Open Space


</td><td>


</td><td>In open spaces covered with grass (albedo 0.25-0.3), the modules had the most significant impact, reducing MRT by up to 3.9 degrees at 13:00.</td></tr>
</table>

Source: Author (graphic processed using Visme (https://www.visme.co/)), 2023

As summarized in Table 3, these simulations highlight the varying effectiveness of the module across different scenarios. The urban farming modules demonstrated the least impact in street scenarios and the most significant impact in open spaces due to higher albedo values. The modules effectively address LCZ 3 conditions in Yogyakarta, adapting spatially and socio-culturally to urban village conditions characterized by dense low-rise buildings and minimal vegetation.

4. Conclusion and Recommendations

In conclusion, the integration of urban farming modules in urban heat island-affected areas shows promise in reducing temperatures. Although the macro-scale analysis reveals only a slight decrease in radiation temperature due to the inability to place modules on major roads, detailed cross-sectional studies highlight significant localized cooling effects around the modules. By examining three specific scenarios—streets, buildings, and open spaces—a consistent reduction in mean radiant temperature was observed, with decreases up to 3.9 degrees Celsius.

Future research should focus on testing urban farming modules in a variety of urban environments and conducting long-term studies to assess their sustainability and lasting impact. Strategies to integrate these modules with existing infrastructure, particularly on major roads and high-density areas, should be developed. Additionally, exploring alternative materials and plant species with different albedo values can enhance cooling efficiency. Policymakers and urban planners should be provided with guidelines to facilitate the widespread adoption of urban farming modules in city planning initiatives.

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