Evaluating the cooling potential of green open spaces in urban environments

Ahmad Dwi Setyawan, *Sapta* Suhardono*, *Muhammad* Indrawan, *Khansa* Afzanaya Rarasti, and *Sovia* Wijayanti

Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, Indonesia 57126

Abstract. This study evaluated the cooling potential of Green Open Spaces (GOS) in Surakarta City, focusing on three parks: Sekartaji Park, Pucang Sawit Park, and Balaikambang Park. The aim was to measure the correlation between vegetation indices and land surface temperature (LST) to evaluate the influence of urban green spaces on the adjacent thermal environment. Using satellite imagery, various vegetation indices, including NDVI, SAVI, and EVI2, were calculated alongside LST assessments. The findings revealed that Balaikambang Park exhibited the most significant cooling impact, with a maximum cooling intensity of 2.55 at a buffer distance of 300 meters, while Pucang Sawit Park recorded a high of 2.14 at 400 meters. Sekartaji Park demonstrated a diminished cooling intensity, reaching a maximum of 1.31 before seeing a substantial decline at 500 meters. Correlation research indicated a substantial negative correlation between vegetation proportion and land surface temperature, especially in Pucang Sawit Park. The findings underscore the significance of vegetation in regulating urban temperatures and stress the necessity for efficient management of Green Open Spaces to optimize their cooling capacity.

1 Introduction

Urbanization has resulted in substantial elevations in land surface temperatures (LST), fostering the development of urban heat islands (UHI) that adversely affect urban ecosystems and the health of city inhabitants. Urban Heat Islands (UHIs), defined by elevated temperatures in urban locales relative to adjacent rural areas, arise from significant alterations in land cover and heightened energy usage [1]. The escalation of land surface temperature (LST) in metropolitan regions profoundly affects thermal comfort, energy consumption, and public health. Research indicates that urbanization results in elevated land surface temperatures (LST), with developed regions exhibiting higher temperatures than vegetative zones [2]. In extreme heat events, metropolitan regions may attain land surface temperatures of up to 50°C, intensifying the urban heat island phenomenon [3]. Urban morphology significantly influences land surface temperature (LST) distribution, since high-density regions tend to have elevated air temperatures yet may exhibit reduced LSTs due to shading

* Corresponding author: sapta.suhardono@staff.uns.ac.id

effects [2,4]. Vegetation and aquatic systems serve as mitigating influences on both land surface temperature and air temperature [1,2].

Urban green areas are essential in alleviating the urban heat island (UHI) impact via multiple cooling methods. Research indicates that urban parks can markedly decrease land surface temperatures (LST) in metropolitan regions [5,6]. The mean effectiveness rate of ecological functions for urban parks in Surakarta attained 74.03% [7], signifying their significant role in urban cooling. The cooling impact is predominantly influenced by vegetation density, with larger parks typically offering enhanced cooling intensity and coverage [6],[9]. Nonetheless, even diminutive green spaces measuring less than 9 hectares might provide significant cooling advantages [6]. Urban parks facilitate cooling via evapotranspiration and shading, measurable through indices like park cooling intensity (PCI) and park cooling gradient (PCG) [9]. The efficacy of green spaces in alleviating urban heat islands (UHI) can be quantified using a greening cooling service index (GCoS), which incorporates both evapotranspirative and radiative cooling effects [10].

Surakarta, a swiftly urbanizing city in Central Java, Indonesia, is facing comparable issues associated with increasing land surface temperature (LST) and urban heat island (UHI) impacts, evidenced by a temperature differential of 1-2.5°C between its urban core and suburban regions, signifying a pronounced UHI effect [11]. Green open spaces in this city, such as Taman Balaikambang, Taman Pucang Sawit, and Taman Sekartaji, are essential for preserving thermal equilibrium in the urban ecosystem. Notwithstanding the beneficial effects of these parks, there exists a restricted comprehension of their cooling capacity in mitigating land surface temperature (LST) and enhancing urban climatic circumstances. Consequently, additional research is required to investigate how these green spaces can improve their efficacy in alleviating urban heat islands and fostering sustainable urban growth.

This research intends to assess the cooling capacity of green open spaces in Surakarta utilizing satellite data from Landsat 8. Spectral indices, including the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index 2 (EVI2), Soil-Adjusted Vegetation Index (SAVI), Land Surface Temperature (LST), and Temperature Condition Index (TCI), are utilized to evaluate temporal variations in vegetation and surface temperature. This research aims to measure the cooling effect of urban parks and their role in improving thermal comfort in Surakarta by examining the correlation between these spectral indices and land surface temperature (LST). This study's findings will elucidate the function of green open spaces in alleviating urban heat islands and will bolster urban planning initiatives focused on fostering sustainable development in Surakarta. This research aims to optimize the cooling capability of green open areas, thereby enhancing urban resilience and environmental sustainability.

2 Materials and Methods

2.1 Location

This research concentrated on Surakarta City, which was undergoing swift development. This resulted in adverse outcomes, including the diminishment of green open places. The research investigated three green open spaces (RTH): Sekartaji Park, Balaikambang Park, and Pucang Sawit Park, also referred to as Sunan Kalijogo Park.

Sekartaji Park is a public open area situated along the riverbank in Surakarta. It is located adjacent to the Anyar River and at the junction near Dr. Oen Hospital. The park was officially launched in 2009 by the then-mayor of Solo. Balaikambang Park is an urban park situated in Surakarta, Central Java. The park is renowned for its natural beauty and lush flora, making it a favored tourist destination in Solo. Constructed in 1921, it has emerged as a significant symbol in Solo. Balaikambang Park is situated in Jalan Balaikambang No.1, Manahan. Pucang Sawit Park, or Sunan Kalijogo Park, is situated in Pucang Sawit, Jebres District, Surakarta City, Central Java. This park is located within the Green Belt area, adjacent to the banks of the Bengawan Solo River.

2.2 Materials

This study employed remote sensing techniques to analyze greenness and heat trends in Surakarta City. Landsat 8 OLI and TIR (Operational Land Imager and Thermal Infrared Sensor) were employed to derive these indices.

2.3 Data Analysis

The data analysis was carried out by transforming the spectral values of the satellite images that had been cropped according to the study area. Broadly speaking, the image transformation included greenness indices (NDVI, SAVI, and EVI2) as well as temperature values (LST and TCI). Details regarding the spectral transformation can be seen in Table 1.

Table 1. Spectral Transformations

Index	Formula	Source
NDVI	(NIR - R) / (NIR + R)	[12,13]
SAVI	((NIR - R) / (NIR + R + L)) * (1 + L)	[13]
EVI2	2.5 * (NIR - RED) / ((NIR + RED + 1)	[14]
LST	$LST = \frac{BT}{[\,1 + \left(\lambda\, x\, \frac{T}{\partial}\right) x\, ln(e)]}$	[15]
TCI	100 * (T max - T) / (T max – T min)	[16]

After completing the image transformations, the next step was to calculate the park cooling intensity. Park Cooling Intensity (PCI) refers to the Land Surface Temperature (LST) inside and outside green open spaces [5]. In this study, PCI was developed to understand the impact of urban parks (as green spaces) on the thermal conditions around the parks. The following equation was used to calculate PCI, expressed in degrees Celsius:

PCI = T exterior − T green space ……………………………..………... (1)

where T exterior is the average temperature in the buffer zone or outside the green space, and T green space is the average temperature within the green space.

In this study, RLST and VCI were also developed to assess the impact of greenness on thermal environments. RLST represents the spatial distribution of thermal environments across different LULC (Land Use and Land Cover) types. The following equation was used to develop RLST in this study [17]:

RLST = LST / average LST ……………………………….……….. (2)

where RLST is the relative land surface temperature of a specific pixel, LST is the LST of the respective pixel, and average LST is the average temperature of the related area.

The Vegetation Cooling Index (VCX) was created to construct the spatial model between temperature represented by RLST and vegetation represented by the PV value. VCX was utilized by [17] to demonstrate the correlation between thermal conditions and vegetation greenness. This study employed the subsequent equation to compute Pv:

$$PV = \left(\frac{NDVI - NDVImin}{NDVImax - NDVImin}\right)^2 \quad (3)$$

where NDVI represents the actual NDVI map of the region, and NDVI max and NDVI min denote the maximum and minimum NDVI values of the region.

This study performed a correlation analysis between temperature conditions and vegetation density. This correlation research explained the association between greenness indices and thermal conditions in urban parks. A multiple regression model (MRM) was employed to assess the impact of land surface temperature (LST) as the dependent variable on cooling effects, with normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and soil-adjusted vegetation index (SAVI) serving as independent variables.

3 Result and Discussion

3.1 Distribution of greenness and thermal indices at buffer zones

The analysis examined various vegetation indices (NDVI, SAVI, EVI2), temperature conditions (TCI), and land surface temperature (LST) for three parks in Surakarta—Sekartaji Park, Pucang Sawit Park, and Balaikambang Park—at varied buffer distances from green space (100-500 meters). The Normalized Difference Vegetation Index (NDVI) indicated that Sekartaji Park had the maximum green space value (0.629548), which consistently decreased with increasing distances, culminating in its lowest value at 500 meters. Balaikambang Park, although initially lower, exhibited a more consistent performance than Sekartaji and Pucang Sawit as distance rose, suggesting that Balaikambang offered superior green cover throughout a broader range. In the Soil Adjusted Vegetation Index (SAVI), all parks exhibited a progressive decline; however, Balaikambang had greater consistency at increased distances, suggesting that its vegetation health was more effectively preserved as one walked away from the central green area.

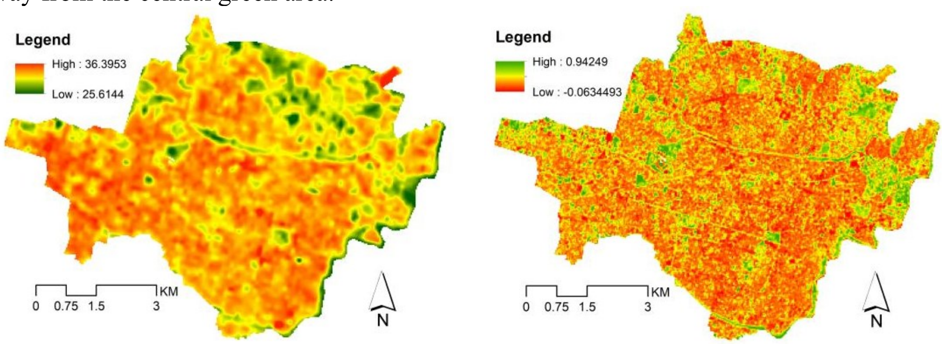

Figure 1. Spatial distribution of LST (left) and NDVI (right)

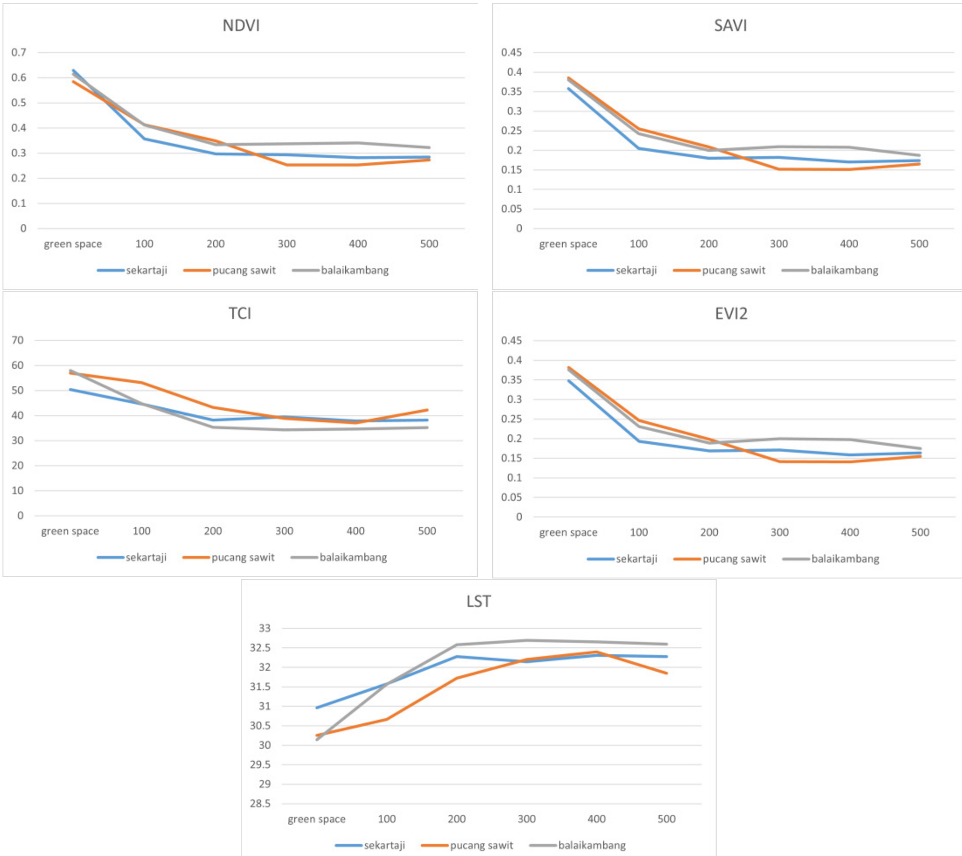

Figure 2. NDVI, EVI2, SAVI, LST, and TCI values in the green space area and at distances from 100 to 500 meters

The Temperature Condition Index (TCI) and Land Surface Temperature (LST) findings further emphasized these disparities. Balaikambang Park exhibited a superior TCI at all distances, signifying colder and more comfortable circumstances, while its LST remained comparatively stable, indicating effective cooling effects. In contrast, Sekartaji and Pucang Sawit had more pronounced temperature elevations at greater distances, with Sekartaji demonstrating a more significant increase in land surface temperature at 500 meters. Balaikambang Park exhibited exceptional efficacy in sustaining vegetation health and providing cooling effects, particularly beyond the adjacent green area. Sekartaji demonstrated strong performance in vegetation indices at short distances but exhibited diminished cooling effects as distance grew.

3.2 Park Cooling Intensity

According to the cooling intensity data for three urban parks in Surakarta at five distinct buffer distances, Balaikambang Park exhibited the most stated and consistent cooling effect, achieving the highest intensity at all distances, peaking at 300 meters (2.55) and maintaining stability up to 500 meters. Pucang Sawit Park exhibited a steady enhancement in cooling effect, reaching a maximum at 400 meters (2.14), followed by a subsequent decline beyond that distance. Sekartaji Park exhibited diminished and more erratic cooling intensity, showing an increase at 200 meters (1.31) followed by a significant decline at 500 meters (0.29).

Balaikambang Park significantly reduced the surrounding environmental temperature, whilst Sekartaji Park exhibited the least cooling effect. The spatial arrangement of vegetation significantly influenced the mitigation of land surface temperature, with larger and more interconnected patches proving to be more effective [18]. The cooling capability was impacted by factors including area, perimeter, shape index, and vegetation patch density [19].

Table 2. Cooling intensity at distances from 100 to 500 meters

Park cooling intensity	Buffer Zone				
	100	200	300	400	500
Sekartaji Park	0.614604	1.315261	1.18011	1.346161	0.296449
Pucang Sawit Park	0.410367	1.470636	1.945981	2.144426	1.591237
Balaikambang Park	1.420521	2.435761	2.550263	2.509375	2.448911

3.3 Vegetation and cooling index (VCX)

The linear regression analysis performed on three urban parks in Surakarta revealed differences in the strength of the correlation between vegetation proportion (Pv) and relative land surface temperature (RLST). In Sekartaji Park, the regression equation y = 0.98 - 0.04x, with a coefficient of determination R^2 of 0.086, demonstrated that merely 8.6% of the variance in RLST could be elucidated by alterations in Pv. This indicated that the vegetation in Sekartaji Park had a minimal effect on lowering surface temperatures. It also suggested that additional factors, such as the park's configuration, kind of vegetation, or physical features, may have a more substantial impact on the area's temperature. The association identified in Sekartaji was notably weak and did not significantly impact surface temperature reduction.

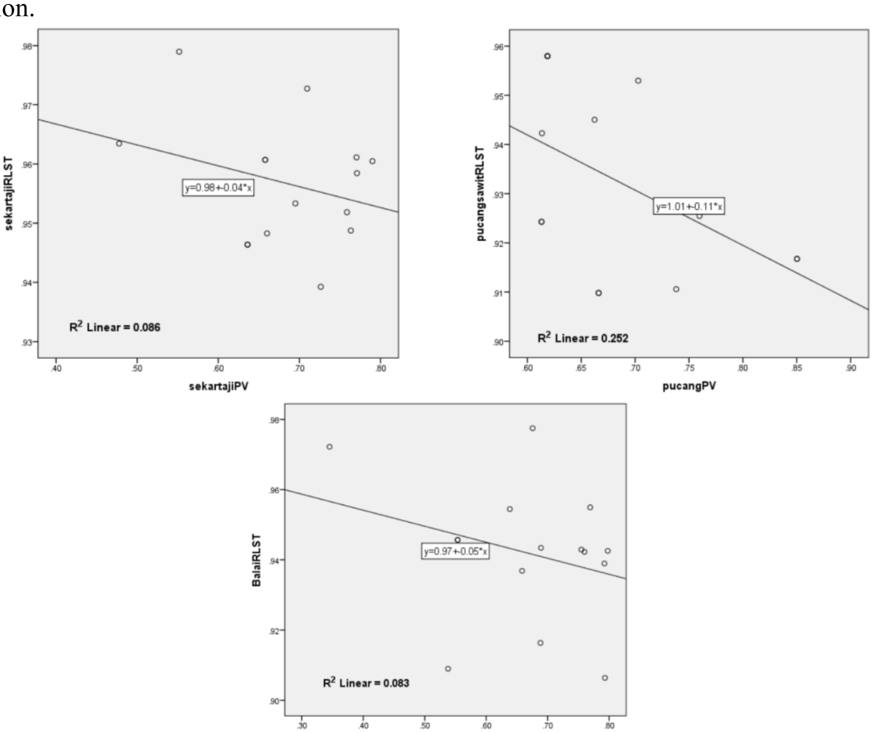

Figure 3. Relationship between RLST and Pv

Conversely, in Pucang Sawit Park, the correlation between Pv and RLST was markedly stronger, characterized by the regression equation y = 1.01 - 0.11x and a R^2 of 0.252, indicating that 25.2% of the variation in RLST could be attributed to vegetation proportion. This indicated that vegetation in Pucang Sawit significantly contributed to the reduction of surface temperatures. Balaikambang Park exhibited a regression equation of y = 0.97 - 0.05x, with a R^2 value of 0.083, signifying a comparable link to Sekartaji, where merely 8.3% of the variation in RLST could be elucidated by Pv. In summary, although all three parks exhibited a negative correlation between Pv and RLST, only Pucang Sawit Park displayed a more pronounced impact of vegetation on temperature mitigation, whereas Sekartaji and Balaikambang Parks exhibited a comparatively lesser effect of vegetation on temperature reduction. This signifies the need for more research to examine the mechanisms influencing land surface temperatures in these three parks and the impact of vegetation under different conditions. Numerous studies have identified a significant negative association between land surface temperature (LST) and vegetation abundance, indicating that regions with dense vegetation exhibit lower temperatures than those with sparse or no vegetation [20,21].

3.4 Multiple Regression Model

Based on the Pearson correlation table above, it could be seen that there was a very strong relationship between the variables tested (LST, NDVI, EVI2, and SAVI). A significant negative correlation was found between LST (Land Surface Temperature) and NDVI, EVI2, and SAVI, with correlation values of -0.836, -0.857, and -0.855, respectively. This indicated that as vegetation values increased (as shown by NDVI, EVI2, and SAVI), land surface temperature (LST) tended to decrease, which was consistent with the role of vegetation in reducing environmental temperatures.

Table 3. Multiple Regression of Vegetation Indices and Temperature

		LST	NDVI	EVI2	SAVI
Pearson Correlation	LST	1.000	-.836	-.857	-.855
	NDVI	-.836	1.000	.988	.990
	EVI2	-.857	.988	1.000	1.000
	SAVI	-.855	.990	1.000	1.000
Sig. (1-tailed)	LST		.000	.000	.000
	NDVI	.000		.000	.000
	EVI2	.000	.000		.000
	SAVI	.000	.000	.000	

A very strong positive correlation was observed between NDVI, EVI2, and SAVI, with near-perfect correlation values (0.988 to 1.000). This showed that NDVI, EVI2, and SAVI were highly related to one another, as expected since these indices were used to measure vegetation levels and plant health. All these correlations were statistically significant with p-values (Sig. 1-tailed) of 0.000, indicating that the relationships between these variables were very strong and not coincidental.

Overall, the interpretation of this table confirmed that increased vegetation was highly effective in reducing land surface temperatures and that NDVI, EVI2, and SAVI were closely interconnected in measuring vegetation conditions. Research consistently showed a negative correlation between LST and vegetation indices like NDVI and EVI2, with vegetation having a cooling effect on surface temperatures [15,22].

4 Conclusion

This study effectively assessed the cooling capacity of Green Open Spaces (GOS) in Surakarta City, focusing on three parks: Sekartaji Park, Pucang Sawit Park, and Balaikambang Park. The findings revealed that Balaikambang Park exhibited the most robust and consistent cooling effect, followed by Pucang Sawit Park, while Sekartaji Park showed a less pronounced and variable cooling effect. The analysis highlighted a strong negative correlation between Land Surface Temperature (LST) and vegetation indices, specifically NDVI (-0.836), EVI2 (-0.857), and SAVI (-0.855). Among these, EVI2 exhibited the strongest correlation with LST, indicating its high sensitivity in capturing variations in vegetation that influence temperature regulation. These vegetation indices provided critical insights into the cooling performance of GOS, confirming that higher vegetation levels, as represented by these indices, are effective in reducing LST.

To increase cooling capacity in urban environments, municipal authorities should contemplate the expansion and enhancement of Green Open Spaces management. Enhancing the diversity and density of flora in current parks might amplify cooling benefits. Prioritization of efforts to preserve the health and sustainability of park vegetation is essential. Regular maintenance programs and the augmentation of plant biodiversity can improve cooling efficiency. Moreover, additional research is required to investigate other variables affecting land surface temperature and the effects of various vegetation kinds. An in-depth examination of the interplay between environmental components and socioeconomic variables may yield additional insights.

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