

Assessing the impact of green open spaces on urban microclimate in Pinrang Regency, South Sulawesi, Indonesia

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Abstract

Rapid urbanisation and global climate change have increased the Urban Heat Island (UHI) phenomenon, which impacts the quality of the urban environment. Green Open Space (GOS) has a strategic role in mitigating microclimate change. However, its availability in various regions, including Pinrang Regency, is still not optimal. This study aimed to determine the contribution of GOS to microclimate regulation in urban environments. This was achieved by comparing environmental parameters between areas inside and outside the GOS in Pinrang Regency – specifically, Pinrang Urban Forest, Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park. The study identified the main factors influencing variations in environmental conditions across these areas and explored the interrelationships among all measured environmental parameters using Principal Component Analysis (PCA). Measurements were conducted at four GOS locations using a Mastech MS6300 device. The Mann-Whitney U test results show significant difference in environmental parameters between areas inside and outside the GOS, where the temperature inside the GOS was 5–6 °C lower than outside, humidity increased by 15–20 %, light intensity decreased by 70 %, wind speed decreased due to vegetation barriers, and noise decreased by 10–15 dB. Identifying the causes of differences in environmental parameters showed that the main contributing factors were vegetation type and density, canopy structure, and surrounding environmental conditions such as exposure to direct sunlight intensity and human activities outside the GOS. In addition, vegetation density analysis using NDVI imagery shows significant differences between GOS. GOS with wide-canopy and high-density vegetation showed more significant microclimate moderating effects than areas with more open vegetation. PCA analysis revealed that temperature, humidity, and sunlight intensity were the dominant factors determining environmental quality in GOS. Therefore, empirical data-based planning and GOS management are essential to improve urban environmental quality optimally.

Key words: humidity, noise level, sunlight intensity, temperature, urban heat island, wind speed.

Introduction

The World Bank (2019) notes that Indonesia will experience significant demographic changes, with more than 70 % of its population expected to live in urban areas by 2045 (Roberts et al. 2019). Rapid urbanisation, coupled with climate change, is causing urban temperatures to rise, a scientific phenomenon known as the Urban Heat Island Effect (UHI) [Intergovernmental Panel on Climate Change (IPCC) 2023]. On an international scale, climate change trends indicate an increase in average global temperatures of more than 1.1°C since the pre-industrial era. According to the IPCC AR6 (2021) projections, the increase could exceed 2°C by the end of this century if no significant mitigation efforts are implemented (IPCC 2021). Accelerated urbanisation in many countries exacerbates the UHI effect, causing city temperatures to rise faster than in rural areas (Nowak et al. 2022). Globally, Green Open Spaces (GOS) are now recognised as one of the most effective Nature-based Solutions (NbS) for addressing the impacts of climate change in urban areas. GOS can absorb carbon, lower surface temperatures by 1.5–7 °C, depending on local conditions, and increase relative humidity, which is important for thermal comfort (Shi et al. 2022, Ziter et al. 2019). Additionally, GOS supports international targets, such as Sustainable Development Goals (SDGs) 11 and 13, which call for the provision of public green spaces to create climate-resilient cities and support global climate action.

GOS play an essential role in urban planning, helping to maintain ecosystem balance, improve environmental quality, and provide public spaces that are accessible to the community (Mukrimin et al. 2025, Setiowati et al. 2018). Pinrang Re-

gency, one of the regions in South Sulawesi, has experienced rapid development in recent years. Infrastructure growth and settlement expansion have significantly changed the landscape of this area (Statistics Indonesia (BPS) Pinrang Regency 2023). These changes have raised concerns about the urban environment, such as rising air temperatures, declining air quality, and reduced biodiversity. In this situation, research on the contribution of green space in maintaining the balance of the urban environment has become increasingly important and urgent (Wu and Liu 2023). Recent research in tropical cities has shown that it is not only the presence of green open spaces that is important, but also urban morphology, such as building density, street canyon proportions (the ratio of street height to street width), and vegetation layout, which greatly influence the urban microclimate. For example, a study in a densely populated residential area in Bandung Province, Indonesia, found that areas with very high building coverage (over 95%) experienced minimal daily temperature variations, indicating trapped heat and poor ventilation. Conversely, areas with lower building density have a wider daily temperature range, better air circulation, and a lower risk of heat stress (Paramita and Matzarakis 2019).

The Indonesian government, through the Regulation of the Minister of Agrarian and Spatial Planning/Head of the National Land Agency Number 14 of 2022, requires each region to provide a minimum of 30 % of its total area as Green Open Space, with details of 20 % for public GOS and 10 % for private GOS. However, implementing this policy in various regions, including the Pinrang Regency, has not been optimal. In 2023, the total area of GOS in the Pinrang Regency only reached

8233 ha out of a total area of 196,177 ha. Based on the provisions, the area of public GOS that should ideally be provided is 20 % of the total area, around 39,235 ha (KEMEN-ATR/BPN 2022). Thus, the current public GOS has only reached about 20.98 % of the target. This means there is still a shortfall of 31,002 ha, or around 79.02 % of the total public GOS requirement. This condition shows that Pinrang Regency has not yet fulfilled the obligation to provide public GOS according to the regulation.

Various studies confirm that GOS is essential for creating more comfortable and healthier urban environments. According to Kraemer and Kabisch (2022), GOS can reduce noise and improve air quality through enhanced air circulation and stabilised air pressure. Du et al. (2021) revealed that GOS with water bodies or aligned with prevailing winds are more effective in maintaining humidity and lowering temperatures compared to areas outside GOS. Ornelas et al. (2023) highlighted that tree canopies in GOS reduce temperatures and provide shade, enhancing thermal comfort. Additionally, a study in Indonesia by Syafitri et al. (2020) showed that non-built areas like parks, urban forests, and ponds have lower surface temperatures than built-up areas, emphasising the GOS's role in microclimate regulation.

Research on GOS in Indonesia has mainly focused on areas, distribution, disaster mitigation, spatial planning, and public space provision. However, studies comparing environmental parameters, such as air temperature, humidity, sunlight intensity, wind speed, and noise levels inside and outside GOS, remain scarce. This indicates a research gap that needs attention to support data-driven GOS planning and management. This study aims to evaluate

the contribution of GOS to urban microclimate regulation in Pinrang Regency. To achieve this, the study compares environmental parameters between areas inside and outside GOS, identifies the causes of observed differences, and explores patterns and relationships among these parameters using Principal Component Analysis (PCA), as a basis for adaptive and empirical GOS planning. This holistic approach is expected to offer a practical and empirical reference for GOS management that meets local needs and addresses global urban challenges.

Materials and Methods

Study area

The research locations included areas within GOS, namely Pinrang Urban Forest, Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park. These areas were selected based on several criteria: a minimum size of approximately 1 ha, significant tree cover (with moderate to high tree density), diversity of vegetation types (including shade-providing species), and their function as public urban parks with active community use. Areas with minimal vegetation cover, under 1 ha in size, or not actively used as public spaces were excluded from the sampling. For comparison, measurements were also taken in surrounding non-GOS areas characterised by dense urban activities and limited vegetation. The elevation in each GOS location is relatively uniform, ranging between 16 and 18 m a.s.l.: Pinrang Urban Forest is at 18 m, Lasinrang Park at 16 m, Lasinrang Monument Park at 17 m, and Bau Massepe Stadium Park at 17 m. The locations of the GOS areas are shown in Figure 1.

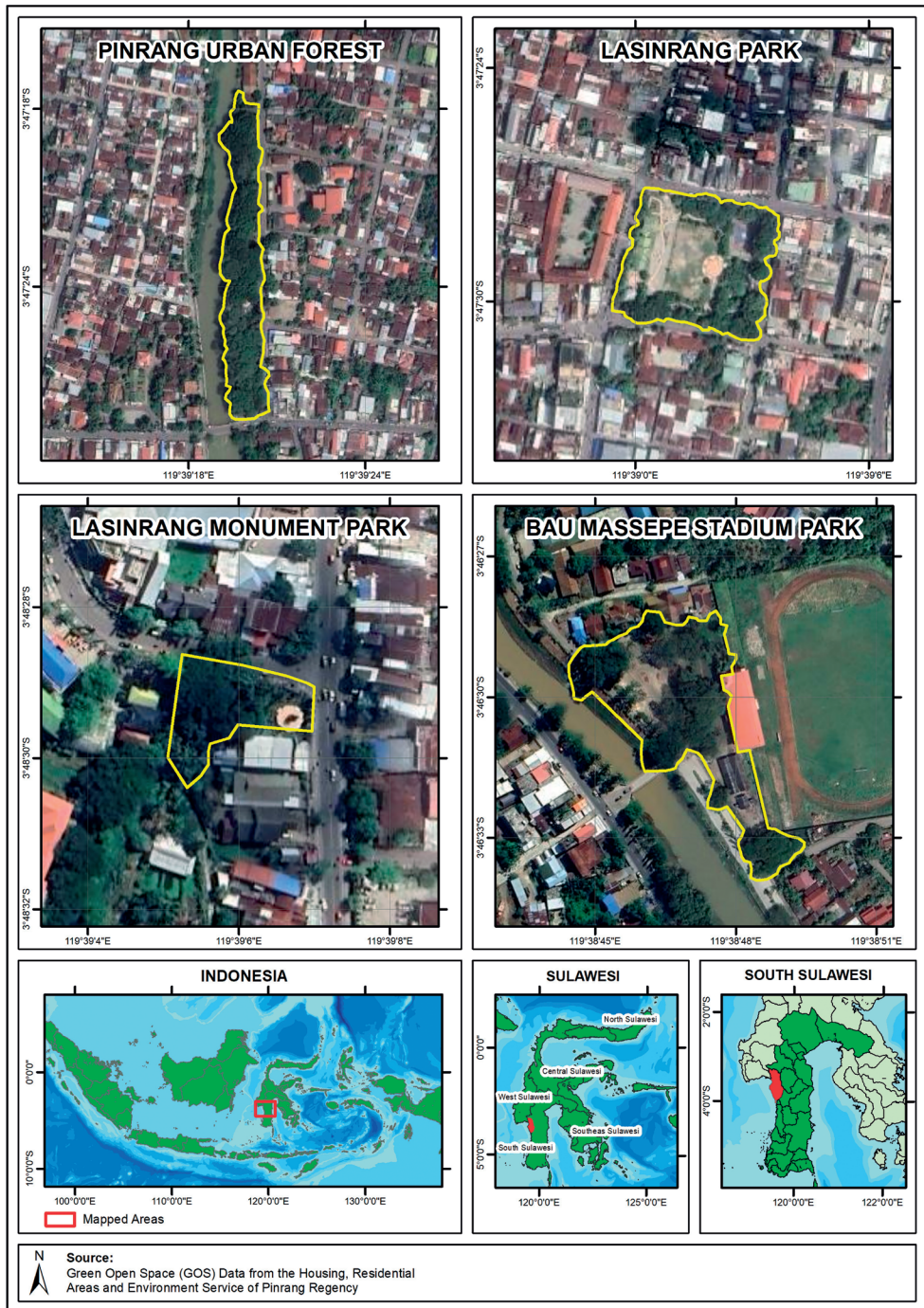


Fig. 1. Research locations of GOS in Pinrang Regency.

Vegetation density analysis

Vegetation density analysis on GOS in Pinrang Regency was conducted using Normalized Difference Vegetation Index (NDVI) analysis, a common and effective approach for assessing vegetation condition based on spectral reflectance from the Earth's surface. Data processing was conducted using Google Earth Engine (GEE) platform, which enables fast and efficient spatial data processing through cloud computing. The data used came from Sentinel-2 satellite imagery acquired in 2023, specifically the near-infrared (B8) and red (B4) channels. NDVI values close to +1 indicate high levels of vegetation (dense and healthy). In contrast, values close to 0 or negative indicate non-vegetative areas, such as water bodies, impermeable surfaces, or open land. The closer to +1, the higher the vegetation density (Kanjir et al. 2018, Wu et al. 2021). The classification of NDVI values is divided into five classes, namely: (1) -1 to -0.03 as water/bare soil, (2) -0.03 to 0.15 as no vegetation, (3) 0.15 to 0.25 as sparse vegetation, (4) 0.25 to 0.35 as moderate vegetation, and (5) 0.35 to 1 as dense/lush vegetation.

Measurement of microclimate parameters

This study used the Mastech MS6300 device, a multifunctional tool designed to support accurate and efficient data collection. It integrates five main functions: temperature (thermometer), relative humidity meter (hygrometer), sunlight intensity (luminometer), wind speed or airflow (anemometer), and sound level meter. Integrating these functions into a single device enables efficient data collection and reduces the risk of inter-tool mismatches. The use of the MS6300 also supports consistency and accuracy of results, as its

specifications are standardised for environmental research needs. Measurement points were set at two locations: under the shade inside the GOS and in an unshaded area outside the GOS. Measurements outside the GOS were taken at 100 m from the GOS boundary. This distance was chosen to ensure that the measurement area is in a zone not directly affected by the GOS vegetation but remains within a radius that reflects the residual or transitional influence of the GOS ecosystem on the surrounding environment. This approach is supported by previous research, such as the studies of Bowler et al. (2010), Colunga et al. (2015), which showed that the thermal and environmental effects of GOS are most significant within a radius of up to 100–500 m, depending on the scale and characteristics of the GOS. Measurements were taken at four different time intervals daily: 06:00–07:00, 09:00–10:00, 12:00–13:00, and 15:00–16:00. Data collection was conducted during the dry season to capture the microclimatic conditions typical of hot weather. Each monitoring site was evaluated repeatedly on multiple days within the same season to ensure consistency and temporal reliability. All measurements were conducted under clear weather conditions to minimise the influence of unpredictable weather factors on the research results. Detailed information on measurement accuracy is presented in Table 1.

Statistical analysis

This study used the Mann–Whitney U test to compare the environmental parameters inside and outside the GOS. This test was chosen because it is suitable for data that is not normally distributed ($p < 0.05$) and that violates the assumption of homogeneity of variance. As shown in Table 2,

Table 1. Mastech MS6300 accuracy specifications.

Parameter	Range measurement	Resolution	Accuracy
Temperature	-10 °C–60 °C	0.1 °C	±1.5 °C
Relative humidity	20–80 % RH	0.1 % RH	±3.0 % RH
	<20>80 %RH	0.1 % RH	±5.0 % RH
Sunlight intensity	0–2000 LUX	1 LUX	± (5.0 % +10)
	x10 (20000)	10 LUX	± (5.0 % +10)
	x100 (50000)	100 LUX	± (5.0 % +10)
Wind speed	0.5–20 m·s ⁻¹	0.1 m·s ⁻¹	± (3.0 % +10)
	1.8–72 km·h ⁻¹	0.1 km·h ⁻¹	± (3.0 % +10)
	96–3942 ft·min ⁻¹	1 ft·min ⁻¹	± (3.0 % +10)
	0.9–38.9 knots	0.1 knots	± (3.0 % +10)
Noise level	30–130 dB (A)	0.1 dB	±1.5 dB
	35–130 dB (C)	0.1 dB	±1.5 dB

Table 2. Results of the Shapiro–Wilk normality test (significance values).

Measurement locations	Temperature	Relative humidity	Sunlight intensity	Wind speed	Noise level
Inside Pinrang Urban Forest	0.012	0.008	0.049	0.973	0.316
Outside Pinrang Urban Forest	0.044	0.271	0.019	0.130	0.025
Inside Lasinrang Park	0.107	0.006	0.073	0.174	0.970
Outside Lasinrang Park	0.010	0.075	0.097	0.244	0.078
Inside Lasinrang Monument Park	0.084	0.008	0.038	0.883	0.184
Outside Lasinrang Monument Park	0.041	0.172	0.030	0.395	0.239
Inside Bau Massepe Stadium Park	0.085	0.003	0.039	0.091	0.248
Outside Bau Massepe Stadium Park	0.050	0.270	0.083	0.103	0.121

Note: Significance values below 0.05 indicate deviation from normal distribution.

the null hypothesis (H_0) states that there is no significant difference in environmental parameters between areas inside and outside the GOS, while the alternative hypothesis (H_1) suggests a significant difference exists. The conclusion is based on the significance value (p -value); if $p < 0.05$, H_0 is rejected, indicating a significant difference between the two areas, while if $p \geq 0.05$, H_0 cannot be rejected, indicating insufficient statistical evidence to support a significant difference.

In this study, Principal Component Analysis (PCA) was employed to investigate the relationships between environmental parameters, including temperature, humidity, sunlight intensity, wind

speed, and noise levels, at the four GOS locations. PCA was chosen not only for its ability to reduce dimensions but also for its effectiveness in identifying dominant patterns and linear relationships between variables (Jolliffe 2002), which aligns with the study's objective of understanding the interactions between parameters in the urban microclimate. This method enables clear visualisation through loading plots, which is important for communicating findings to multidisciplinary stakeholders, including urban planners and policymakers. Additionally, the use of PCA maintains consistency with previous research in the field of urban microclimate, which has widely applied this method to uncover

interrelationships among environmental factors before employing more complex predictive models. Given that the environmental data in this study exhibit moderate to strong linear correlations, PCA is considered a suitable and reliable tool for identifying underlying patterns while maintaining the interpretability essential for practical recommendations in GOS planning.

Results and Discussion

Vegetation density level

The analysis of vegetation density based on NDVI imagery, as shown in Figure 2, reveals an apparent variation in vegetation cover, both within and around the GOS area in Pinrang Regency. Pinrang Urban Forest has the densest vegetation,

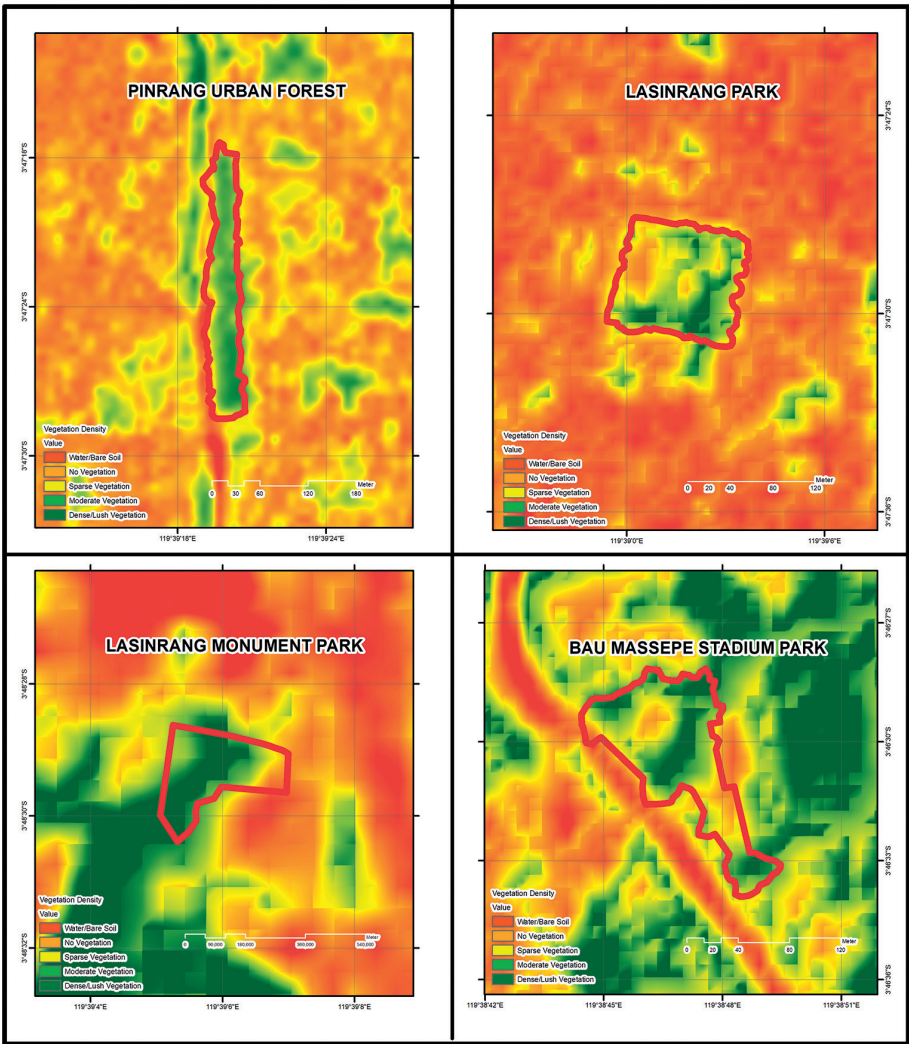


Fig. 2. Vegetation density level in Pinrang Regency.

characterised by the dominance of dark green regions that extend vertically. This dense vegetation is not only concentrated within the GOS area but also extends slightly into the surrounding area, which can increase the cooling effect on areas outside the park (Yan et al. 2021). In contrast, Lasinrang Park shows a limited distribution of dense vegetation, with vegetation cover dominated by a combination of sparse to medium vegetation. The NDVI map shows that dense vegetation is mainly concentrated in the centre of the park, while areas of lower vegetation density surround the edges. This pattern suggests that the park's ability to reduce temperature and increase humidity is localised, rather than evenly distributed throughout the park (Wu et al. 2021).

Lasinrang Monument Park shows a disjointed (uneven) vegetation pattern, where dense vegetation is concentrated in the southern part of the park area. The northern and eastern sections show minimal or sparse vegetation, indicating an imbalance in green space distribution. This uneven distribution can result in the park's effectiveness in reducing sunlight intensity, noise, and heat being reduced overall (Rahman and Hasan 2024). Bau Masepe Stadium Park shows a unique pattern with moderate to dense vegetation concentrated in the north and southeast of the park. Although the overall density of vegetation is higher than in Lasinrang Park and Lasinrang Monument Park, the distribution remains fragmented (not fully integrated). The design of this park appears to combine green and open areas, which can limit its ability to provide equitable microclimate benefits (Zhang et al. 2025). Thus, the NDVI analysis confirms that vegetation density varies greatly between green spaces in Pinrang, and this affects the ecological function of each GOS.

Comparison of environmental parameters inside and outside GOS

A comparison of environmental parameters between areas inside and outside the GOS in Pinrang Regency is summarised in Figure 3. This figure illustrates the variations in temperature, humidity, sunlight intensity, wind speed, and noise level observed at different times of the day across the sites studied.

Temperature

The temperature in Figure 3 shows a significant difference between areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), confirming the importance of vegetation in reducing air temperature within the GOS compared to urban areas lacking vegetation. This statistical result not only indicates significance but also highlights the ecological relevance of vegetation in microclimate regulation. Evapotranspiration processes, the shading effect of the tree canopy, and increased surface albedo contribute to this temperature reduction. In contrast, areas outside the GOS directly exposed to sunlight and dominated by urban activities experience higher temperatures, indicating the presence of a UHI effect.

According to Livesley et al. (2016), Mukrimin et al. (2025), urban forests and green parks can act as thermal buffers through evapotranspiration and canopy shading. Evapotranspiration is the process of water vapour release by plants into the atmosphere, which absorbs heat and lowers local temperatures (Febrita et al. 2021). The tree canopy also reduces direct sunlight intensity, inhibiting the ground surface and the air below. The temperature measurements show that the average temperature inside the GOS is

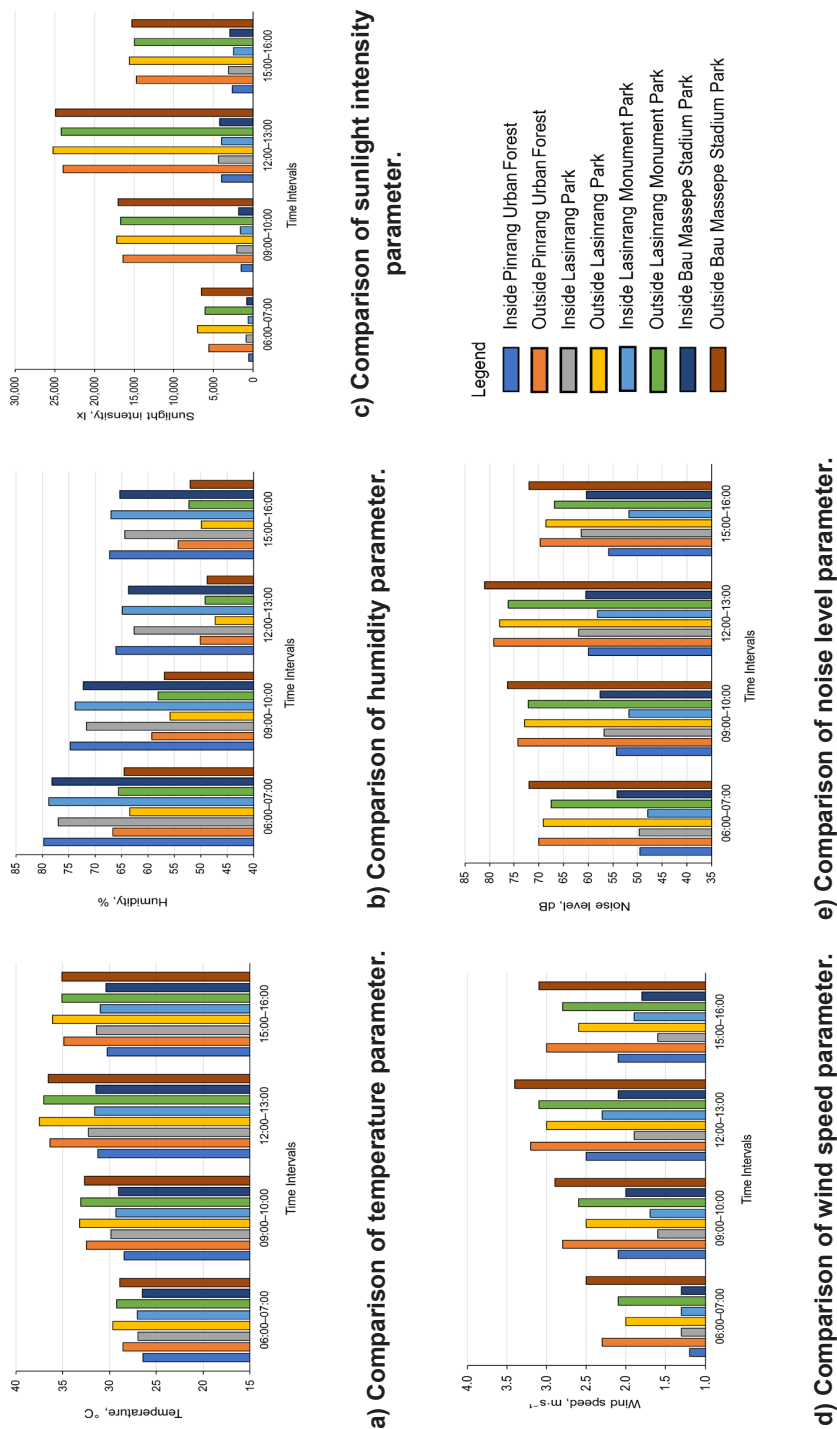


Fig. 3. Comparison of environmental parameters inside and outside GOS in Pinrang Regency.

consistently lower than outside the GOS at all-time intervals. The temperature inside the Pinrang Urban Forest (06:00–07:00) in the morning was in the range of 26.5–27.0 °C, while outside, the GOS reached 28.6–29.2 °C, with a difference of about 2 °C. The difference was even more striking during the day (12:00–13:00), with temperatures inside the GOS ranging from 31.2–31.6 °C, while temperatures outside the GOS reached 36.4–37.5 °C, indicating a difference of up to 5–6 °C. These results reinforce the findings of Varşak and Altay (2024) that densely vegetated areas can reduce temperatures by 4–7 °C compared to urban areas with minimal vegetation.

Humidity

The air humidity in Figure 3 shows a significant difference between areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), confirming the critical role of vegetation in increasing air humidity. This statistically significant result highlights not only the numerical contrast but also the functional ecological role of vegetation in regulating humidity. Vegetation supports the process of evapotranspiration, where plants release water vapour into the atmosphere, increasing relative humidity locally. In addition, vegetation-covered soil surfaces retain moisture better than hard surfaces, such as asphalt and concrete, which are dominant outside GOS (Erlwein et al. 2021).

Vegetation density is positively correlated with air humidity levels. Pinrang Urban Forest, with dense vegetation, provides higher humidity than parks with more open vegetation. This finding aligns with the previous research by Gunawardena et al. (2017), Mbarep et al. (2021), highlighting that forested areas can create a comfortable microclimate by increasing humidity

while reducing temperature. Hwang et al. (2023) also confirmed that the denser the vegetation, the greater the contribution to increased humidity. Based on the data, the relative humidity inside the GOS is consistently higher than outside the GOS. At 06:00–07:00, the humidity inside Pinrang Urban Forest reached 79.7 %, higher than 66.6 % outside the GOS. This pattern continued until noon (12:00–13:00), where the humidity inside Pinrang Urban Forest was recorded at 66.0 % compared to 50.1 % outside the GOS. Similar differences were observed in other parks, such as Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park, although the values varied depending on the vegetation density. Research by Li et al. (2024) supports these results, showing that dense vegetation can increase air humidity by 15–20 % compared to urban areas without vegetation. Pinrang Urban Forest, with the densest vegetation, showed the highest humidity compared to other parks with lower vegetation density, such as Bau Massepe Stadium Park and Lasinrang Park. In contrast, the lower humidity outside the GOS reflects the direct impact of urbanisation, where hard surfaces increase the UHI effect, characterised by high temperature and low humidity (Rizwan et al. 2008).

Sunlight intensity

The sunlight intensity in Figure 3 shows a significant difference between the areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), confirming that the GOS effectively reduces light intensity through the mechanism of vegetation canopy closure. This statistically significant result highlights not only the numerical contrast but also the ecological role of dense vegetation in modulating incoming sunlight

intensity and improving microclimate conditions. Dense vegetation creates a significant shading effect, absorbing and blocking direct sunlight intensity, thereby lowering ground surface temperature and the surrounding environment. Previous studies by Beute and de Kort (2018), Zhao et al. (2023) have shown that high sunlight intensity increases body heat load, especially in urban areas with minimal vegetation, causing thermal discomfort, particularly during the daytime.

Measurement data show consistently lower light intensity inside the GOS, for example, at 06:00–07:00, sunlight intensity in Pinrang Urban Forest was recorded at 552 lx, much lower than 5594 lx outside the GOS. At midday (12:00–13:00), the light intensity inside Pinrang Urban Forest reached 3987 lx, while outside the GOS reached 23,919 lx. This pattern was also observed in Lasinrang Park, Lasinrang Monument Park, and Bau Massepe Stadium Park, with differences directly proportional to vegetation density. The decrease in light intensity within the GOS also correlates with a higher increase in relative humidity. Dense vegetation supports microclimate moderation by lowering light intensity and increasing humidity, thereby reducing the impact of extreme heat. Research by Takebayashi et al. (2017) supports these results, where dense vegetation can reduce sunlight intensity by up to 70 % compared to areas without vegetation. In contrast, the high sunlight intensity outside the GOS reflects the lack of shade vegetation, exacerbating the UHI phenomenon through high temperature and low humidity.

Wind speed

The wind speed in Figure 3 shows a significant difference between the areas inside

and outside the GOS (p -value = 0.000, $p < 0.05$), indicating that the vegetation inside the GOS acts as an aerodynamic barrier that effectively reduces wind flow through physical resistance. The dense trees, shrubs, and complex vegetation structures within the GOS absorb and distribute wind energy, as found by Gunawardena et al. (2017), who stated that dense vegetation canopies create a more aerodynamically stable environment. Vegetation can break up wind turbulence, providing thermal protection to the surrounding environment. In contrast, areas outside the GOS, which lack vegetation, allow winds to flow more freely, increasing speed and turbulence, and exacerbating UHI effects due to higher moisture evaporation. Measurement data showed consistently lower wind speeds inside the GOS than outside, such as at 12:00–13:00, where wind speeds outside Pinrang Urban Forest reached $3.2 \text{ m}\cdot\text{s}^{-1}$ compared to $2.5 \text{ m}\cdot\text{s}^{-1}$ inside. Similar patterns were found in other parks, such as Lasinrang Monument Park, with differences suggesting vegetation is a natural barrier to reduce wind speed. This finding supports the view of Hui et al. (2024) that urban vegetation creates significant aerodynamic barriers while lowering the air temperature in the area.

Noise level

The noise levels in Figure 3 show significant difference between areas inside and outside the GOS (p -value = 0.000, $p < 0.05$), indicating that GOS is essential in reducing noise in urban environments. This statistically significant result highlights not only the contrast in numerical values but also the functional role of vegetation as a natural acoustic buffer. The dense vegetation inside the GOS, such as trees and shrubs, acts as natural acous-

tic barrier that absorbs and blocks sound waves, reducing the impact of noise from human and vehicular activities (Dzhambov and Dimitrova 2014). For example, at 06:00–07:00, the noise inside Pinrang Urban Forest was recorded at 49.5 dB, far below the noise level outside the GOS, which reached 70.0 dB. This noise reduction aligns with the findings of Margaritis and Kang (2017), and Rey-Gozalo et al. (2023), who reported that dense vegetation in GOS can reduce noise levels by 10–15 dB. The effect is reinforced by Gidlöf-Gunnarsson and Öhrström (2010) who explained that complex vegetation structures can increase sound absorption capacity through vegetation's leaves, stems, and soil.

The interaction between wind speed and noise further clarifies the contribution of the GOS in creating a comfortable acoustic environment. Lower wind speeds inside the GOS, for example, $1.2 \text{ m}\cdot\text{s}^{-1}$ in the morning to $2.5 \text{ m}\cdot\text{s}^{-1}$ in the afternoon, reduce the propagation of sound waves. Conversely, outside the GOS, stronger wind speeds can increase the propagation of sound waves. This is consistent with research by Zannin et al. (2013), which found that high-speed winds in urban areas can accelerate the spread of noise from the sound source to the surrounding area. High noise exposure, especially outside the GOS, has serious health consequences. Chronic noise above 65 dB increases the risk of hypertension, sleep disorders, and cardiovascular diseases, as revealed in the WHO (Environmental Noise Guidelines) (Clark and Paunovic 2018, Münzel et al. 2018). El Masri et al. (2024) also highlighted that chronic noise triggers psychological stress that can develop into anxiety and depression. In addition, the combination of noise with high wind speeds exacerbates the dispersion

of air pollutants, increasing the risk of respiratory diseases such as asthma.

Identify the causes of differences in environmental parameter values in GOS

The differences in environmental parameter values within the GOS in Pinrang Regency are presented in Figure 4. This figure shows variations in temperature, humidity, sunlight intensity, wind speed, and noise level recorded at various GOS locations, highlighting disparities in microclimatic conditions related to vegetation cover and surrounding urban characteristics. One of the leading causes is the lack of attention to vegetation distribution in some GOS, such as in Bau Massepe Stadium Park and Lasinrang Park, which show higher temperatures, lower humidity, and higher noise levels than greener areas, such as Pinrang Urban Forest. The lack of vegetation increases UHI effects that worsen thermal conditions and environmental comfort. In addition, development patterns that do not consider ecological aspects are also significant factors, as many GOS are dominated by artificial structures rather than natural elements that should be the central part of green spaces.

In addition, uncontrolled urbanisation and a lack of regulation in protecting GOS worsen urban microclimate conditions in some locations. Higher wind speeds in open areas without vegetation barriers, as seen in Lasinrang Monument Park and Bau Massepe Stadium Park, indicate that the design of GOS does not consider microclimatic aspects that should be able to create cooler and more comfortable environmental conditions. In addition, the high noise levels in some locations indicate that the GOS does not fully function as a

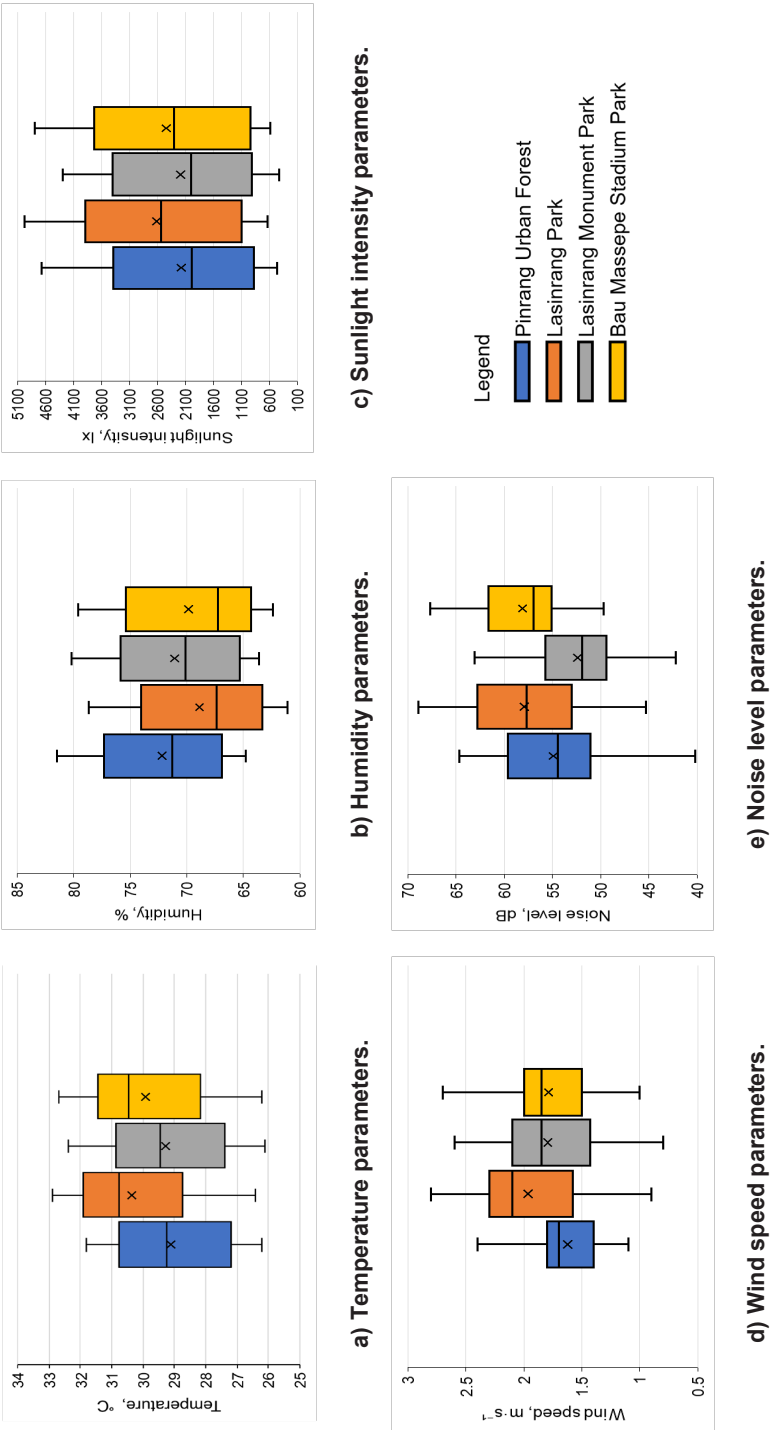


Fig. 4. Comparison of environmental parameters in GOS Pinrang Regency.

noise pollution mitigation area, especially in areas close to main roads and urban activity centres.

It is also considered that each tree species has a different influence on microclimate due to differences in morphology, crown density, transpiration rate, and other physical characteristics. In the urban forest, broad-canopy species, such as *Ficus benjamina* L., *Terminalia catappa* L., and *Samanea saman* (Jacq.) Merr. effectively reduce temperature and increase humidity because they can shade the area underneath and retain sunlight intensity. Other dense-leaved trees, such as *Swietenia macrophylla* King and *Pterocarpus indicus* Willd., also help absorb pollutants and reduce noise. In contrast, fast-growing *Neolamarckia cadamba* (Roxb.) Bosser and *Gmelina arborea* Roxb. can accelerate the restoration of open areas to a greener state (Aluyah and Rusdian- to 2019). Some fruiting species, such as *Mangifera indica* L., *Artocarpus heterophyllus* Lam., and *Dimocarpus longan* Lour., have medium to wide canopies and support biodiversity, but are generally not as shady as *F. benjamina* or *S. saman*.

In Lasinrang Park, tree species like *Casuarina junghuhniana* Miq. and *Ficus microcarpa* L.f. provide more limited shade due to their narrower canopy structure. At the same time, *Terminalia mantaly* H. Perrier, *Handroanthus chrysotrichus* (Mart. ex DC.) Mattos, and *Caryota mitis* Lour. (fish-tail palm) tend to function as ornamental trees with narrower canopies. This makes the garden area more open and makes it easier for sunlight to reach the land surface, which results in increased temperature and decreased humidity. In Monument Park, palms (e.g. *Ptychosperma elegans* (R.Br.) Blume, *Livistona chinensis* (Jacq.) R.Br. ex Mart., and *Roystonea regia* (Kunth) O.F.Cook) and some shrubs,

such as *Justicia gendarussa* Burm.f. and *Euphorbia* L., act more as aesthetic elements and do not provide as high thermal protection as trees with wide canopies. However, *S. macrophylla* and *T. mantaly* trees still help to reduce heat and noise around the park (Environmental Protection Agency 2012).

Meanwhile, in Stadion Park, large-canopy species, such as *S. saman*, *P. indicus*, and *T. catappa* help to shade specific areas, but poor organisation leads to uneven shade. Other species, such as *G. arborea*, *M. indica*, and *Leucaena leucocephala* (Lam.) de Wit, contribute to heat and moisture absorption, although their capacity varies depending on density and growing conditions (Rötzer et al. 2023). Thus, species with wide canopies compositions (e.g., *F. benjamina*, *S. saman*, *T. catappa*, and *S. macrophylla*) proved to be most effective in reducing temperatures and increasing thermal comfort. In contrast, narrow canopies or more ornamental species (such as various palms, cypresses, and shrubs) tended to produce more limited shading and heat absorption effects.

Variations in microclimate parameters among the four GOS locations were not only caused by internal factors, such as vegetation density through NDVI, but were also influenced by the characteristics of the surrounding urban environment. For example, Pinrang Urban Forest is surrounded by low-density residential areas, water bodies (rivers), main roads, government offices, and schools. The presence of water bodies and open spaces helps to enhance the cooling effect through evaporation and air circulation, thereby creating a more stable and comfortable microclimate (Deng et al. 2022, Febrita et al. 2021). Furthermore, Lasinrang Park is located in the city centre, surrounded

by shopping centres, major roads, high-rise buildings, and schools, which cause urban heat stress and high noise levels. This densely built-up environment also has the potential to obstruct airflow and increase heat reflection from hard surfaces (such as asphalt and concrete) (Amani-Beni et al. 2021, Sari 2021). Lasinrang Monument Park borders a main road and office buildings, resulting in moderate levels of heat exposure and urban noise, depending on traffic intensity (Amani-Beni et al. 2021, Sari 2021). Meanwhile, Bau Masepe Stadium Park is located on an inter-district road, in a relatively dense residential area, and near a body of water (river). This combination can have mixed effects: on the one hand, the presence of water and surrounding vegetation supports a cooling effect; on the other hand, high traffic volumes have the potential to increase temperature and noise levels (Deng et al., 2022). Differences in urban environmental contexts, such as proximity to highways, the type and density of buildings, the presence of water bodies, and the level of human activity, can influence the performance of each GOS in regulating the microclimate.

This disparity emphasizes the need for a thorough evaluation of the design and management of GOS in Pinrang Regency. Local governments and urban planners need to adopt an ecological and sustainability-based approach to GOS planning, ensuring that each site has sufficient vegetation, natural barriers to noise, and designs that support a balance between social and environmental aspects. Suppose there are no concrete steps to improve these conditions. In that case, the differences in urban microclimate in each GOS will become more pronounced, and the main functions of GOS as microclimate regulators, carbon sequestration, and im-

provement of air quality and thermal comfort will not be maximised.

Identification of environmental parameter patterns through PCA

The results of the principal component analysis, visualised through the loading plot in Figure 5 and supported by the eigenvectors in Table 3, show that two main factors dominate the variation of the data. The first component (PC1) is mainly influenced by temperature (0.486), sunlight intensity (0.483), wind speed (0.382), and noise level (0.375), which have high positive weights, while humidity (-0.488) has a negative weight. This indicates that high temperatures, vigorous sunlight intensity, and strong winds are associated with higher noise levels, while humidity tends to be lower. This phenomenon can be explained by increased human activity and changes in the physical properties of the environment due to hot and dry conditions. As shown in Table 4, the first two principal components (PC1 and PC2) collectively account for 84.3 % of the total variation in the dataset, indicating that they effectively represent the primary structure of the data.

The second component (PC2) is dominated by elevation (0.858), followed by wind speed (0.474), indicating that site elevation significantly affects wind speed, with data variability that PC1 cannot fully explain. Meteorological variables, such as temperature, humidity, and noise level have a small contribution to PC2, indicating that topographic factors play more of a role in distinguishing neighbourhood characteristics based on topographic aspects than weather conditions. The following components (PC3 to PC6) have relatively small loading patterns on the total data variation, so their contribution to the total

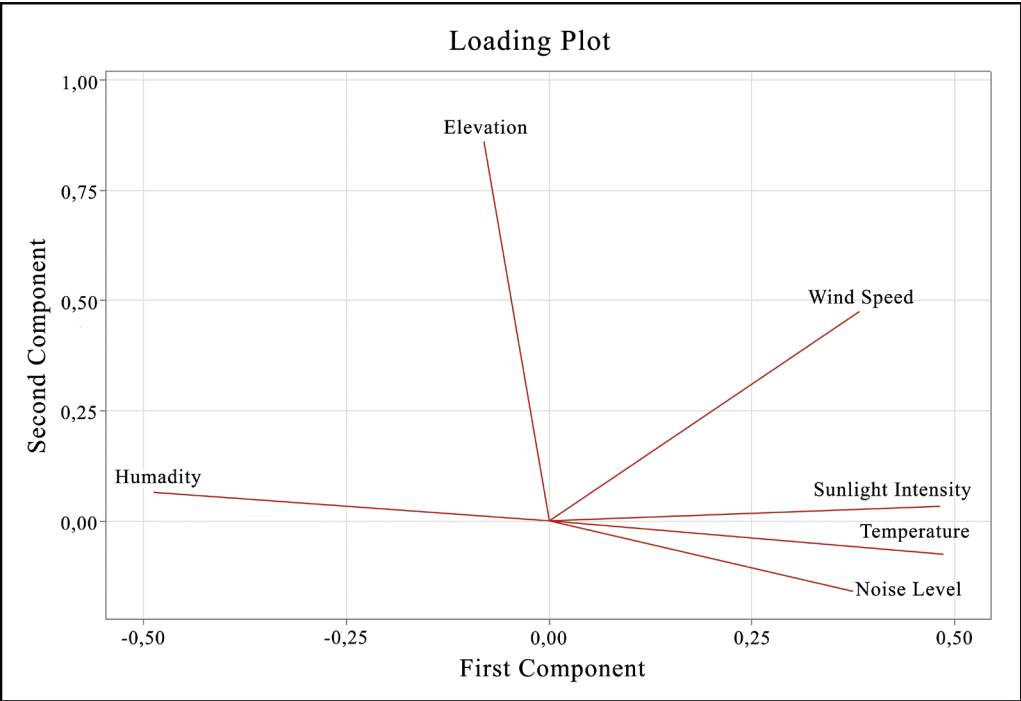


Fig. 5. PCA loading plot contribution of environmental variables to principal components.

Table 3. Eigenvectors.

Variable	PC1	PC2	PC3	PC4	PC5	PC6
Temperature	0.486	-0.076	0.163	0.137	0.742	0.402
Humidity	-0.488	0.065	-0.125	-0.345	-0.011	0.789
Sunlight intensity	0.483	0.033	0.220	0.290	-0.658	0.448
Wind speed	0.382	0.474	0.184	-0.763	-0.044	-0.107
Noise level	0.375	-0.161	-0.900	-0.132	-0.063	0.043
Elevation	-0.080	0.858	-0.255	0.423	0.104	0.026

Table 4. Eigenanalysis of the correlation matrix.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
PC1	3.8480	0.641 (64.1%)	0.641 (64.1%)
PC2	1.2123	0.202 (20.2%)	0.843 (84.3%)
PC3	0.5225	0.087 (8.7%)	0.930 (93.0%)
PC4	0.2519	0.042 (4.2%)	0.972 (97.2%)
PC5	0.0981	0.016 (1.6%)	0.989 (98.9%)
PC6	0.0672	0.011 (1.1%)	1.000 (100%)

data variation is lower than that of PC1 and PC2. Nonetheless, these components still reflect the specific contribution of each variable in local variations, such as temperature changes to noise levels in certain conditions or the impact of humidity in areas with particular elevations.

Overall, the results of this analysis categorise the variables into two main dimensions: 1) the meteorological dimension, which includes temperature, humidity, sunlight intensity, and noise, and 2) the geographical dimension, which includes altitude and wind speed. The negative correlation between humidity and other weather variables confirms that high-temperature environments tend to be drier and noisier. Meanwhile, altitude variations contribute significantly to wind speed,

broadly affecting atmospheric dynamics. Based on the PCA score plot visualisation in Figure 6 of six environmental parameters, each area has a different distribution pattern. Massepe Stadium Park (blue) tends to cluster in the negative quadrant of the first axis, indicating different environmental characteristics compared to the other sites. Lasinrang Monument Park (red) is more widely distributed on the first and second axes, suggesting a more dynamic variation in environmental parameters. Lasinrang Park (green) is in the negative quadrant of the first axis and positive quadrant of the second axis, indicating significant differences in ecological patterns compared to other locations. Meanwhile, Pinrang Urban Forest (purple) has a more sep-

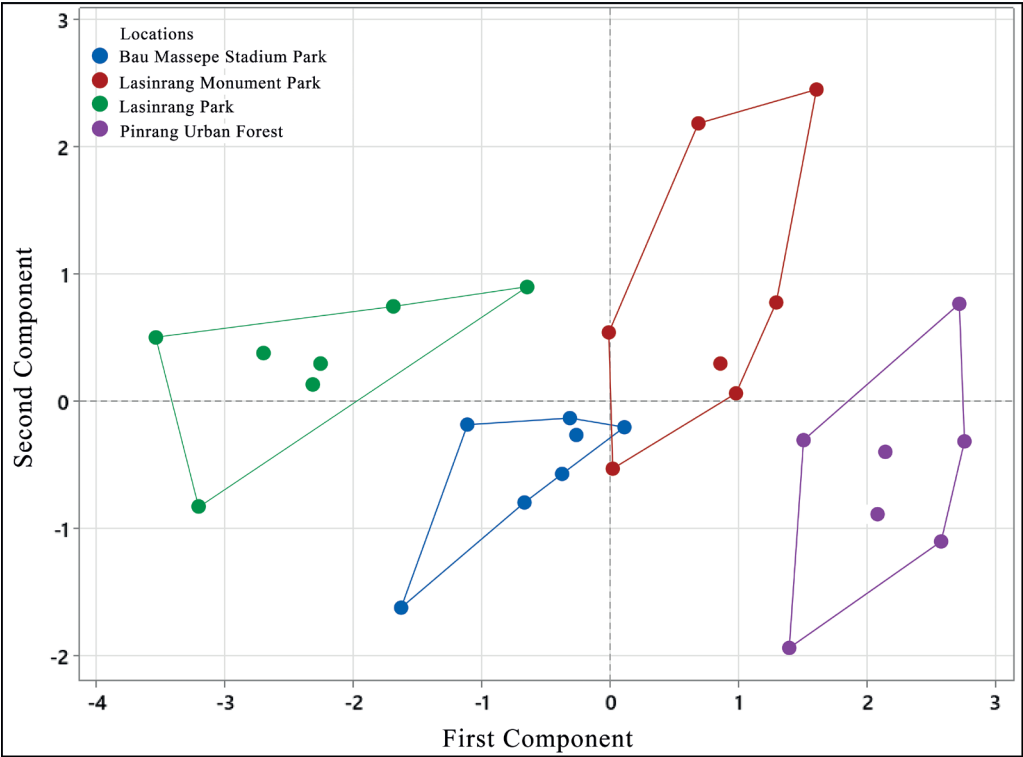


Fig. 6. PCA score plot of environmental parameters in four GOS locations.

arated distribution on the first axis with higher positive values, indicating unique characteristics that distinguish it from other sites. This distribution pattern reflects the microclimate conditions in each GOS that can be influenced by environmental factors, such as vegetation, topography, and human activities.

It should be noted that the PCA results presented here are exploratory in nature and do not imply definitive causal relationships between the variables. In addition, surrounding urban elements, such as building density, traffic, and human activity, may influence local microclimate measurements and therefore affect the patterns identified in the PCA. These factors are recognised as potential limitations of this analysis.

Conclusions

The results of this study show significant differences in environmental parameters between areas inside and outside GOS in Pinrang Regency. The analysis indicates that GOS is important in reducing air temperature, increasing relative humidity, reducing sunlight intensity, slowing wind speed, and muffling noise.

In particular, vegetation within GOS has been shown to reduce air temperature by 5–6 °C compared to areas outside GOS. The main mechanisms contributing to this cooling effect include evapotranspiration, the shading effect, and increased air humidity. In addition, the higher humidity inside the GOS, which reaches up to 15–20 % difference compared to the area outside the GOS, provides better thermal comfort for the community. The lower intensity of sunlight inside the GOS also strengthens its role as a natural shade, re-

ducing it by up to 70 % compared to open areas. In addition, wind speeds inside the GOS tend to be lower due to the barrier effect of the vegetation, which helps create a more stable microclimate environment. The study also confirmed that the vegetation within the GOS is an effective natural acoustic barrier, with a 10–15 dB reduction in noise levels compared to areas outside the GOS.

Based on the results of this study, it can be concluded that GOS not only functions as an aesthetic element of the city but also has a crucial role in maintaining the balance of urban ecosystems and improving the community's quality of life. Therefore, efforts to manage and develop GOS must continuously improve quantity and quality to mitigate the negative impacts of urbanisation and climate change. Considering these findings, it is recommended that local governments accelerate the realisation of the 30 % target area as GOS under applicable regulations. In addition, implementing more effective vegetation-based design strategies, such as increasing plant diversity, arranging tree canopies, and integrating water elements in GOS, can be a more optimal solution in supporting urban environmental sustainability.

However, it is important to note that the effectiveness of GOS in regulating the microclimate is influenced by various factors not examined in this study, such as tree age, vegetation density, seasonal variation, and historical land management. These factors may enhance or limit the environmental benefits observed. Therefore, future studies are encouraged to incorporate these elements to provide more comprehensive understanding of the role of vegetation structure and dynamics in urban climate regulation.

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