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LOW-COST PORTABLE BIOCLIMATIC BACKPACK FOR DYNAMIC MICROCLIMATE MONITORING IN OPEN SPACES

MOCHILA BIOCLIMÁTICA PORTÁTIL DE BAIXO CUSTO PARA MONITORAMENTO DINÂMICO MICROCLIMÁTICO EM ESPAÇOS ABERTOS

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Abstract

Innovative systems using low-cost portable microcontrollers applied to human biometeorology studies are an alternative to conventional microclimate measurement devices. This study aims to test and evaluate a low-cost portable environmental monitoring system (PLEMS) focusing on the urban scale at the pedestrian level. The method consists of the following steps: description of the PLEMS device, checking sensors' accuracy, and application in thermal walks on a university campus. The backpack device consists of a set of low-cost sensors designed to assess pedestrians' environmental comfort conditions in a broad sense, integrating measurements of microclimatic variables, air quality, lighting and noise levels. The equipment allows users to obtain the environmental quality of the urban environment in a multi-point/ multi-sensorial way or even more accurately and assertively evaluate the proposals of urban interventions. The PLEMS device application demonstrated reliability in measuring microclimatic variables and application feasibility in dynamic monitoring of intra-urban environments. The device is characterized as an instrument with a vast field of applications, especially those aimed at understanding the influence of urban design on thermal comfort conditions in open Spaces.

Keywords: Outdoor thermal comfort, Environmental monitoring system, Low-cost microcontroller, Bioclimatic backpack.

Resumo

Sistemas inovadores utilizando-se de microcontroladores portáteis de baixo custo aplicados a estudos de Biometeorologia humana são uma alternativa aos dispositivos convencionais de medição microclimática. Esta pesquisa objetiva testar e avaliar o protótipo de um sistema portátil de monitoramento ambiental de baixo custo (PLEMS, em inglês) voltado à escala urbana ao nível do pedestre. O método consiste das seguintes etapas: descrição da PLEMS, aferição dos sensores embarcados e aplicação em estudo de conforto térmico em espaços abertos a partir de percursos a pé em campus universitário. A mochila constitui-se de um conjunto de sensores que permitem avaliação das condições de conforto ambiental dos pedestres de forma ampla, integrando medições de variáveis microclimáticas, qualidade do ar, níveis de iluminância e de ruído. O equipamento permite aos usuários auferir a qualidade ambiental do meio urbano de forma multipontual e multissensorial ou ainda avaliar de forma mais precisa e assertiva as propostas de intervenções urbanísticas. A aplicação da PLEMS demonstrou confiabilidade na medição das variáveis microclimáticas e viabilidade de aplicação em monitoramentos dinâmicos de ambientes intraurbanos. A PLEMS caracteriza-se como um instrumento com vasto campo de aplicação, principalmente aquelas destinadas a compreender a influência do desenho urbano nas condições de conforto térmico no espaço aberto.

Palavras-chave: Conforto em espaços abertos, sistema de monitoramento ambiental, microcontrolador de baixo custo, mochila bioclimática.

Authors' contributions:
IJAC: conceptualization, formal analysis, investigation, methodology, validation, visualization, writing-draft & original, writing-review & editing. **WI**: conceptualization, investigation, methodology, programs, validation, visualization, writing-original draft. **ELK**: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, writing-original draft, writing-review & editing. **SML**: conceptualization, funding acquisition, investigation, methodology, project administration.

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Introduction

Research in Human Biometeorology (Mcgregor, 2012), especially studies focusing on thermal comfort conditions in open spaces, is essential to ensure the quality of life of the urban population. As a backdrop for these studies, there is growing urbanization seen mainly in developing countries, essentially in the so-called "Global South" and particularly in Asia and Africa (Kundu; Pandey, 2020), as well as the pressures created by climate change, observed worldwide, exacerbated even further in urban centers (Arsad *et al*., 2022; Estrada; Perron, 2021).

Several studies use stationary meteorological stations to investigate the microclimatic effects of urban transformations, mainly focusing on identifying the intensity of urban heat islands (Ng *et al.,* 2012; Wang *et al.,* 2021). As in many cases, meteorological stations are positioned at specific points in the urban fabric or even far from the city center (in the case of stations located at airports), the data collected cannot represent the different thermal exposures in urban centers, considering the diversity of existing spatial patterns.

In this context, the spatially distributed recording of meteorological variables is of fundamental importance for comfort studies in open spaces at the pedestrian scale. However, this data is usually scarce due to the high cost of the equipment involved for monitoring or the need for a high number of measurement points (Lima *et al.,* 2022). To overcome the limitations posed by fixed station measurement techniques, several studies have utilized mobile measurement methods. These methods involve installing sensors in vehicles such as cars, bicycles, or even using backpacks while walking (Lau *et al.,* 2017; Cureau *et al*., 2022).

In developing countries, where there is a lack of financial resources for research, alternative and economical methods have been sought to standardize measurement procedures. This promotes and develops studies in the field of human biometeorology. A recent review in Brazil highlighted regions that lack or are still in the early stages of studies, where the scarcity of resources for research is a limiting factor (Krüger *et al*., 2022).

In order to overcome the limitations of the high cost of measuring devices and professional commercial sensors, research aimed at the technological development of systems based on low-cost microcontrollers appears as an alternative to traditional equipment used to monitor microclimatic data at the pedestrian scale, such as "comfort meters" (Trento; Trento; Kruger, 2020). Free hardware electronic prototyping platforms are designed to create user-friendly tools for introductory computer science and physics. They can also be utilized in robotics and instrumentation, among other applications. These platforms are affordable, adaptable, and easy to use. Some examples available on the market include the Arduino Platform and, more recently, the Raspberry Pi. The Raspberry Pi allows the development of compact, lightweight devices that integrate various sensors for environmental variables, offering greater flexibility compared to existing equipment. These platforms are commercially available at a low cost, making them suitable for conducting research within limited budgets (Callejas; Durante; Apolonio, 2014).

Given the potential presented by dynamic microclimatic surveys in environmental comfort research at an urban scale, this study aimed to test and evaluate a Portable Low-cost Environmental Monitoring System (PLEMS) for pedestrian-scale microclimatic surveys in urban areas (Krüger *et al*., 2022; Krüger *et al*., 2023).

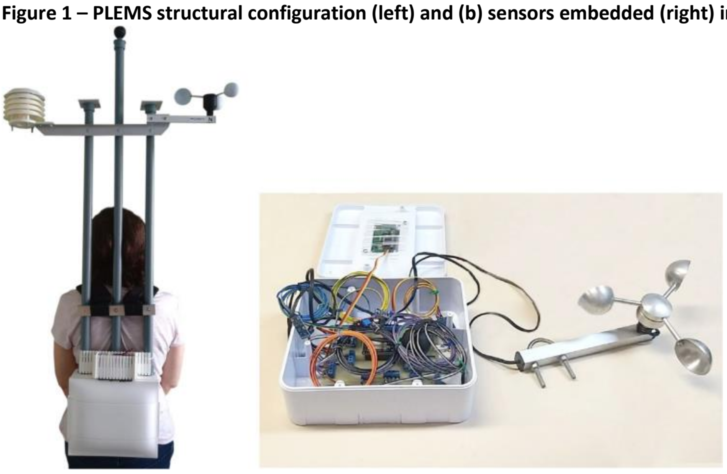
Method

Description of the Portable Low-cost Environmental Monitoring System - PLEMS

The design of PLEMS was based on international and national research. Design Thinking (Rowe, 1991) steps were followed, assuming that the bioclimatic backpack should contain low-cost sensors that would enable a broad assessment of environmental conditions in the urban environment, not being restricted to the thermal perspective. In addition to the trivial thermal monitoring sensors, such as air temperature and humidity, globe temperature and air speed sensors were coupled.

The backpack is innovative due to the inclusion of sensors that can measure air quality (CO_2 concentration), illuminance, and environmental noise simultaneously. Additionally, a Global Positioning System (GPS) has been added to facilitate the geographic location of points of interest during measurement campaigns as measurements do not occur at a fixed point. The system also includes components to enable the equipment to automatically record data, such as a real-time clock and a portable memory card module (Figure 1).

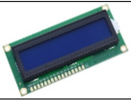
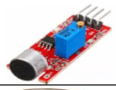
Figure 1 – PLEMS structural configuration (left) and (b) sensors embedded (right) in the Backpack



Source: the authors.

In cost research (nationally and internationally), it was found that several sensors met the specifications related to resolution and accuracy required for application in the field of human Biometeorology, taking class C (comfort) of ISO 7726 (ISO) as a reference (ISO, 1998). Since the project premise is focused on low cost, it was decided to select those that met the criteria of the standard above and those that were inexpensive, considering the price of the sensor and the shipping cost. Due to the limitations of the Arduino UNO microcontroller, initially considered to compose the system, and due to the number of sensors to be installed in the PLEMS, it was decided to replace it with an intermediate microcontroller, the ESP32, which is equivalent to the Arduino model MEGA, but with a lower value in terms of cost. Chart 1 presents the PLEMS components, with their respective costs quantified during the preparation phase (in dollars). Chart 2 shows the technical characteristics of the sensors and their accuracy.

Chart 1 - List of components used in the PLEMS prototype

Electronic component specification	Image	Description	Acquisition cost
ESP32S CP2102 30 pins		Microprocessor	$ 14.19
Liquid Crystal Display with I2C adapter		LCD to display sensors information	$ 7.21
Real Time Clock DS3231 Module		Component used to record the date and time during the measurements	$ 7.91
microSD card slot		Memory storage	$ 2.75
GPS GY-NEO6MV2 module		Global Positioning System	$ 17.81
AHT10 module		Temperature and humidity sensors set	$ 4.74
DS18B20 module		Temperature sensor used to manufacture globe thermometer	$ 2.36
ANBR-1 wind speed		Cup Anemometer Sensor	$ 53.50
MQ-135 gas module		Used to measure the level of CO2	$ 4.93
BH1750-FVI GY-30 module		Ambient Light Intensity Sensor	$ 3.96
KY-038 module		Microphone sound sensor	$ 2.75
Temperature and humidity (AHT10) shelter		Printed in PLA (an aluminum film was installed on the top plate)	$ 51.52
Globe thermometer		Plastic globe painted in light graphite color (40mm diameter)	$ 0.99
Powerbank 5V		Portable charger used to power the Microprocessor circuits	$ 34.68
MicroSD card		Storage of microclimatic data	$ 5.92
Electronic components		Circuit board, cables, resistors, connectors, among others	$ 29.29
Structural parts of the prototype		Plastic base, PVC pipes, handles, cable ties, among others	$ 29.72
Total cost (May 2023)			$ 274.03

Source: the authors. Note: * Budgeted cost in March 2023, dollar exchange rate in October 2023.

Chart 2: Details and technical specifications of the PLEMS sensors

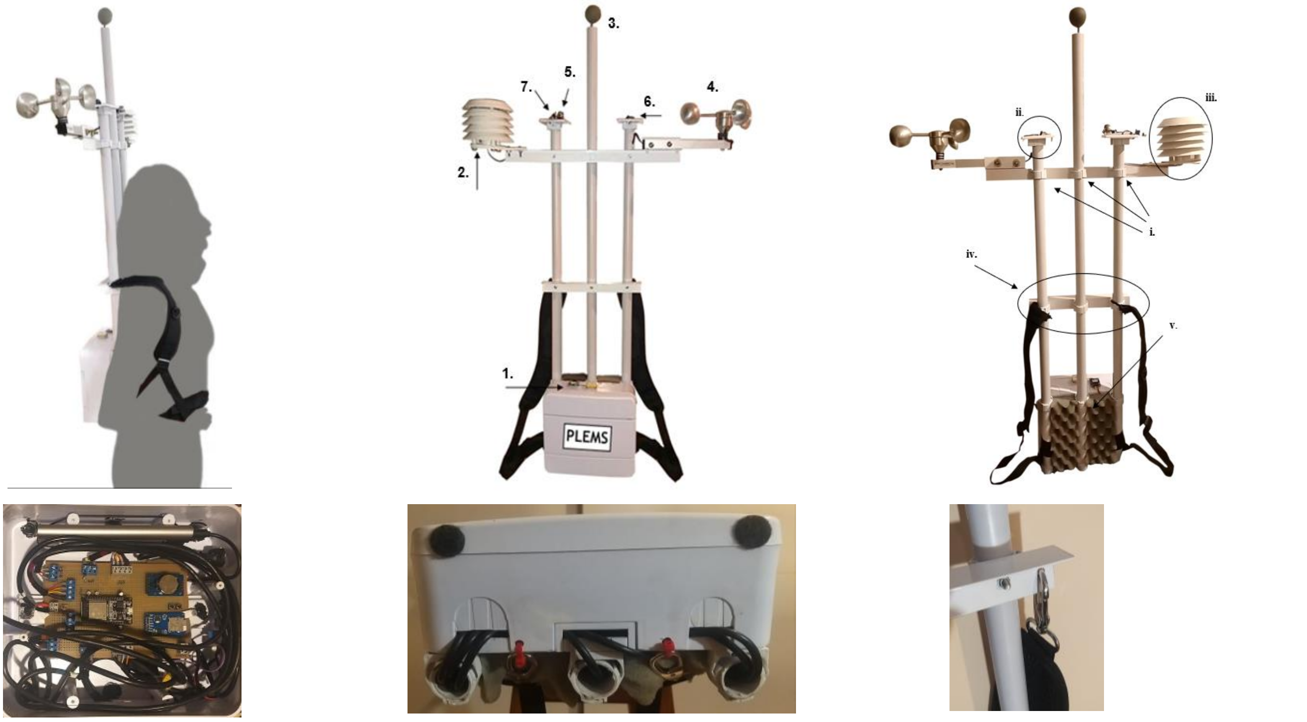
Sensor specification	Manufacturer	Measured variable	Response time	Reading range (required in ISO 7726)	Accuracy
GPS GY-NEO6MV2 (1)*	u-blox®	Latitude, longitude, number of connected satellites, and ground speed	27 seconds to initialize and 1 second between successive measurements	Geographic coordinates: (not applicable)	5 meters (not applicable)
AHT10 (2)	ASAIR®	Air temperature	5 < 30s	-40 to 85°C (10 to 40°C)	± 0.3°C (± 0.5°C)
		Relative air humidity	8s	0 a 100% (0.5 to 3.0kPa)	± 2% (0.15kPa)
DS18B20 (3)	Maxim Integrated Products®	Globe thermometer	0.75s	-55 to 125°C (10 to 40°C)	± 0.5°C (± 2°C)
ANBR-1 (4)	WRF industry®	Wind speed	3.1s	0.19 to 37.5 m/s (0.05 to 1.0m/s)	< ±5% (±0.05 to 0.10m/s)
MQ-135 (5)	Winsen®	Concentration level of CO2	1s	(10 to 1000ppm (not applicable)	±5% or ± 50 ppm** (not applicable)
BH1750-FVI GY-30 (6)	ROHM Semiconductor®	Illuminance level	<1s	1 < 65.535 lx (not applicable)	± 20% (not applicable)
KY-038 (7)***	JOY-IT®	Instantaneous sound pressure levels	1s	10Hz to 50kHz (not applicable)	Not provided (not applicable)

Note: *( ) The number in parentheses is associated with its positioning in Figure 2a; ** ppm - part per million; ***the sensor was adjusted using Minipa MSL-1325A equipment based on the emission of a pure tone at 1000Hz at a sound pressure level of 70dB; n/a – not applicable. Source: the authors.

The PLEMS device was created to monitor the environmental conditions that a person experiences during different activities in open spaces, such as recreational, physical, or work-related tasks. The aim was to develop a compact and lightweight device with sensors positioned at a height that would not impact the user's movements (refer to Figure 2, on the left). To achieve this, the ESP32 microcontroller was placed inside an electrical distribution board to house the equipment. The sensitive components, including air temperature and humidity sensors (2), globe thermometer (3), anemometer for air speed measurement (4), CO2 concentration meter (5), illuminance meter (6), and sound pressure level (noise) sensor (7), were positioned away from the base and user interference using PVC rods.

To summarize, the bioclimatic backpack comprises a base to which three PVC rods are attached using plastic clamps (i). Two of these rods are 0.80 m high, and the central rod measures 1 m, on which the temperature thermometer is placed. The globe is affixed at a distance to minimize the backpack holder's impact on the measurement. Related to its sensor, efforts were made to symmetrically place them inside a plastic sphere with a 40mm diameter to avoid the influence of thermal bridges. Two electrical outlet wall plates are used to maintain sensor alignment (ii). The temperature and humidity sensors are shielded by a radiation barrier made from Polylactic Acid Plastic, which was 3D printed (iii). The digital model for the barrier is available from the open-access repository (Thingiverse, 2023). Additionally, the radiation barrier was varnished and an aluminum foil film was inserted into the bottom part of the upper plate (Ham, 2015). An adjustable beam (iv) allows for the adjustment of the height (required) of the sensors to match the height of the backpack users. The backpack straps were secured with nylon cable ties. Finally, "eggshell" foam was added between the PVC rods (v), ensuring greater ergonomics of the prototype (Figure 2, top right). Construction details are shown in Figure 2.

Figure 2 – Details of the backpack attachment to the user (top left), location of the sensors (top center and top right) and PLEMS construction details (bottom left, center and right)

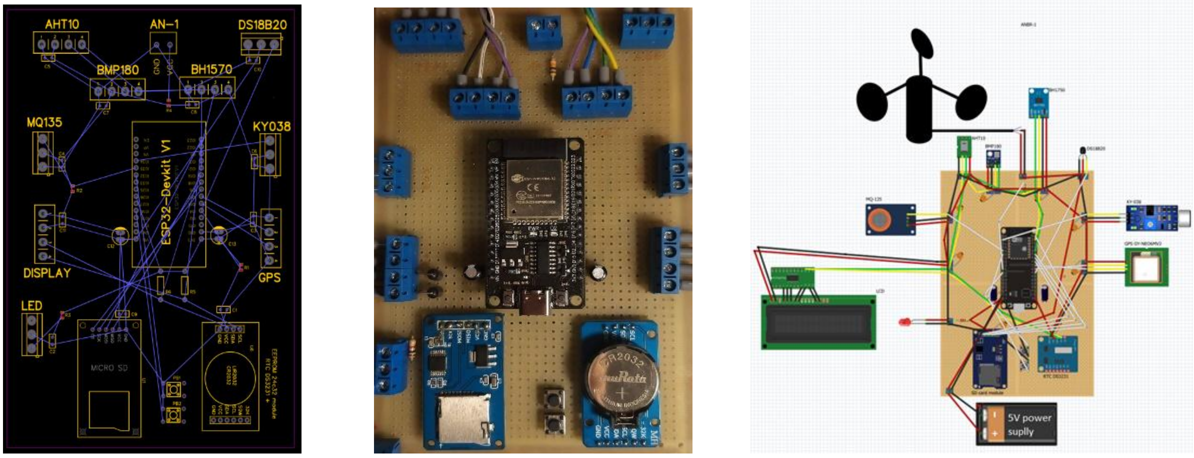


Note: Legend a) 1 – GPS; 2 – thermo-hygrometer; 3 – globe thermometer; 4- shell anemometer; 5 – CO2; 6 - Illuminance; 7 – Sound pressure level. Legend c) i – plastic cable ties; ii – wall plate; iii – radiation barrier for the thermohygrometer sensor made of PLA; iv – adjustable beam; v – "eggshell" shaped foam. Source: the authors.

The sensors are part of the sensitive part of the transducer, which captures electrical signals and generates output proportional to the measured quantities. To interface the data captured by the sensors, the transducer, and the PLEMS users, a source code was developed using the Arduino IDE language (C++). This code transforms electrical signals into physical quantities, processing them later for data analysis. It is also responsible for storing data on environmental variables and additional GPS functions in a ".csv" file on the MicroSD Card Module.

The PLEMS system was initially developed on a circuit board consisting of two 830-point breadboards, using jumper cables as connections, according to Nouman *et al*. (2019). Subsequently, the circuit was optimized in the EasyEDA software (Figure 3, left), starting to use a standard board of size 10×15cm, using soldered terminations (Figure 3, center), eliminating the need for jumper cables, which made the system more stable during movement. The idealized sensors can be seen in Figure 3 (on the right).

Figure 3 – Diagram of the electronic circuit (on the left), circuit board with the transducer and fixing terminals (center), and sensors designed for the prototype (on the right)

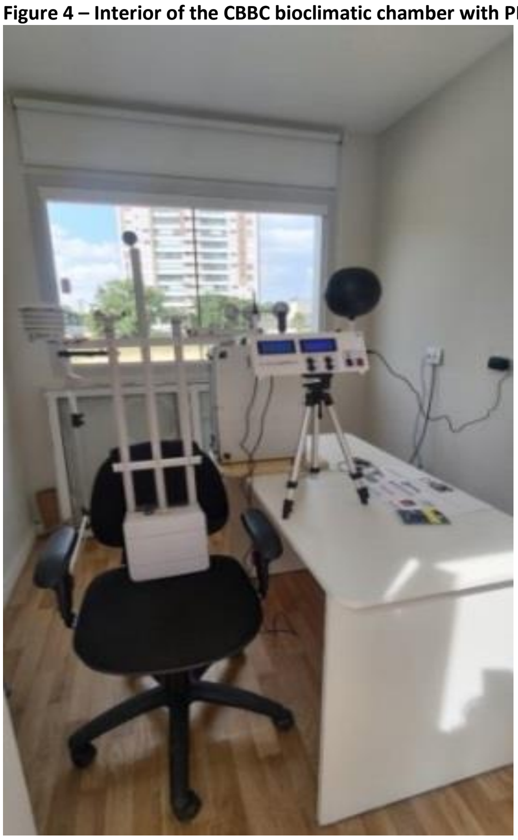


Source: the authors.

Procedure for evaluating the reliability of the environmental sensors in the PLEMS

The PLEMS sensors' reliability was tested in the Low-Cost Bioclimatic Chamber (CBBC) located on the UTFPR Campus in Ecoville. This facility focuses on researching environmental comfort and the performance of the built environment (Trevisan *et al*., 2020). The evaluation of the environmental sensors' reliability involved measuring and comparing them with reference equipment that was properly calibrated to ensure their accuracy within the requirements specified for class C (comfort) of ISO 7726 (ISO, 1998) (Figure 4).

Figure 4 – Interior of the CBBC bioclimatic chamber with PLEMS and the reference equipment



Source: the authors.

The "SENSU Comfort Meter" equipment was used to measure the temperature, humidity, globe thermometer, and illuminance sensors. To measure the sound pressure level (noise) and the wind speed, a MINIPA sound level meter (model MSL-1325A®) and a Kestrel propeller anemometer (model 3000) were used. The sensors were placed 1.80 m above the floor at the center of the bioclimatic chamber (CBBC) to monitor the environmental conditions for three hours. Measurement sampling took place every minute, resulting in 180 measurements. To measure the thermo-hygrometer, the split-type air conditioning setpoint was activated to 16°C. Once this temperature was reached, the air conditioning was turned off, and the environment was monitored in a remote mode without the presence of people.

To validate the sensors, we conducted simple linear regression analyses between the data measured by PLEMS (dependent variable) and commercial sensors (independent variables) to make statistical inferences about the linear association measures between them. We estimated the error between the data measured by PLEMS and commercial sensors using the statistical indicator Average Absolute Error (EAM) to assess the data quality before and after the measurements. We applied the non-parametric Kruskal-Wallis test to independent samples to identify statistically significant differences (p-value < 0.05) between the variables measured by the sensors. (Dowdy; Wearden; Chilko, 2004).

Application of PLEMS in an outdoor thermal comfort study

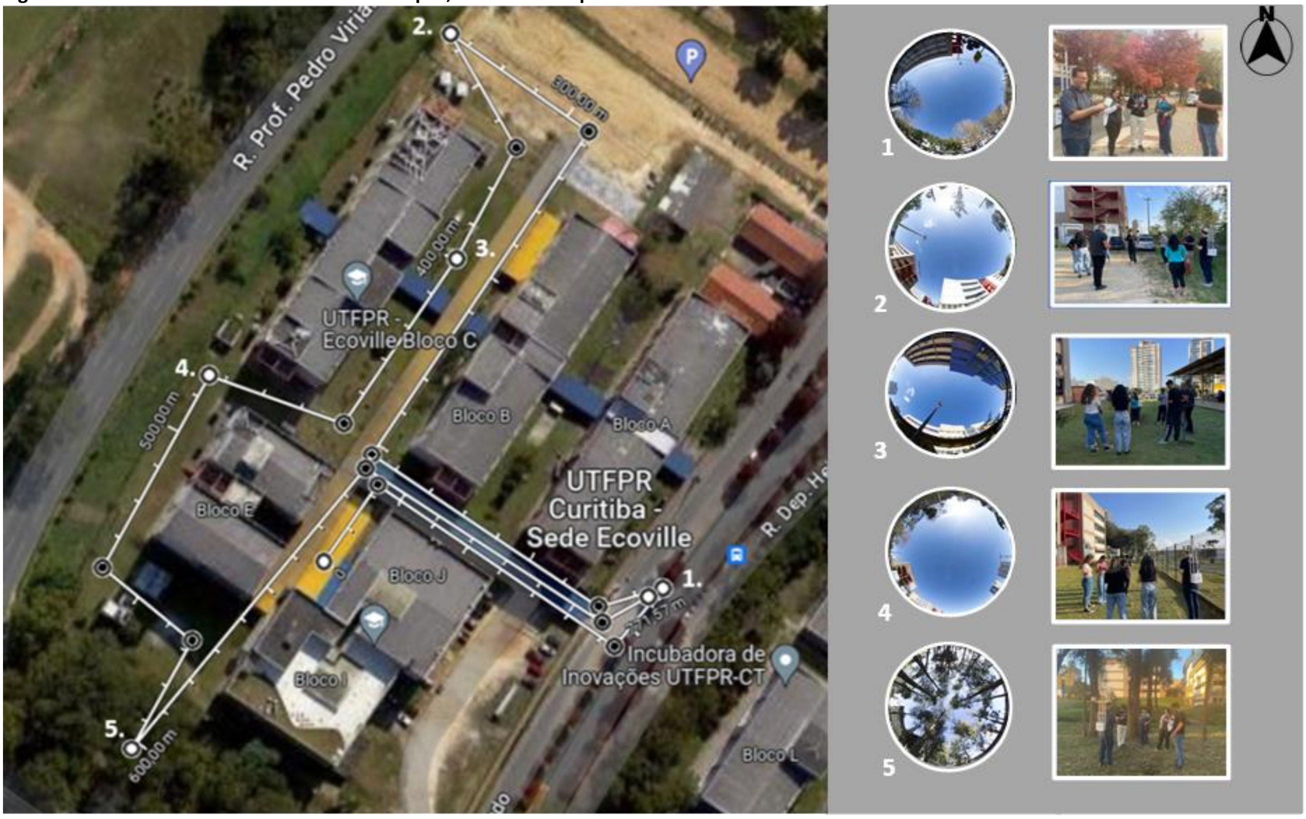
Microclimatic monitoring

The test performance evaluated the structural mechanic's resistance of PLEMS components, its ergonomics, and the measurement and validation of environmental variables. To this end, exploratory environmental monitoring campaigns were conducted in the autumn and winter seasons of 2023, in Curitiba, PR, which has a humid subtropical climate (Cfb - Köppen-Geiger). The performance evaluation occurred under standardized atmospheric weather conditions and in some morphological environmental conditions, aiming to access the sensors' ability to respond dynamically to microclimatic variation imposed by different construction patterns in the research circuit.

The researcher walked around the UTFPR campus, Ecoville headquarters, carrying a backpack with the PLEMS device attached to it. This stage aimed to check the equipment's robustness and its ability to produce consistent responses, under various atmospheric weather conditions. A circuit with five points of interest, each featuring different morphological configurations and land use/ occupation patterns, was defined for this purpose (Figure 5).

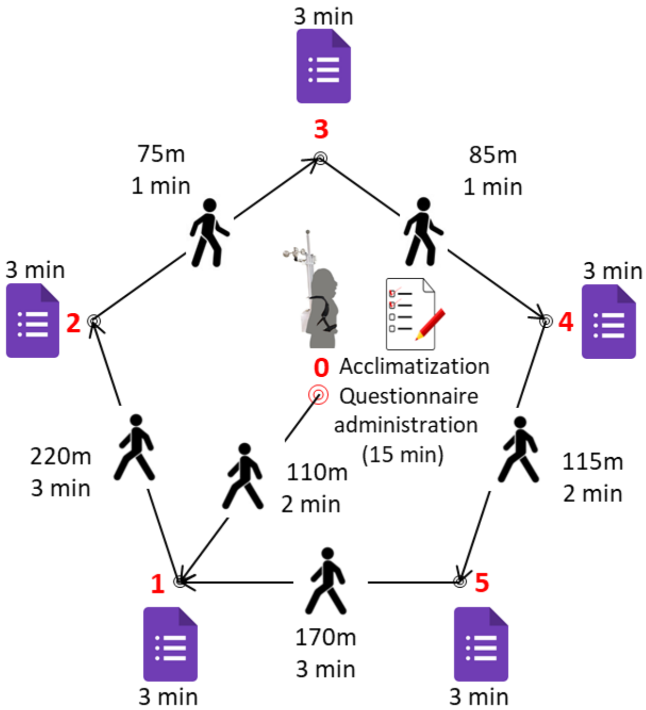
Point 1 is situated on the campus entrance sidewalk, along an avenue that provides access to the university blocks and is near a bus stop. The ground surfaces here are covered with concrete and asphalt, with trees planted in the central median. Point 2 is at the northwest end of the campus, in an unpaved parking area with exposed bare ground. To the northwest, there is a heavily trafficked avenue, while to the south, a campus block surrounds this point. Point 3 is located within a canyon formed by two campus blocks, with surfaces covered in grass and concrete. This area includes facilities for leisure and rest. Point 4 is positioned outside the access perimeter to the campus facilities, in a grass-covered area. Nearby, to the northwest, there is the same avenue mentioned in Point 2, while to the south, a campus block also surrounds this point. Point 5 is at the south end of the campus, in an environmental preservation area under tree canopies. The soil here is covered by shrubs and grasses. To the northwest, there is the same heavily trafficked avenue that surrounds Points 2 and 4, while to the south, a local road adjacent to the campus is found. Further details of the circuit and data collection sequence are shown in Figure 6. Chart 3 presents the shadow mask, Sky View Factor (SVF) index, and the morphological characteristics of each point.

Figure 5 - Circuit carried out on the UTFPR campus, Ecoville headquarters



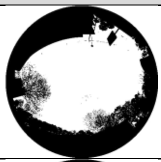
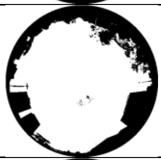
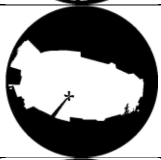
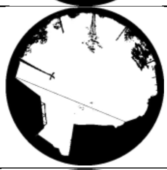
Source: the authors.

Figure 6 - Circuit times and distances



Source: the authors.

Chart 3 – Overall morphological features of the circuit points

Point	Shadow mask	SVF	Average height of buildings and/or trees in the vicinity	Ground cover	Soil permeability	Shading characteristics
1		0.542	Buildings: 15m Trees: < 5m	Concrete pavement/asphalt	Impermeable	Shadow cast by the nearby buildings
2		0.706	Buildings: 15m Trees: > 30m	Exposed soil	Permeable	Shadow cast by existing trees to the north and buildings to the south
3		0.424	Buildings: 15m Trees: absent	Grass/Concrete Pavement	Partially permeable	Shadow cast by adjacent buildings
4		0.643	Buildings: 15m Trees: > 30m	Grass	Permeable	Shadow cast by existing trees to the north and buildings to the south
5		0.177	Buildings: absent Trees: > 30m	Exposed soil/underbrush	Permeable	Shadow cast by the tree canopy

Source: the authors.

Subjective environmental assessment

Given the PLEMS device's focus on dynamic measurements, a multi-sensory perception experiment was conducted at the researched points. Undergraduate volunteers participated by walking through the described circuit while environmental variables were measured simultaneously. The aim was to determine whether dynamic exposure to different morphological patterns would influence subjective responses. The research adopted convenience and non-random sampling techniques, and the questionnaire application was approved by the Ethics Committee.

The equipment's sensitivity to weather, especially during rain events, is an important consideration for field research planning. Therefore, to standardize atmospheric conditions, the circuit was covered under clear skies and low wind speeds, as cloud cover and sudden gusts could affect the interviewees' perceptions. Before starting the walk, interviewees acclimated for about 15 minutes in an outdoor area. This time was also used to initialize the PLEMS instrument, collect personal data (biometrics, clothing, long-term acclimatization), and sign the free and informed consent (TCLE).

The researcher, carrying the PLEMS, stood at each collection point with the PLEMS device facing north to standardize the measurement. A maximum of eight volunteers per campaign walked simultaneously. To normalize the interviewees' metabolic rates, displacements between points occurred at a controlled pace, averaging 4 km/h (2.3 MET). Each point was visited for 3 minutes to stabilize the sensors, allowing participants to acclimatize to the surroundings before administering the perception interviews. Only the average value of the environmental variables measured at each point during the 3 minutes was considered for environmental exposure purposes.

Since relative perception questions were asked between points, Point 1 was used as the start and end of the circuit. The 800m circuit was completed in approximately 50 minutes. Figure 6 illustrates the circuit timeline, showing distances and average travel times between points.

In addition to the conventional questions suggested in ISO 10551 (ISO, 1995) regarding environment thermal perception and preferences votes, the questionnaires, administered in the afternoon due to the availability of volunteer students, involved the evaluation of environmental perception in a broader sense, including light intensity satisfaction, noise, and air quality annoyance votes, thus allowing a multisensory assessment (Lam *et al.*, 2020). Subjective data were collected using structured forms in Google Forms (Chart 4), accessed through a QR code via a smartphone at each visited point. In addition to the subjective perception, we sought to conduct relative comparisons between the researched points, questioning the environmental perception of the current point concerning the previous one visited, according to the questions presented in Chart 5, to verify the volunteers' sensitivity in dynamically differentiating the different microclimates covered in the circuit.

The sample obtained in the autumn and winter campaigns was 25 (in 7 campaigns) and 38 undergraduates (in 5 campaigns), respectively, making a sample of 63 questionnaires applied at each point (or n=378, for the complete circuit). Due to the large amount of data collected, this article focused only on the subjective analysis of the interviewees' thermal comfort (questions "a", "b", and "c" in Chart 4 and question "a" in Chart 5). In the PLEMS testing stage, the analysis focused only on microclimatic variables and the subjective thermal perception assessment.

To relate the thermal perceptions reported by participants during the interviews with the thermophysiological effects triggered by the environmental variables (Ta, °C; RH, %; v, m/s; and Tmrt, °C) recorded at each point, the UTCI Index (Universal Thermal Climate Index) (Bröde *et al*., 2012) was used. It was calculated using the BioKlima v.2.6 software (Błażejczyk, 2020), considering the microclimatic variables recorded at each point during the interviews. The level of heat stress was segmented according to the stress classes suggested for the UTCI index by Bröde *et al*. (2012): 9 to 26°C - no heat stress; 26 to 32°C - moderate heat stress; 32 to 38°C - strong heat stress; above 38°C to 46°C - very strong heat stress; and > 46°C - extreme heat stress.

Chart 4- Environmental perception questionnaire

a) How do you feel about the thermal environment?						
-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot
b) Regarding the microclimate of this location, how are you feeling?						
0	1	2	3			
comfortable	slightly uncomfortable	uncomfortable	very uncomfortable			
c) At this moment, regarding the microclimate of this point, how would you prefer it to be?						
-3	-2	-1	0	+1	+2	+3
much colder	colder	slightly colder	no changes	slightly warmer	warmer	much warmer
d) Regarding the light intensity at this point, how do you feel?*						
-2	-1	0	+1	+2		
very unsatisfied	unsatisfied	indifferent	satisfied	very satisfied		
e) Regarding the noise level at this point, how do you feel?*						
0	1	2	3			
not annoyed	slightly annoyed	very annoyed	extremely annoyed			
f) Regarding the air quality at this point, how do you feel?*						
0	1	2	3			
not annoyed	slightly annoyed	very annoyed	extremely annoyed			

Source: the authors.

Chart 5 - Relative environmental perception questionnaire*

a) In relation to the previous point, you consider the thermal environment at this point to be:		
0	1	2
colder	similar	warmer
b) In relation to the previous point, you consider the light intensity at this point to be:		
0	1	2
less intense	similar	more intense
c) In relation to the previous point, you consider the noise level at this point to be:		
0	1	2
less noisy	similar	noisier
d) In relation to the previous point, you consider the air quality at this point to be:		
0	1	2
less polluted	similar	more polluted

Source: the authors. *Questions not applicable to Point 1 at the start of the walk.

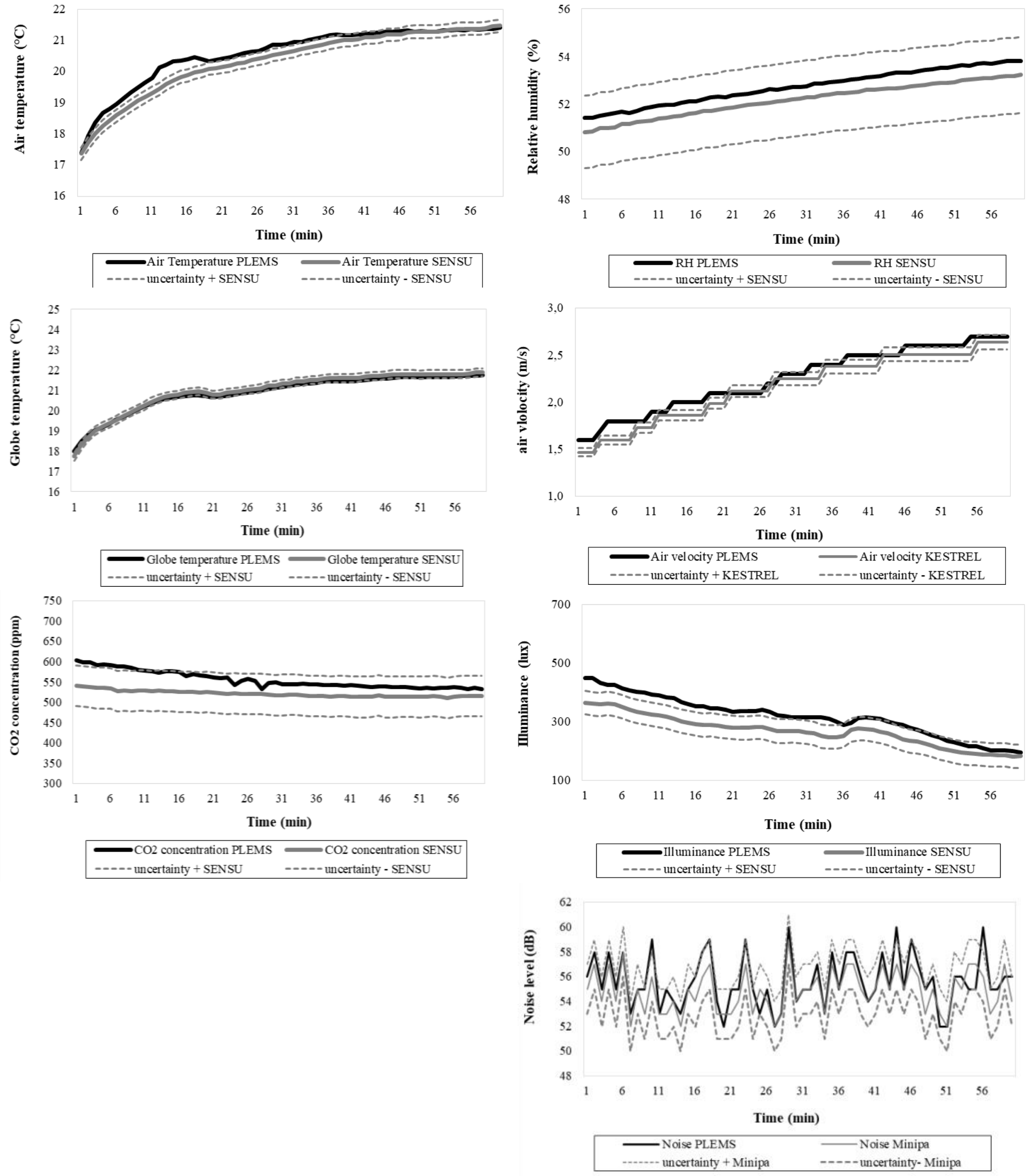
Results

In the next sections, we compare the PLEMS sensor measurements with other robust equipment and show performance tests conducted during the dynamic study on outdoor thermal comfort.

PLEMS sensors: measuring and calibration

Figure 7 shows the data collected inside the CBBC bioclimatic chamber by the PLEMS sensors (in black) and by the reference equipment (in gray). Dashed lines that indicate the measurement error ranges of the reference equipment sensors are also displayed in the graphs. Note that the physical quantities (Ta, °C; RH, %; Tg, °C; va, m/s; CO_2 concentration, ppm; illuminance, lux; instantaneous noise, dB, shown from the upper left corner to the lower right corner, respectively) underwent variations as indicated in Chart 6.

Figure 7 - Measurements between PLEMS and reference equipment: Ta (°C), RH (%), Tg (°C), va (m/s), CO_2 concentration (ppm), illuminance (lux) and instantaneous noise (dB) (from top left corner to bottom right corner)



Source: the authors.

Although PLEMS data is within the error range of reference equipment, except for temperature and air velocity measurements, the Kruskal-Wallis non-parametric analysis indicated that there is a significant statistical difference (p-value<0.05) between the measurements carried out on the equipment for the relative humidity, globe temperature, CO_2 concentration, and illuminance variables, for which a sensor adjustment procedure was applied using simple linear regression analysis. For the globe thermometer, deviations between measurements also occur due to the difference between the diameters of the globe equipment. For ease of use, it was decided to adjust it directly through the fitted equation obtained between the data measured in the reference sensor and in the PLEMS without carrying out the correction suggested by ISO 7726 (ISO, 1998) when using a diameter other than that specified in this standard.

The coefficient of determination (R^2) verified in the regressions was high for most sensors, indicating that the environmental variables measured by PLEMS and reference equipment have a strong correlation (Chart 6). The calibration procedure was adequate since the average absolute errors after calibration were reduced concerning the initial data, resulting in sensors capable of reproducing environmental variables within the usual accuracy found in measuring equipment.

Chart 6 - Information about the calibration test of sensors embedded in the PLEMS

Environmental variable	Measuring range	Mean Absolute error without adjustment (ref-PLEMS)	p-value	R^2	Mean absolute error after adjustment (ref-PLEMS)
Air temperature	17 a 22°C	0.24	0.214	0.975	Not applied
Relative Humidity	49 e 55%	0.55	0.001	0.995	0.04
Globe temperature	17 a 22°C	0.13	0.046	0.998	0.03
Air velocity	0,4 a 1,7 m/s	0.09	0.273	0.971	Not applied
CO_2 concentration	500 a 600 ppm	34.62	8.2E-20	0.912	1.70
Level of Illuminances	200 a 450 lux	49.35	3.3E-05	0.986	4.62
Instantaneous Level of noise	50 a 60 dB	1.08	0.055	0.689	Not applied

Source: the authors.

Performance test and application of environmental perception questionnaires

The results of the performance test using the pre-defined circuit around the university campus are presented below. This includes a description of the variables measured, their relationships with the selected points, and an analysis of participants' subjective perceptions during the PLEMS measurement campaigns.

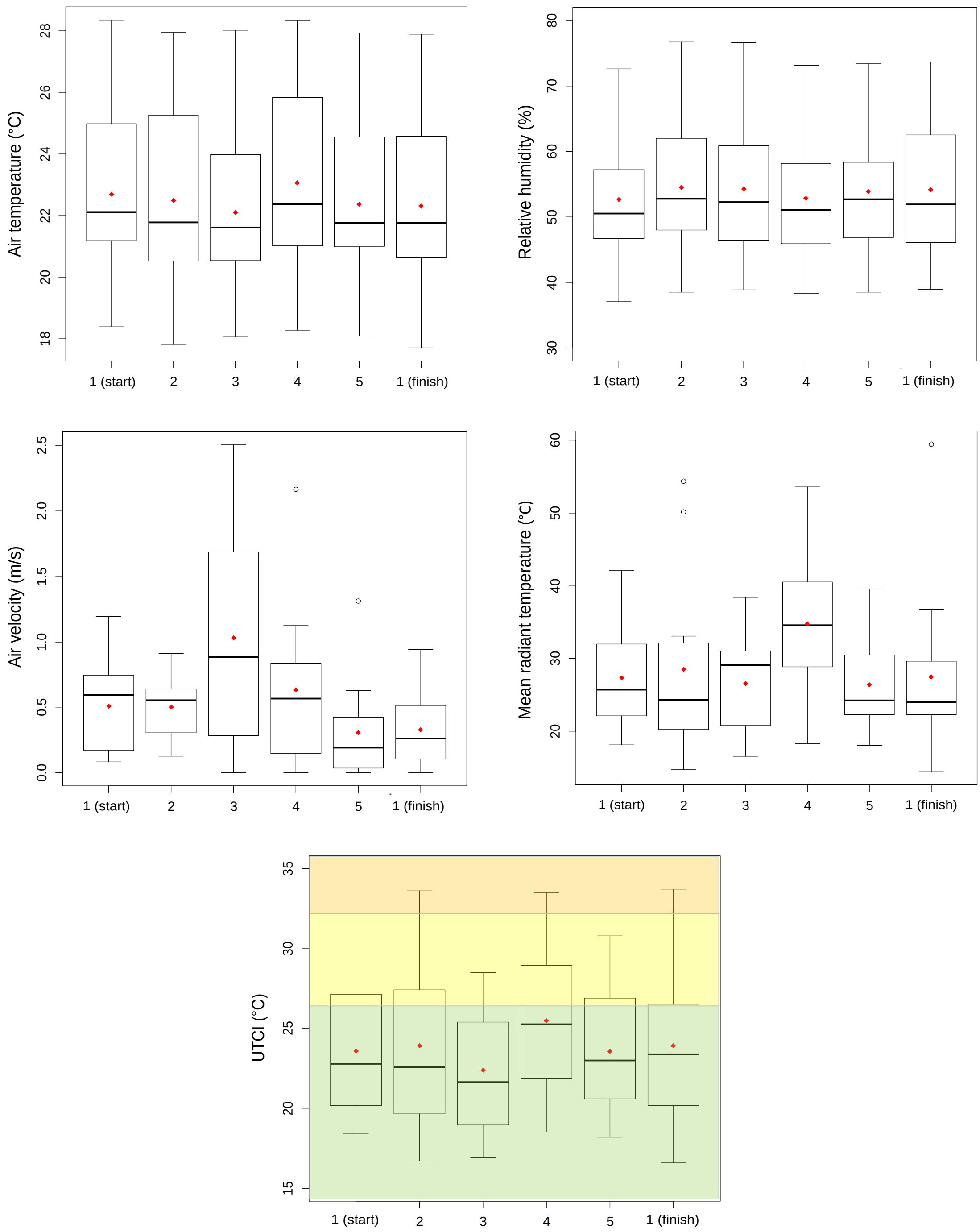
Environmental data collected by PLEMS

The environmental data (Ta, RH, Tmrt, v) collected during the autumn and winter campaigns, along with the derived UTCI index, are shown in the box plots (Figure 8, from top left to bottom center). Differences in means and medians are observed between the points, with significant variations in the data range (first and third quartiles) and some outliers present in the sample.

The highest average value identified for air temperature (Figure 8, above left) during the campaigns is observed at point 4, while the lowest is at point 3. Point 4 is characterized by being a spot exposed to solar radiation during the afternoon period (to the southeast), also influenced by campus buildings that receive sunlight and radiate it to the surrounding environment, which may have influenced this point to become the hottest among the others. Point 3 is located between two buildings on the campus, which form an artificial canyon, leaving this point shaded during measurements and consequently with lower temperatures. Despite being shaded by the existing trees, at point 5 a slightly higher value was recorded than at point 3, probably due to the shape of the canopy that does not completely block the sun from entering in the afternoon.

In relation to air relative humidity (Figure 8, top right), point 1 remained less humid, possibly due to its waterproof nature. Despite being permeable and covered by grasses and/or shrubs, neither point 4 nor point 5 showed the highest humidity levels. The highest values occurred at point 2, likely due to the exposed soil. Regarding air velocity (Figure 8, center left), the arrangement and orientation of buildings around point 3 create a morphological configuration that channels the prevailing winds, while point 5, located within a forest with high surface roughness, hinders wind passage. For mean radiant temperature (Figure 8, center right), similar to air temperature, the highest values were found at point 4, indicating that the surrounding walls of existing buildings influenced this point due to long-wave radiation emission. Conversely, the lowest value occurred at point 5, due to partial shading from trees and the absence of nearby buildings, with values very close to those recorded at point 3, in a shaded canyon provided by the building.

Figure 8 - Boxplot of environmental variables (Ta, UR, Tmrt, v, in that order below, respectively) and UTCI index (in colors) at the circuit points



UTCI (°C)	Heat stress classes
32 < UTCI < 38°C	Strong heat stress
26 < UTCI < 32°C	Moderate heat stress
9 < UTCI < 26°C	No heat stress

Source: the authors.

Considering the collected microclimatic variables, the UTCI (Figure 8, center below) was derived for the circuit points to verify the level of thermal stress. The UTCI is strongly correlated with the mean radiant temperature, which quantifies the thermal load on the human body and is considered the main factor influencing thermal discomfort (Middel *et al.,* 2020). Stress levels at the points varied from no thermal discomfort to strong heat discomfort during the campaigns. Point 4 imposed the highest stress level due to its insolation conditions, followed by point 2, which showed greater variability in intensity due to periods of shading and exposure depending on the campaign times. Point 3 offered the best exposure conditions as it was constantly shaded during the campaigns, followed by point 5, which, despite being shaded, could not completely block the sun due to the shape of the tree canopy during monitoring periods.

Thus, based on the behavior observed in the collected variables during the campaign, we can infer that the PLEMS device is capable of dynamically responding to microclimatic variations imposed by the existing morphological conditions of the built environment within the selected circuit. This makes it a suitable instrument for dynamic environmental analysis.

Environmental perception declared by interviewees in the points

In relation to anthropometric characteristics (Chart 7), it was observed a balance between biological sex and a greater presence of young people aged up to 25 years, as expected since the interviews took place within a university environment. BMI analysis reveals that, although most of the interviewed volunteers are within healthy BMI limits, there is a large number of overweight people, an increasing trend already reported for the Brazilian population (Brasil, 2016). The insulation provided by clothing showed great variability among interviewees, with people wearing summer clothes (0.26 clo) on the hottest days, and typical winter clothes (1.12 clo), mainly on cold days. The evaluated average insulation was 0.53 clo, which corresponds to a typical costume used in the region (t-shirts, pants and underwear).

Chart 7 - Anthropometric data from the autumn-winter campaigns

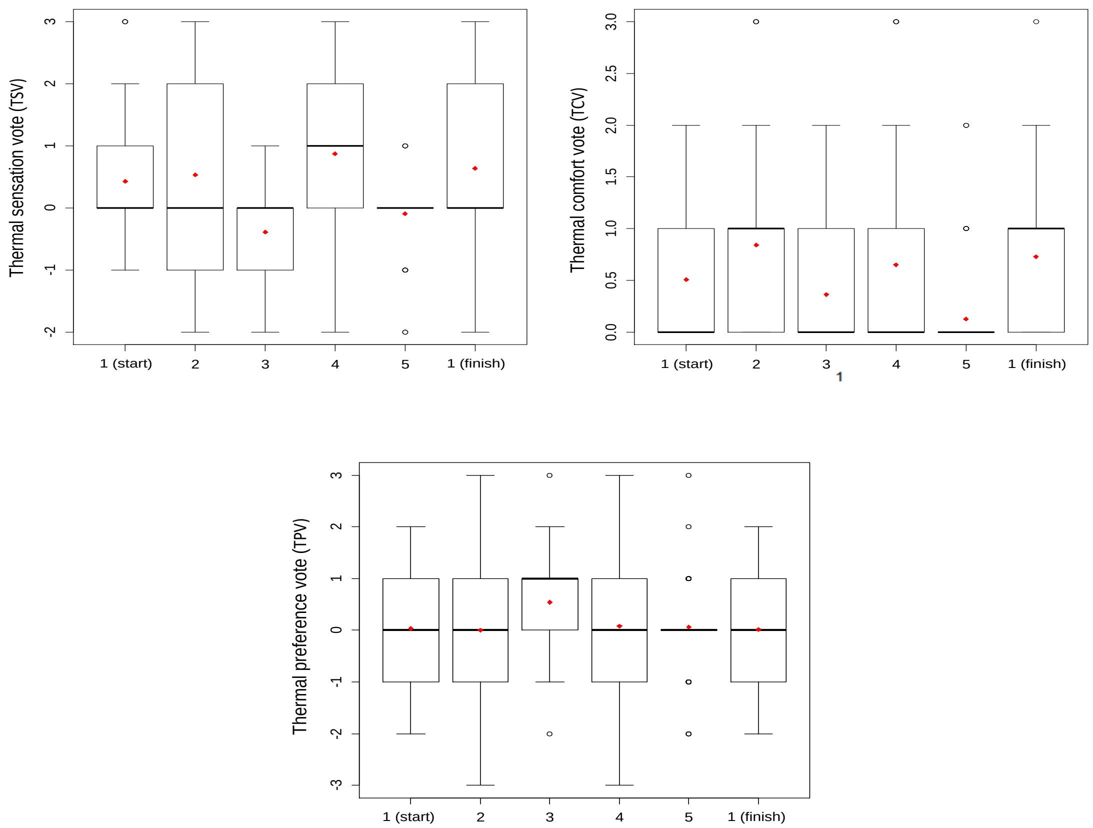
Parameter	Category	Number of respondents	Percentage (%)
Biological sex	Male	32	50.8%
	Female	31	49.2%
Age	Up to 25 years old (youth)	49	77.8%
	Between 25 to 64 years old (adult)	13	20.6%
	Above 64 years old (Elderly)	1	1.6%
Body mass index (BMI = weight/ height^2)	Under weight	1	1.6%
	Healthy	37	58.7%
	Overweight	18	28.6%
	Obese	7	11.1%

Source: the authors.

Figure 9 shows the subjective responses to questions "a," "b," and "c" from the questionnaire in Chart 4, which relate to the thermal environment. Respondents generally perceived Points 1 (start), 2, 4, and 1 (finish) as slightly warm (+1), while Point 3 was slightly cool (-1). Point 5 was unanimously considered comfortable (0), excluding outliers (Figure 9, top left). The average pattern of thermal sensation aligns with the objective data, showing a similarity between reported thermal perception and the UTCI calculations at the circuit points.

Note that there are differences in variability between responses. Point 2 is perceived on average with thermal neutrality conditions (0), but variability is observed, with thermal perception ranging from slightly cool (-1) to warm (+2). In turn, point 5 shows centrality in the thermal neutrality vote with little variation (the boxplot shows, in addition to the practically coinciding mean and median, only outliers). It is also interesting to note that the interviewees, when returning to point 1 (finish), declare on average that they feel hotter than at the beginning of the circuit, also showing greater variability in their responses than initially. This behavior gives the impression that, coming from point 5, with lower radiation intensity, the interviewees made a more consistent judgment of the starting point of the circuit, since at the beginning they had not yet carried out a comparative assessment between points.

Figure 9 - Boxplots of thermal sensation (on the left above), comfort votes (on the right above) and thermal preference (in the center below) declared by the interviewees



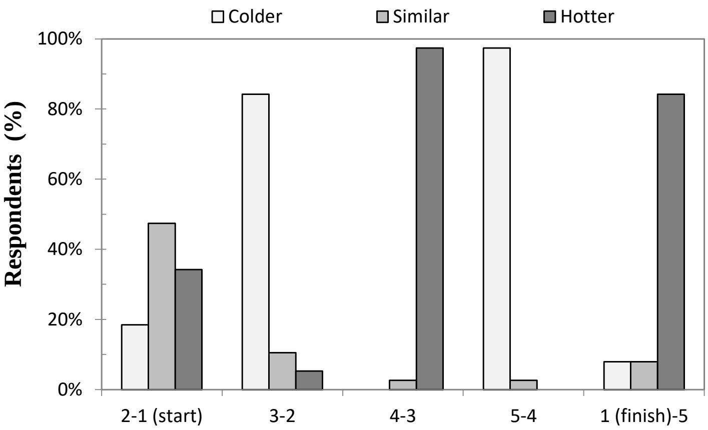
Source: the authors.

In relation to the thermal comfort votes at the points (Figure 9, on the right above), points 1 (start), 2, 4 and 1 (finish), most exposed to the sun, are on average the most thermally uncomfortable, while at point 3, less discomfort is reported and, in point 5, the comfort votes are unanimous, confirming what was reported regarding thermal sensation in these last two points.

Regarding thermal preference (Figure 9, center below), at points 2 and 4 there was great variability in the responses, followed by points 1 (start) and 1 (finish), which did not differ from each other. This is due to the fact that the campaigns were conducted in periods with thermal conditions that were sometimes cold and sometimes hot, in which interviewees wished the point was hotter and colder, respectively. Despite the different conditions in the campaigns, point 5 seems to be able to neutralize these variations, while in point 3 there is a tendency for interviewees to want it warmer, most likely due to its morphological configuration, due to the shading by the buildings.

The relative perceptions (item "a" in Chart 5) between the point's thermal environments declared by the interviewees can be seen in Figure 10. Point 2 is perceived by the majority as similar to 1, with a tendency to be hotter. When relativizing point 3 in relation to point 2, interviewees almost unanimously perceived the latter as colder. These contrasts are repeated from point to point, with a large inversion between points 4 and 5. An interesting fact to be reported is that the relative perception of point 1 (finish) being hotter than point 5 helps explain the perception changes observed in the thermal sensation and comfort votes reported in point 1 (finish), despite the level of stress not being much higher in the second compared to the first. A plausible explanation for this exacerbation can be attributed to the fact that point 5 is immersed in a forest, which may cognitively trigger the impression that this point is more pleasant than it actually is, thus momentarily influencing the interviewees' perception. This situation is also observed in the study conducted by Klemm *et al*. (2015).

Figure 10 – Relative perceptions of the thermal environment declared by interviewees



Source: the authors.

Thus, the analysis of environmental data and UTCI, along with the subjective responses from the volunteers, demonstrates that the PLEMS is a viable alternative for use in dynamic outdoor thermal comfort campaigns.

Discussion

Field tests with the PLEMS device demonstrated that points with higher SVF had higher temperatures (He *et al*., 2015; Chen *et al*., 2012). Additionally, areas with impermeable soil and built surroundings showed increased thermal stress levels (Santamouris, 2013; Rajagopal; Priya; Senthil, 2023). The canyon conformation at Point 3 resulted in shading and reduced thermal impact on participants, as indicated in the literature (Evola *et al.*, 2020). In the vegetated area, even considering its small size, the thermal reduction was significant, especially in terms of air temperature and mean radiant temperature. This heat mitigation effect was evident even within a few meters between Points 4 and 5, with a notable drop in mean radiant temperature and milder thermal stress conditions in the forest area. This highlights the important role of small parks in urban environments, which are thermally more beneficial when distributed in greater numbers rather than as larger isolated parks (Gillerot *et al.,* 2022; Motazedian; Coutts; Tapper, 2020). In this context, PLEMS effectively captured differences in morphology, land cover, and sky view factor.

An initial concern was that the subjective responses, collected during the relatively short periods of movement between points, would not provide noticeable variations in environmental conditions. However, the environmental perception responses indicated that thermal sensation, thermal comfort, and thermal preference votes varied depending on the exposure conditions measured by the sensors installed in PLEMS.

Including questions of relative comparison between points (Chart 5) proved to be a valid instrument, clarifying situations of drastic changes in the perception votes between sequential points. As psychological perception is part of thermal sensation (Höppe, 2002), the votes reported by individuals in the contrasting conditions observed between Points 4 and 5 showed unanimous thermal comfort conditions in the forest. As a result, the psychological effect of green areas on perceived thermal sensation was evidenced during the circuit, as observed in studies by Klemm *et al.* (2015) and Mosca, Dotti San e Giachetta (2021).

Conclusion

In general, using the PLEMS device in a circuit within the university campus demonstrated adequate mechanical resistance of the structural components and good ergonomics. The sensors responded satisfactorily to variations in environmental conditions across different microclimates, enabling a dynamic assessment of environmental parameters supported by subjective perception at each point of the circuit. Additionally, participants were able to express their multisensory perceptions as they interacted with different microclimates, showing consistency and coherence with studies in Human Biometeorology.

On the face of the findings, a vast field of future applications for PLEMS is envisaged, beyond urban biometeorology. These applications aim to analyze and understand the influence of urban design on thermal comfort in outdoor spaces. The instrumentation embedded in PLEMS is assumed to be suitable for monitoring heat islands and CO_2 concentration levels in urban areas, as well as studying noise and wind flows within specific intra-urban areas

In terms of incremental innovations, the potential of using more modern free hardware electronic prototyping platforms, such as those provided by RaspberryPi, with greater processing speed and data storage, use of communication technology via Bluetooth, among others, is identified as improvements.

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