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ECOLOGICAL INTERVENTIONS TO IMPROVE THERMAL COMFORT IN A SCHOOLYARD IN AREQUIPA, PERÚ

INTERVENCIONES ECOLÓGICAS PARA MEJORAR EL CONFORT TÉRMICO EN UN PATIO ESCOLAR EN AREQUIPA, PERÚ

INTERVENÇÕES ECOLÓGICAS PARA MELHORAR O CONFORTO TÉRMICO EM UM PÁTIO DE ESCOLA EM AREQUIPA, PERÚ

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RESUMEN

Los patios escolares se han convertido en espacios residuales carentes de confort térmico debido al incremento de la edificación para cubrir la sobrepoblación estudiantil. Por ello, se simularon estrategias arquitectónicas ecológicas para demostrar su eficacia en el mejoramiento del confort térmico en Arequipa, Perú; a partir del análisis de la temperatura fisiológica estándar de niños. Se adoptó un enfoque mixto, que combinó el software Sun Path para el análisis de asoleamiento, en base al Protocolo SOPARC y mediciones in situ, con Rayman para la simulación de confort térmico y Revit y ENVI-met para comprobar las estrategias aplicadas. Los resultados evidencian la mejora de la sensación térmica, siendo notable, aquella intervención en la que se efectuó el cambio de pavimento de tierra a césped, adición de vegetación arbórea e implementación de un invernadero ecológico. Por lo que, está investigación valida la optimización de las condiciones térmicas mediante un análisis previo y una posterior intervención mediante simulación.

Palabras clave
confort térmico, ENVI-met, patio, microclima

ABSTRACT

Schoolyards have become residual spaces lacking thermal comfort due to increased construction to accommodate student overpopulation. As a result, ecological architectural strategies were simulated to demonstrate their effectiveness in improving thermal comfort in Arequipa, Perú; based on an analysis of children's standard physiological temperature. A mixed-methods approach was used, employing Sun Path for solar analysis, based on the SOPARC Protocol, and on-site measurements. The results obtained in situ were then used with RayMan to verify the strategies applied in Revit and ENVI-met. Results show an improvement in thermal sensation, with the most notable intervention being the change from dirt to grass paving, the addition of tree vegetation, and the implementation of an ecological greenhouse. As such, this research validates the optimization of thermal conditions through prior analysis and subsequent intervention via simulation.

Keywords
thermal comfort, ENVI-met, schoolyard, microclimate

RESUMO

Pátio de recreação das escolas se tornaram espaços residuais com falta de conforto térmico devido ao aumento do estoque de edifícios para atender à superpopulação de alunos. Portanto, estratégias arquitetônicas ecológicas foram simuladas para demonstrar sua eficácia na melhoria do conforto térmico, analisando a temperatura fisiológica padrão das crianças. Foi adotada uma abordagem mista, combinando o software Sun Path para análise da luz solar, com base no Protocolo SOPARC e em medições in situ, com o Rayman para simulação de conforto térmico e o Revit e o ENVI-met para testar as estratégias aplicadas. Os resultados mostram a melhoria da sensação térmica, sendo notável aquela em que foi realizada a mudança do pavimento de terra para grama, a adição de vegetação arbórea e a implementação de uma estufa ecológica. Portanto, esta pesquisa válida a otimização das condições térmicas por meio de uma análise prévia e uma intervenção posterior por meio de simulação.

Palavras-chave:
conforto térmico, ENVI-met, pátio, microclima

INTRODUCTION

Schoolyards currently have limited green areas, which has an impact on the academic performance of children (Bernardes & Vergara, 2017) who spend a significant amount of time in schools. On the other hand, Binabid et al. (2024) suggest that rising temperatures and thermal discomfort impact activities and the use of open spaces in the educational sector, particularly in arid and desert climates. Therefore, it is crucial to apply local adaptive strategies to mitigate the impact of climate change.

Because of this, Lanza et al. (2021) promote the implementation of green areas in schoolyards, as they contribute to reducing the environmental temperature thanks to the shade and evapotranspiration of vegetation, thereby improving human thermal comfort. Duarte-Tagles et al. (2015) and Pasek et al. (2020) demonstrate the importance of human interaction with nature by highlighting its benefits for the quality of life and its positive impact on cognitive, mental functions, emotional growth, and mood in students.

It has been observed that schoolyards can become a passive design solution to achieve sustainable architecture in hot areas, such as the United Arab Emirates (Salameh, 2024). However, some traditional schools have asphalt paving slabs (Akoumianaki-Ioannidou et al., 2016), which increases the levels of thermal discomfort due to climate change. In that sense, Namazi et al. (2024) analyzed micro meteorological conditions to identify the impact that vegetation and materials had using HOBO, which collects temperature and humidity data to make comparisons between hard and soft ground, processed with FLIR Thermal Studio (Lindemann-Matthies & Köhler, 2019; Lanza et al., 2021; Namazi et al., 2024) to compare thermal comfort models based on climatic parameters (Marchante González & González Santos, 2020).

On the other hand, Mahmoud and Abdallah (2022) and Salameh (2024) use ENVI-met to design (Jansson et al., 2018) and validate scenarios (Oregi et al., 2024), which is complemented with the RayMan software to calculate the physiological equivalent temperature index (PET) that measures the real thermal sensation by using meteorological and human energy balance variables (Royé et. al., 2012). Similarly, Abdallah (2022) evaluated students' perceptions through the application of questionnaires, while Lanza et al. (2021) and Lavilla Cerdán (2013) used the observation method to minimize its impact on children's behavior, employing the SOPARC Protocol. This method enables the measurement of physical activity levels and their interactions with green elements. Finally, Bates et al. (2018) mapped the behaviors by using geographic information systems.

Therefore, few studies have validated the optimization of thermal comfort with virtual interventions. Due to this, this research focuses on analyzing the thermal conditions in a schoolyard in Arequipa, Peru, to apply different strategies and demonstrate the improvement of PET in dry and hot climates through simulation.

CASE STUDY

The case study is located at a south latitude of 16°23'41.8", west longitude of 71°29'09.9", and an altitude of 2649 m.a.s.l. The mountainous climate is characterized by hot and dry conditions, with maximum temperatures ranging from 14°C to 29°C and minimum temperatures between 5°C and 9°C (National Institute of Statistics and Informatics, 2022). The institution is surrounded by buildings up to 10 meters high. The study was conducted in September 2024, at the end of winter and the beginning of spring, which provided significant but tolerable solar conditions, allowing for a representative analysis of thermal and shade behavior in outdoor spaces.

METHODOLOGY

The study employs a mixed approach, where the climatic conditions are analyzed *in situ*, followed by the application of ecological architectural strategies using virtual simulation (Figure 1). A sunlight analysis was made using the Sun Path software, and three weather forecast sources: *The Weather Channel* (2024), *Tiempo3* (2024), and *Meteo Consult* (2024) forecasts were chosen instead of TMY files. Since the latter represent average data and do not correspond to specific real days, the sunniest day and schedules for on-site measurement were identified. The measurement points were selected based on the spatial characteristics, materiality, and unevenness in the schoolyards. Then, the SOPARC protocol was used to record the activities and movements of the 203 students during their 30-minute recess. For the temperature measurements (dry bulb), a TA318 digital thermos-hygrometer with an external probe was used, which measures temperatures ranging from -50°C to 70°C with an accuracy of ±1°C and relative humidity from 25% to 98% with an accuracy of ±5% RH. The wind speed was obtained from the Habotest HT605 digital anemometer, with a measuring range of 0~30m/s and an accuracy of +/-2%. From this data, along with the PET analyzed using

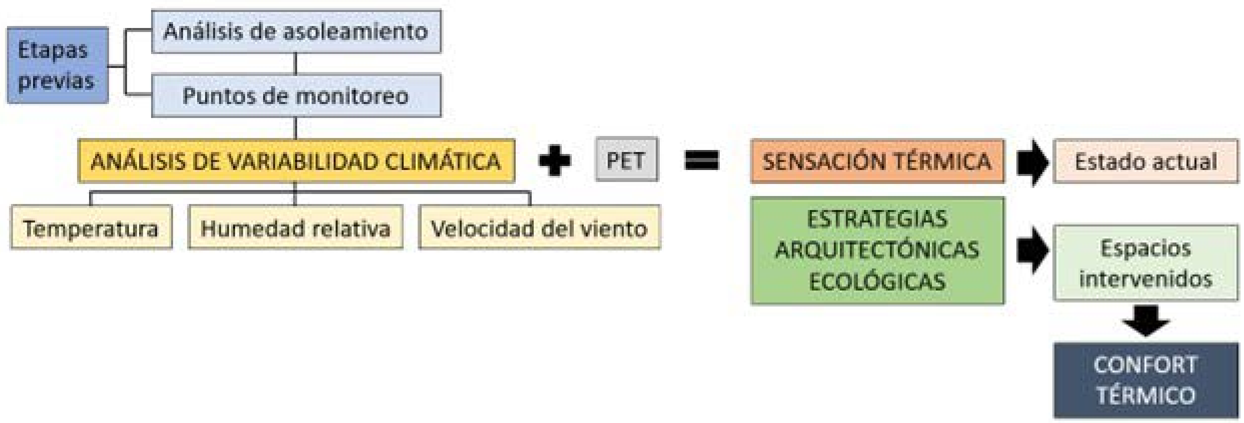

Figure 1. Methodological design. Source: Preparation by the Authors.

SOPARC (protocol) and Rayman (software), the thermal sensation for children aged 6 and 11 was calculated. Additionally, ecological architectural interventions modeled in SketchUp were simulated. Subsequently, the effects on thermal comfort were evaluated using simulations with the ENVI-met software.

SUNSHINE ANALYSIS

The measurement times were defined using the Sun Path software. At 8:00 a.m., the sun rises, generating a warm thermal sensation; at 10:30 a.m., solar radiation increases, exposing a large part of the schoolyard to the sun; and at 1:30 p.m., with the solar descent, radiation and thermal perception decrease. Additionally, it is noted that the surrounding buildings do not provide shade to the schoolyard (Figure 2).

Location of monitoring points

Six points were selected (Figure 3) based on their spatial characteristics, materiality, and unevenness. P1 and P2 are located at the highest level, featuring natural grass. P1 is protected by natural vegetation, while P2 is protected by artificial roofing. P3 and P4 are at the same level, with natural ground. However, P3 has 30% solar coverage and includes a stone path that allows one to walk through the vegetable garden and a green area, whereas P4 lacks solar coverage. Finally, P5 and P6 are sports tiles with similar characteristics, differentiated by their size.

The sensors were placed 1.5 meters above ground level, following the recommendations of the CIBSE Guide A: Environmental Design (CIBSE, n.d.), as this height is representative of the user's level. In addition, the sensors exposed to the sun were P1, P3, and P4, while those in the shade were P2, P5, and P6, which have solar protection elements (Figure 4). The selection of these points responds to the need to represent the contrasting conditions of the space, which allows for

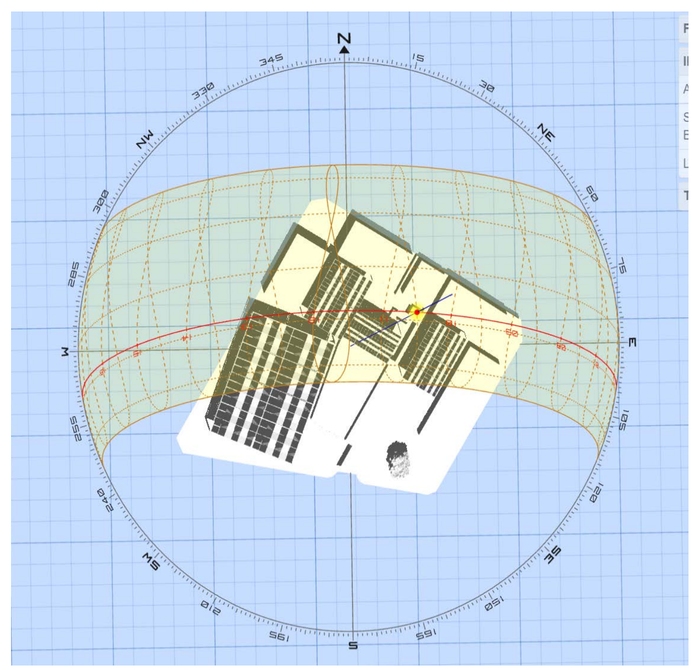

Figure 2. Sunshine at 10:30 a.m. Source: Prepared by the Authors based on Sun Path.

an accurate assessment of the thermal behavior in the schoolyard.

The SOPARC protocol, accompanied by a simultaneous photographic record, was used to track the movement of 203 children for 30 minutes, which is the duration of the unstructured game under teacher supervision. This allowed identifying the most crowded areas and those preferred by them, based on indicators of location, gender, primary activity, activity level, and interaction with green elements.

As shown in Figure 5, P1 and P2 are not registered, as they are designated as exclusive areas for pre-school. Therefore, the most frequently used areas for children

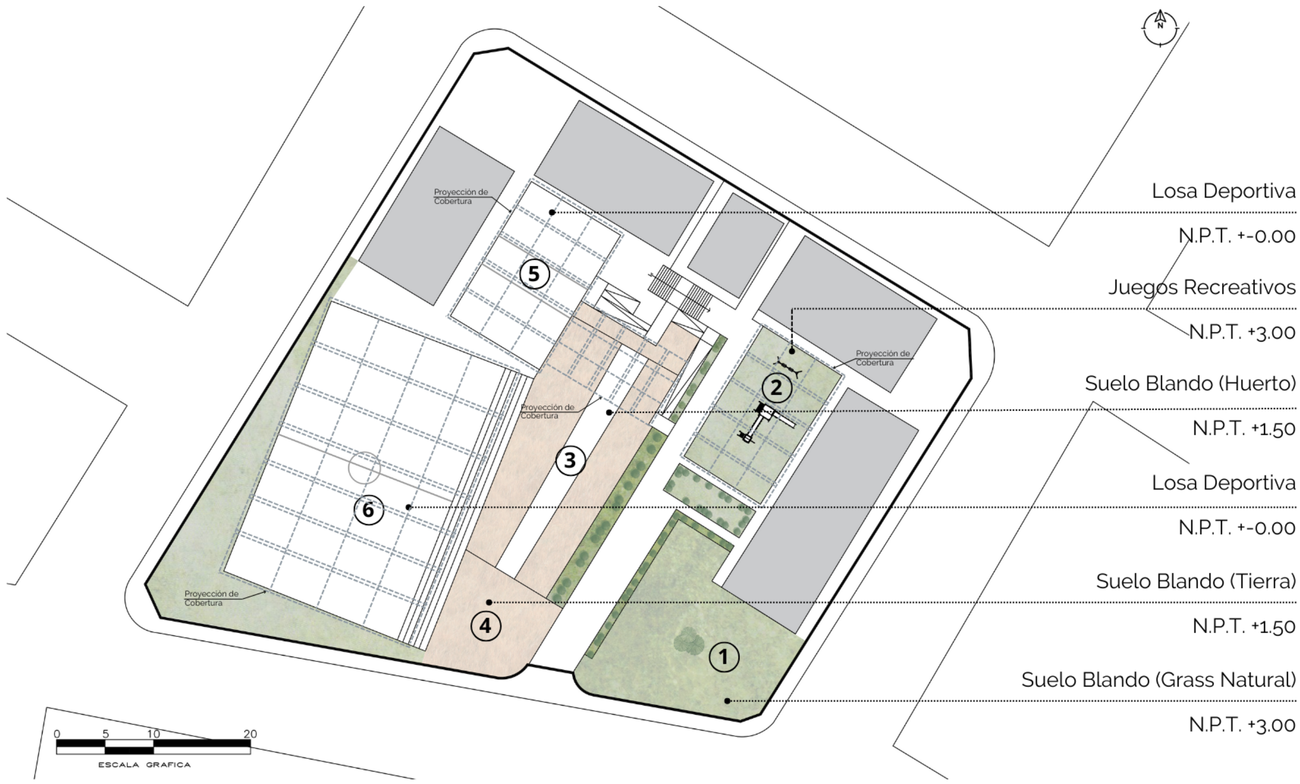

Figure 3. Location of the monitoring points. Source: Preparation by the Authors.

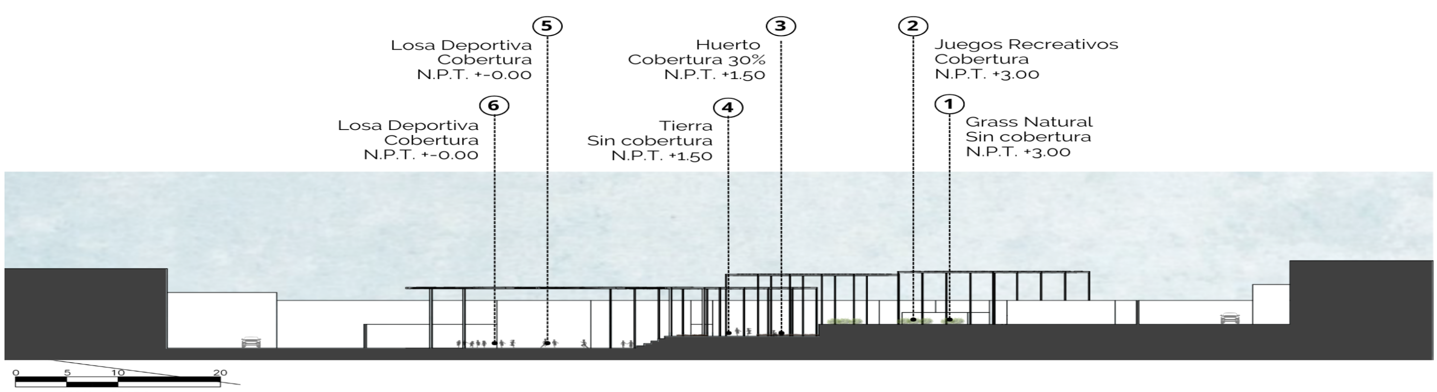

Figure 4. Basic characteristics of the spaces. Source: Preparation by the Authors.

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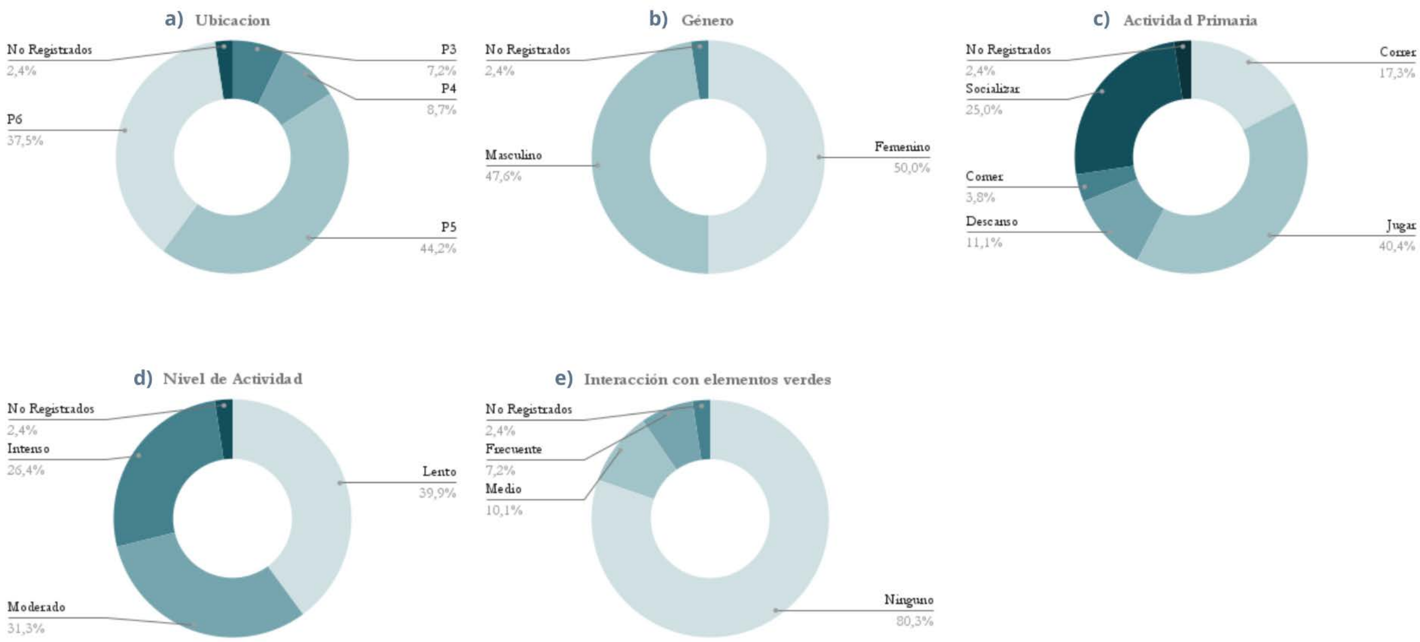

Figure 5. Indicators based on the SOPARC protocol. Preparation by the Authors.

Figure 6. Movement flows and activity level. Source: Preparation by the Authors.

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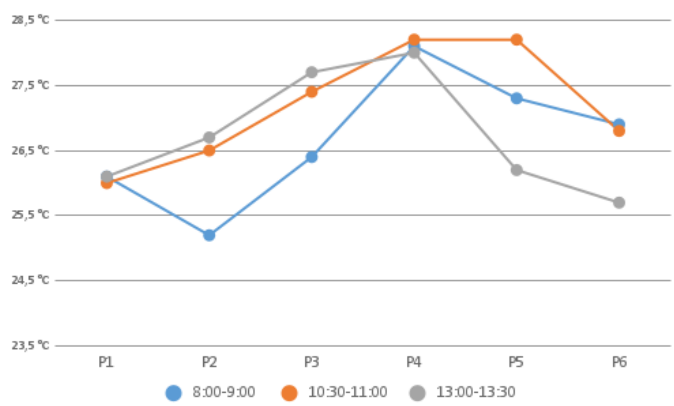

Figure 7. Air temperature. Source: Preparation by the Authors.

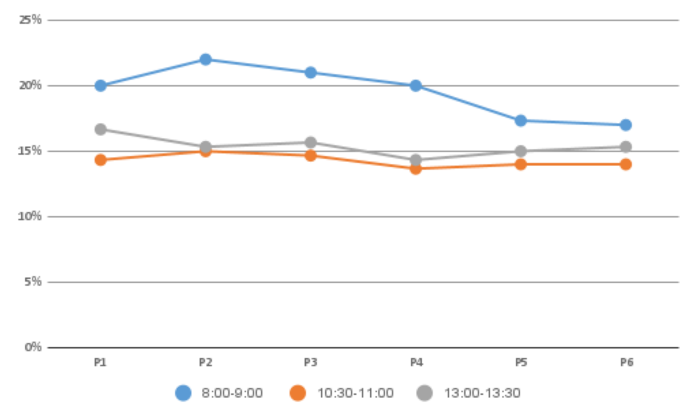

Figure 8. Relative Humidity. Source: Preparation by the Authors.

aged 6 to 11 years old are P5 and P6, as they contain sports tiles that are their main activity (a). It should be noted that the study sample has a similar ratio between boys and girls (b), as the predominant activity is playing, followed by socializing, which takes place in a space with bleachers that encourage group meetings and running (c).

The most significant flow of movement is focused on P5 and P6, with greater participation of girls and boys, respectively (b) (Figure 6). However, it is observed that the predominant activity level is of the slow type (d) that registers that 39.9% of students because they prefer the type of passive recreation in P4, followed by 31.3% with moderate activity and 26.4% who perform intense activity since they practice some sport such as soccer in P5 and P6. Additionally, it is noted that 80.3% do not interact with the green area, which in this case is the vegetable garden (P3), likely due to the lack of recreational equipment that is more appealing to children (e).

RESULTS

The climate variability measurements were made based on the preliminary data, which were input into the Rayman Software to calculate the PET index (Deng & Wong, 2020). Subsequently, the results were compared with the thermal comfort classification of Morakinyo et al. (2018) using the children's behavior map. Then, all the spaces were intervened with ecological design strategies, applying the Guide: *The Adventure of Learning. How to Intervene in a Schoolyard* (Basurama, 2024). Finally, through simulation with the Revit and ENVI-met software, the current condition is compared with the intervened spaces.

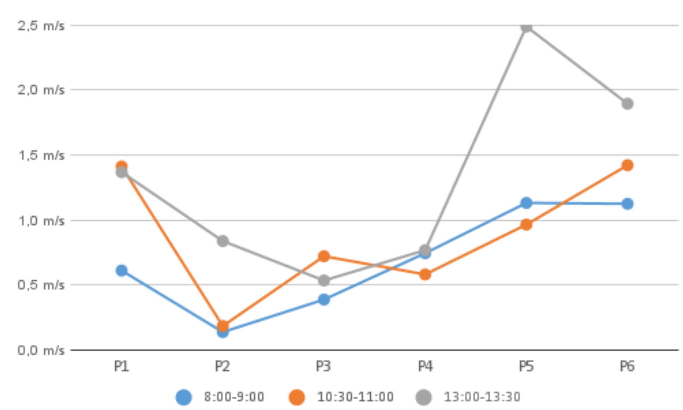

Figure 9. Wind speed. Source: Preparation by the Authors.

CLIMATE VARIABILITY ANALYSIS

The analysis was divided into three time blocks: from 8:00 am to 9:00 am, when students are in the classroom; from 10:30 am to 11:00 am, during the school break, when the schoolyard is busy; and from 1:00 pm to 1:30 pm, when school finishes for the day and students move towards the door. This division facilitated an accurate assessment of the thermal behavior according to the yard's occupation.

The maximum air temperature is considered an indicator of the most unfavorable scenario (Figure 7), since the higher the temperature, the lower the thermal comfort due to the warm climate of the case study. Therefore, of the 6 points chosen, it is observed that P4 registers the highest temperature levels with an average of 28.1°C at different times of the day. Despite being at the intermediate level, its temperature could increase due to the lack of solar protection and the presence of natural soil on the ground.

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Table 1. Synthesis of climate variability. Source: Preparation by the Authors.

POINTS	ET (°C)	RH (%)	WS (m/s)	DBT (°C)	RE (W/m2)	PET1	PET2
P1	27.0	13	2.37	18.8	715.2	30.0°C	30.6°C
P2	27.8	15	1.33	18.8	715.2	35.0°C	35.0°C
P3	28.6	14	1.53	18.8	715.2	35.2°C	35.3°C
P4	29.8	13	1.89	18.8	715.2	35.8°C	35.8°C
P5	29.5	13	3.75	18.8	715.2	32.2°C	32.3°C
P6	28.3	14	3.00	18.8	715.2	31.7°C	31.7°C

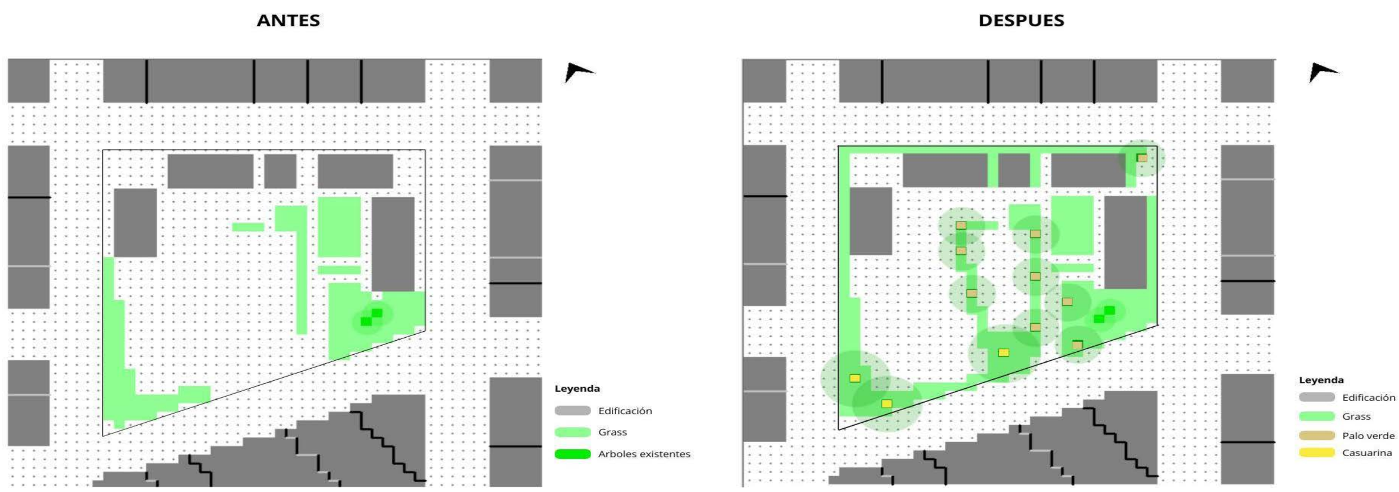

Figure 10. Comparative based on the addition of trees and green areas. Source: Preparation by the Authors.

As in the previous indicator, P4 is identified as the most affected, as it presents the lowest humidity during the critical time of 10:30 am to 11:00 am (Figure 8), when students are at their maximum stay at a moderate activity level, which justifies the need for strategies to improve thermal comfort. In this schedule, P5 also exhibits elevated temperatures, despite being made of concrete, which suggests that the reduced proportion of the space, similar to P4, influences thermal accumulation, as smaller surfaces tend to retain more heat. Additionally, because its land surface is exposed to the sun, it prevents the formation of microclimates. Similarly, P5 and P6 have low relative humidity levels, which suggests that concrete also contributes to moisture loss, despite having solar coverage.

The results of Figure 9 indicate that high wind speeds in hot mountain climates can excessively reduce thermal sensation, generating discomfort, especially in children who are resting or have limited activity. P5 and P6 are more exposed to the wind due to the lack of control elements, such as vegetation or walls, although this happens when students are already in their classrooms, minimizing the impact. On the other hand, P2 has the lowest speeds due to its environment being surrounded by buildings that block the prevailing southerly winds, unlike P5, where the wind circulates freely without obstacles.

THERMAL SENSATION

To evaluate the thermal sensation, climatic data were used, which included the dry bulb temperature and global radiation obtained from Windy.com (2024) and TuTiempo.net (2024), synthesized in Table 1. Along with the characteristics of the children and the coordinates of the school, the PET was obtained for each point using the RayMan software. In order to perform the simulation in this program, the data obtained from the indicators, geographical information of the infrastructure and the characteristics of age, gender, weight, height and metabolic rate of two children aged 6 and 11 years representing, respectively, the first and last grade of primary education are added, which was extracted from the Ministry of Health (2015), as established in the *Technical Guide for Anthropometric Nutritional Assessment*.

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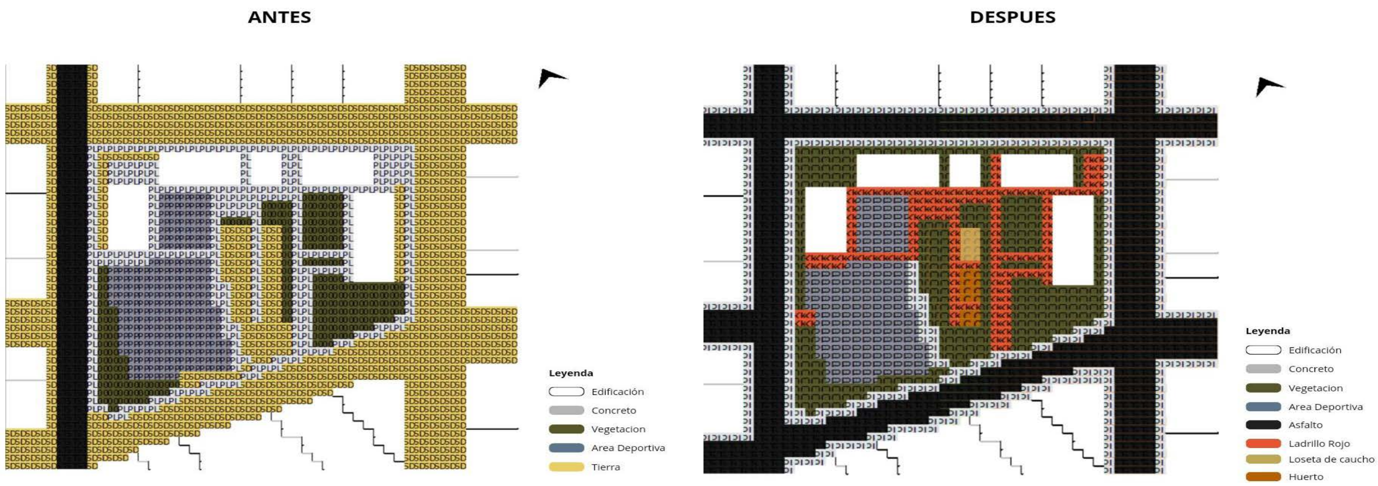

Figure 11. Comparative in terms of materiality. Source: Preparation by the Authors.

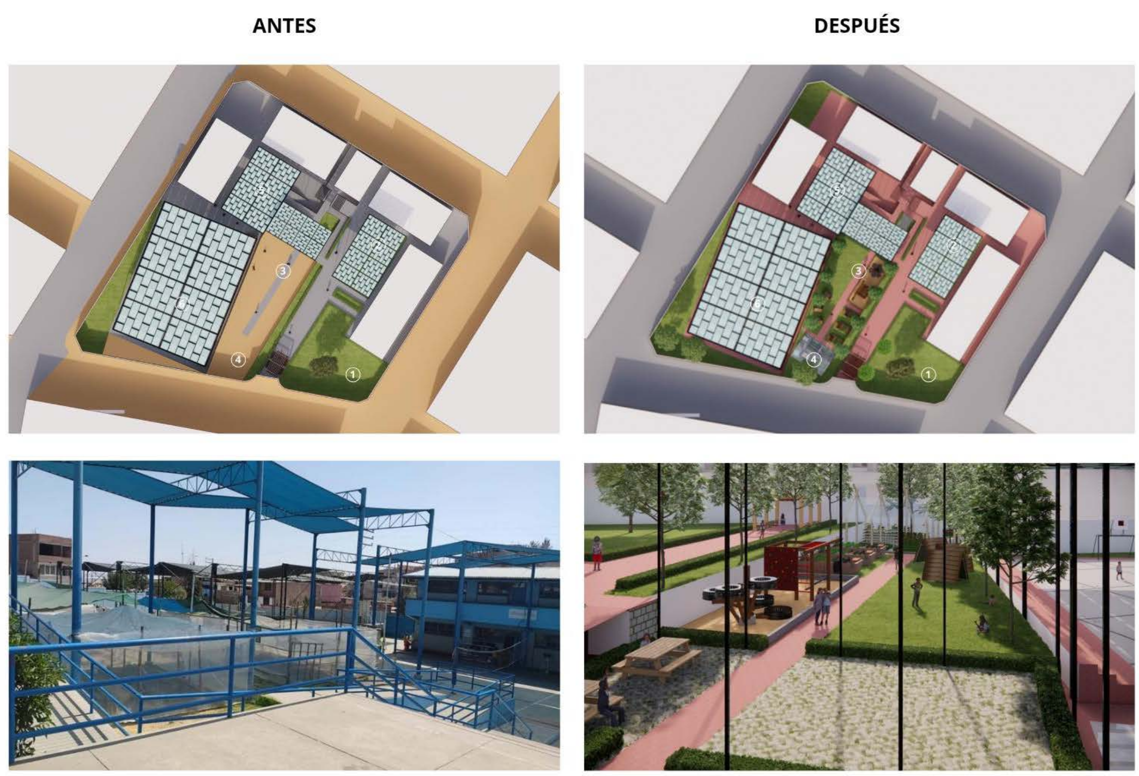

Figure 12. Implementation of ecological furniture. Source: Preparation by the Authors.

The PET values obtained were around 30°C for both age groups (PET1 and PET2). According to the thermal sensation scale, P1 and P6 were classified as “warm”, while P2 to P5 reached the level of “hot”. No point was located within the thermal comfort range (18 °C – 23 °C) recommended for children aged 6 to 11 years. P1 exhibited better thermal conditions due to its vegetation and natural shade. In contrast, in P6, despite the concrete pavement and its larger surface area, the presence of shade and direct ventilation helped mitigate thermal accumulation.

APPLICATION OF ECOLOGICAL ARCHITECTURAL STRATEGIES

ENVI-met allowed simulating interventions aimed at reducing the thermal stress using ecological furniture, an increase in vegetation, and a change in paving. Casuarinas and palo verde trees were incorporated for their dense foliage and height, which ensured continuous shade in transit and rest areas, regardless of the solar angle (Figure 10). The vegetation cover increased by 70% with the inclusion

Table 2. Details of the implementation of architectural strategies. Source: Preparation by the Authors.

POINTS	Implementation of ecological furniture (unit)	Increase in trees (unit)	Increase in green area %	Change of paving %	Observations
P1	-	2	-	10%	-
P2	-	1	-	10%	-
P3	3	5	40%	30%	Playgrounds
P4	4	2	55%	20%	Vegetable garden
P5	-	-	-	30%	Sports tiles
P6	-	2	10%	30%	Sports tiles

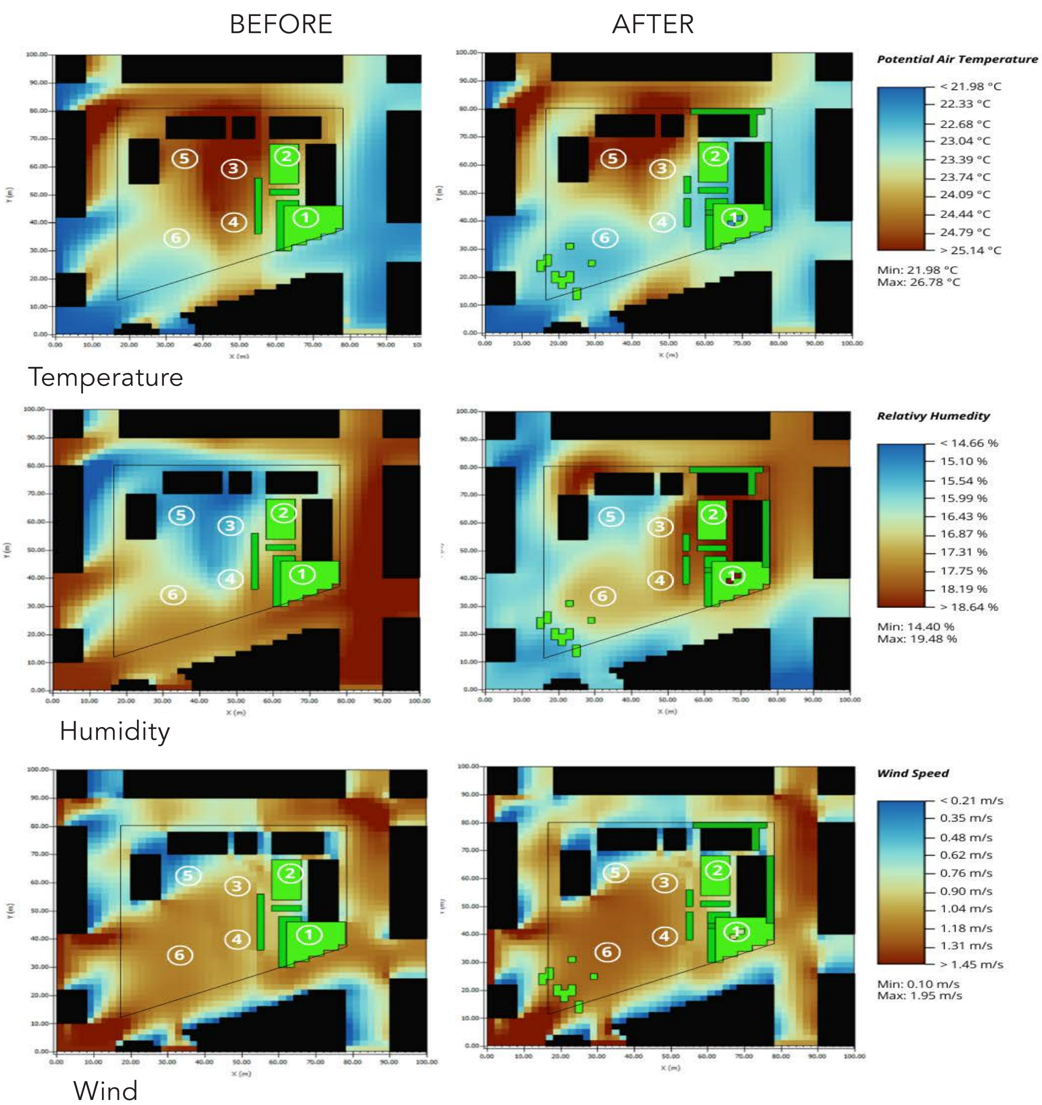

Figure 13. Comparative analysis of climate variability. Source: Preparation by the Authors.

of 12 trees, resulting in a cooler and more comfortable environment.

90% of concrete walkways were replaced by crushed red brick (Figure 11) that does not reflect the sun and is a high-strength rigid material, and 10% with rubber tile for P3, since it has a high absorption coefficient, being a flexible material of high resistance, attractive for its variety of colors and optimal for the impacts of students when they fall, since in the analysis of activities it was determined that this area was used for running.

Based on the analysis of activities, an ecological recreational furniture set consisting of tables, chairs,

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Table 3. Comparison of PET results. Source: Preparation by the Authors.

POINTS	PET 01 °C Before	PET 01 °C After	Difference °C	PET 02°C Before	PET 02°C After	Difference °C	Thermal sensation (Before)	Thermal sensation (After)
P1	30.5	29.1	1.4	30.6	29.2	1.4	Lukewarm	Slightly warm
P2	35.0	29.3	5.7	35.0	29.3	5.7	Hot	Slightly warm
P3	35.3	28.9	6.4	35.3	28.7	6.6	Hot	Relatively warm
P4	35.8	28.7	7.1	35.8	28.6	7.2	Hot	Relatively warm
P5	32.2	30.9	1.3	32.3	30.8	1.5	Hot	Slightly warm
P6	31.7	30.2	1.5	31.7	30.2	1.5	Lukewarm	Slightly warm

games with tires, planters, huts, and a greenhouse was designed (Figure 12) to integrate recreational activities in little-traveled spaces (P3 and P4), meeting ergonomic criteria for the comfort of elementary-level students.

Wood, tires, rope, bamboo, plastic bottles, and fishing nets were prioritized as materials. All these specifications of materiality were submitted to Envi-met, which allowed comparing the current state of the schoolyard with the proposed intervention through simulation.

In Table 2, it is evident that the most significant changes occurred in P3 and P4. For example, in P3, the recreational games were relocated, the number of trees and green areas was increased, and 30% of the paving was replaced. While in P4, the vegetable garden area was added, which expanded the green area by 55% and thus improved thermal comfort.

COMPARISON OF THE CURRENT STATE WITH THE INTERVENTION BY SIMULATION

By integrating ecological architectural strategies, the heat was reduced in P6 and P4 from 1.4°C to 1.6°C, respectively. The humidity increased by 6% due to the expansion of green areas, and the wind speed remained constant (Figure 13).

Finally, with the new climate simulation values, PET was evaluated with Rayman and compared with the initial values. The PET index decreased, reaching an average reduction of 3.92°C in PET 1 and 3.98°C in PET 2 (Table 3). It was P4 that experienced the most significant heat reduction, due to the change from paving to a green area, the addition of one tree, and the installation of an ecological greenhouse. On the contrary, P1 reduced only 1.4°C because only two trees were added, being a non-significant intervention. According to Table 3, the model of Marchante González and González Santos (2020) was adapted, moving from "heat stress" to "no heat stress". In P5, the average reduction was 1.4°C, due to exposure to wind gusts. Therefore, the three trees planted as a natural barrier allowed the thermal sensation to improve markedly. The notable reductions occurred in P2, with a 5.7°C gradient, as well as in P3 and P4.

DISCUSSION

This research demonstrates the potential for improving school playgrounds through ecological architectural strategies. Although the "comfortable" state was not reached on the thermal sensation scale, a "relatively warm" level was achieved, close to the goal. As such, this model could be replicable, with different adaptations depending on the local materiality.

The strategies focused on increasing trees, green areas, modifying paving, and redesigning furniture, which collectively managed to reduce the thermal sensation by an average of 3.96 °C. It should be noted that the modifications were not focused on the constructive mass, as happens in Salameh (2024), who modified the proportions and shape of the schoolyard. In addition, it was demonstrated how natural barriers act against wind gusts with the implementation of casuarinas and palo verde trees, with reductions of 1.4°C in P5 and 7.1°C in P4, confirming the optimization of space by the shade indicated by Namazi et al. (2024) and Abdallah (2022) to mitigate heat effectively. Additionally, since the building's orientation did not provide shading for the schoolyard, it was necessary to add trees, which aligns with Oregi et al. (2024) in emphasizing the importance of considering the orientation of the building and its neighboring buildings.

The 90% change in paving generated improvements that align with Namazi et al. (2024), who replaced dark and artificial materials with thermally comfortable school spaces. On the other hand, Guo et al. (2022) measured their variables at 14 points categorized solely by their materiality. In contrast, this research considered six measurement points classified by materiality, floor unevenness, and spatial characteristics, which allowed clarification that although some of them were located 3 m from level 0, they were not the most ventilated. The wind gusts were produced on the lower levels that lacked any type of protection. In addition, an unusual piece of data recorded was the increase in the variation of the winds in P5, with a peak of 2.50 m/s, unlike the other points that fluctuate between 0.62 m/s and 0.14 m/s, which is because, when receiving the wind gusts directly, a kind of cyclone is formed in P5 that generates a slight cold stress, which affects the thermal perception in that area of the schoolyard.

As limitations of the study, it is emphasized that, on being an infant population, unlike Jansson et al. (2018), surveys were not included in the methodology, as obtaining student authorizations is complicated. Additionally, due to the study's execution time and the availability of equipment, the climatological information was collected in a single day, so it should not be assumed to be representative of the entire year. There was limited time available for observing the activities and movement of the students, as the schoolyard is mainly used during the school recess period, which lasts only 30 minutes.

CONCLUSIONS

The integration of ecological architectural strategies significantly improved the thermal conditions in the schoolyard, reducing the PET level by 3.96°C. This was achieved by increasing the green area by 70%, strategically placing 12 trees, modifying 90% of the paving, and adding seven pieces of ecological furniture.

P4 was the most affected point in terms of temperature and humidity, which is why it registered the highest initial PET. This was reduced by 7.1°C, more than the rest. This can be explained because all the strategies were used, unlike P1, where only two trees were added.

It is evident that, at higher temperatures, lower humidity, and wind speeds, the PET index increases. However, wind gusts are not a potential indicator, since the points with high wind values (P5 and P6) also had a slightly warm thermal sensation. The application of strategies in P1 and P6 did not change the level of thermal sensation, but it did reduce it by 1.4°C and 1.5°C, respectively.

Although most recreational spaces are equipped with artificial shading structures, high temperature peaks were still recorded (28.2°C in P5). Therefore, it is necessary to explore alternative strategies at the ground level that enable balancing the thermal sensation of children during their active and passive activities.

Finally, in future research, this study could validate its interventions in different seasons. In addition, the sample could be expanded to analyze different casuistics that allow understanding the thermal conditions of schoolyards in various contexts.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, K.G.V.C., P.C.D.M., V.R.I.I.; Data Curation, K.G.V.C., P.C.D.M.; Formal analysis, K.G.V.C., V.R.I.I.; Acquisition of K.G.V.C. funding; Research, K.G.V.C., P.C.D.M., V.R.I.I.; Methodology, K.G.V.C., P.C.D.M., V.R.I.I.; Project management, K.G.V.C.; Resources, K.G.V.C.; Software, K.G.V.C.; Supervision, P.C.D.M., V.R.I.I.; Validation, K.G.V.C., P.C.D.M., V.R.I.I.; Visualization, K.G.V.C., V.R.I.I.; Writing – original draft , K.G.V.C., P.C.D.M., V.R.I.I.; Writing – proofreading and editing, K.G.V.C., P.C.D.M., V.R.I.I.

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