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Comfort for Users of the Educational Center Applying Sustainable Design Strategies, Carabayllo-Peru-2023

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Abstract: The educational problems in the area, economic disparities, conflict situations, and deficiencies in educational infrastructure directly affect the quality and accessibility of education. Therefore, the present research aims to generate comfort for users of the educational center by applying sustainable design strategies in Carabayllo, Peru. The study started with a literature review, an analysis of flora and fauna, passive design strategies, and climatic analysis applying sustainability strategies supported by digital tools (AutoCAD, Revit Collaborate, Climate Consultant, OpenStreetMap, JOSM, Rhinoceros, and Grasshopper). As a result, the design proposes an educational center that ensures year-round comfort through energy efficiency, the use of eco-friendly materials, and green roofs. Additionally, it includes the implementation of dry toilets, biofilters, and xerophytic vegetation for orchards, promoting food production and enhancing the treatment of nearby public spaces. In conclusion, this proposal enhances the quality of life for users by applying passive design strategies and sustainability principles, adopting clean energy sources, and efficiently managing waste, thereby contributing to the Sustainable Development Goals (SDGs).

Keywords: education center; sustainable approach; bioclimatic architecture; quality of life; thermal comfort

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1. Introduction

Education, a fundamental driver for social transformation and individual progress, directly impacts the mobility, prosperity, and freedom of individuals, as well as the sustainable development of society [1]. It contributes to reducing inequalities and enables people worldwide to lead healthier and more sustainable lives, as established by Goal 4 of the SDGs [2]. A quality educational environment has the power to inspire and empower future generations, allowing them to reach their full potential and positively contribute to their communities [3]. For individuals, it promotes employment, income, health, and poverty reduction. For societies, it contributes to long-term economic development, promotes innovation, strengthens institutions, and fosters social cohesion. Furthermore, education is a powerful catalyst for climate action through widespread behavioral change and training for green transitions [4]. For this reason, sustainable design is crucial in creating learning spaces that are functional and environmentally friendly. By integrating sustainable technologies and practices into school infrastructures, these environments are transformed into examples of sustainability and efficiency [5].

In this context, the term environmental education emerged in the late 1960s, originating from concerns about severe environmental conditions observed in various parts of the world. By the early 1970s, environmental education gained significant relevance in various global forums [6]. Over the past decades, intense levels of pollution have resulted from human activities such as industry, automotive transportation, technology, irresponsible consumerism, and insufficient or non-existent investment in solid waste treatment and recycling policies. This reflects a lack of environmental awareness and education worldwide. Half a century later, humanity remains largely unaware of the real magnitude of its activities on environmental degradation [7–9].

It is also important to highlight how the implementation of environmental education can transform society. In 1980, during the Conference on Environmental Education held in Tbilisi—now Georgia, then USSR—it was concluded that environmental education is the most effective mechanism to halt ecosystem degradation. Therefore, each country should promote it to foster positive environmental behavior.

As exemplars of sustainable educational buildings, it is important to mention the Willowdene Group of Schools, which has become the first Adventist school to primarily use solar energy. This initiative not only ensures a reliable energy supply, improving the teaching and learning experience, but also promotes environmental awareness among students and staff by reducing the institution's environmental impact, as shown in Figure 1 [10]. The adoption of sustainable technologies, such as solar energy systems, not only enhances educational infrastructure but also educates and empowers students towards a more sustainable future. This aligns with the philosophy of creating healthy and efficient learning environments, as seen in exemplary educational practices worldwide [11].

Figure 1. Willowdene Group of Schools in Jamaica, reprinted with permission from Ref. [10]. 2024, Central Association of Jamaica.

In Latin America, it is notable to mention the Sustainable School in Jaureguiberry, Uruguay, designed by architect Michael Reynolds. This is the first sustainable public school in Latin America. The 270 m^2 building was constructed in just seven weeks. Approximately 60% of the materials used in its construction are recycled (including tires, plastic and glass bottles, cans, and cardboard), while the remaining 40% are traditional materials. In addition to being self-sufficient in energy consumption and promoting organic food production within its premises, the school uses rainwater for human consumption, handwashing, garden irrigation, and finally for toilets. It features a blackwater treatment process that includes a septic tank made from recycled materials (in this case, tractor tires) and a wetland outside the building, as shown in Figure 2 [12].

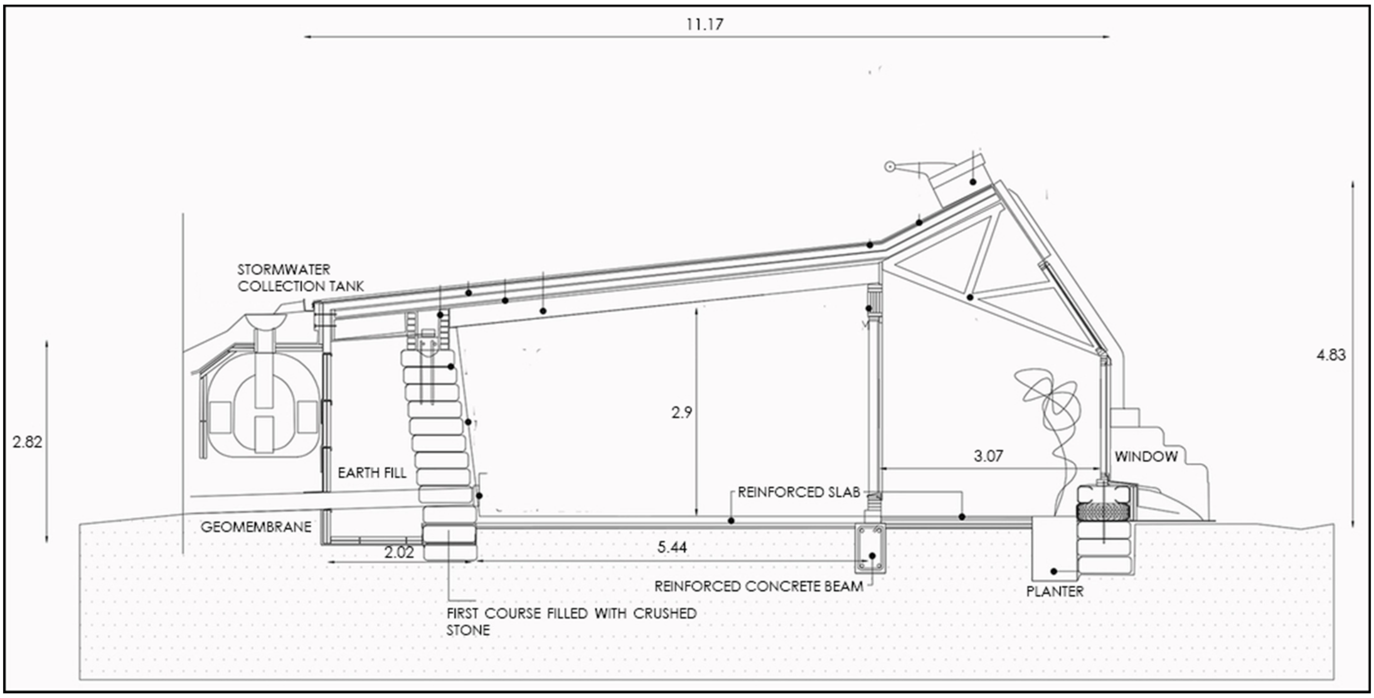

Figure 2. Sustainable School in Jaureguiberry in Uruguay, adaptec with permission from Ref. [12]. 2016, Lorena Presno, Diego Roche and Lucas Damiani.

Another notable project is the Mencoriari Technology and Environment Laboratory in San Martín de Pangoa. This building integrates architectural space with pedagogical space to promote environments adapted to the locale, fostering education oriented towards the environmental and cultural revaluation of the rainforest and enhancing accessibility to local employment opportunities [13]. Finally, the plant-drying classroom takes on the appearance of a greenhouse and includes a rainwater harvesting system, as shown in Figure 3 [14].

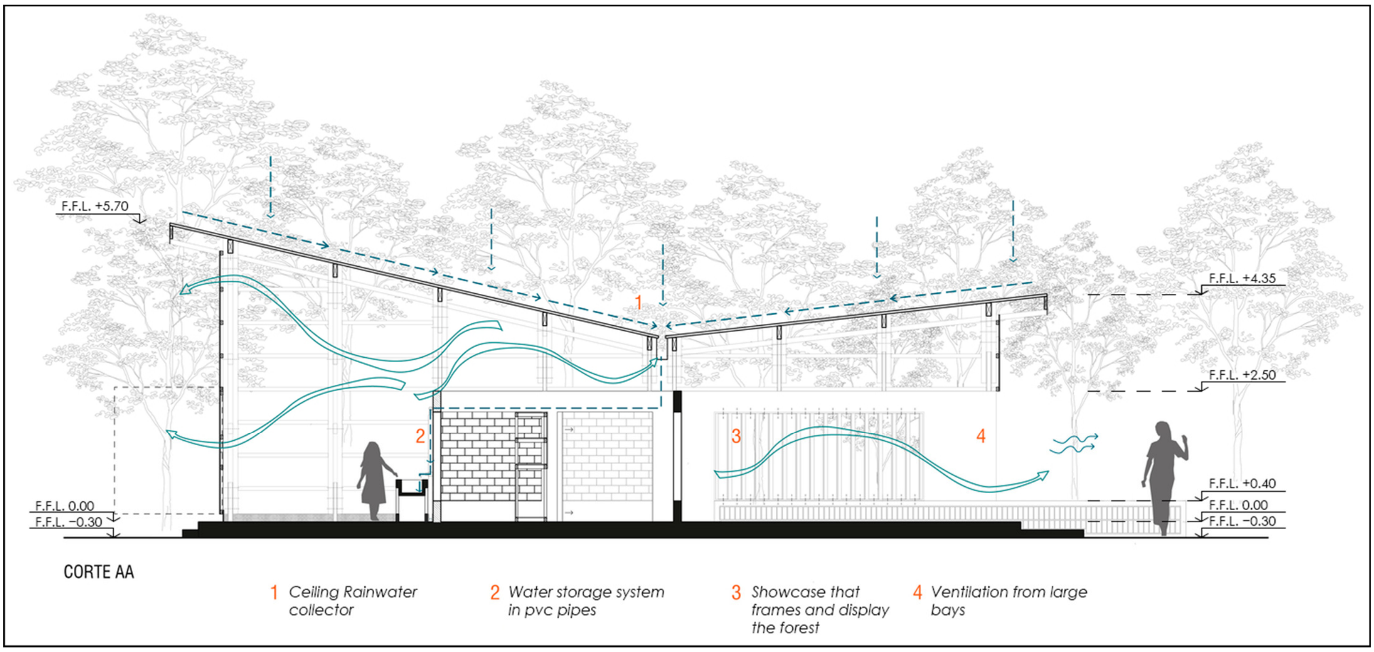

Figure 3. Mencoriari Technology and Environment Laboratory, adapted with permission from Ref. [13]. 2022, Semillas.

The focus of these educational projects aligns with innovative practices in other global contexts. For example, in Finland, education emphasizes learning itself rather than the obligation to attend school. In this country, 95% of six-year-olds participate in a preschool program where many learn to read and write. Finnish education centers on the holistic development of the individual, allowing each student to experience a sense of belonging and the freedom to fully develop [15]. Similarly, the educational infrastructures in this country are designed to create a warm and welcoming environment where students feel “at home”. This philosophy is reflected in various aspects of school design: hallways are decorated with warm colors and student artwork, promoting an atmosphere of relaxation and freedom of movement, without excluding self-discipline. This approach contributes to an educational environment where anxiety levels related to learning, such as in mathematics, are significantly lower than in other countries [16]. However, despite being a universal human right, access to and completion of education in other parts of the world is hindered by various factors, including economic disparity and conflict situations [17]. These challenges result in children in vulnerable contexts being up to three times more likely to be out of school and to drop out of primary school before completion [18]. Poor families often struggle to send their children to school due to the need to prioritize daily subsistence. In contexts of conflict or extreme vulnerability, the situation is even more severe, exacerbating school dropout rates and limiting access to quality education.

In this challenging educational scenario, the situation in Peru is highlighted. Regarding educational infrastructure regulations, the PRONIED (National Program of Educational Infrastructure) requires an environmental assessment sheet for the preparation of technical documents for evaluating environmental factors. Additionally, the “General Design Criteria Standards for Educational Infrastructure” mentions in the principle of habitability that thermal, acoustic, and lighting comfort conditions must be considered [19]. Moreover, the PEIP (Special Public Investment Program for Bicentennial Schools) developed specific design strategies for each climate zone (coast, rainy coast, jungle, highlands, and frost) through environmental studies to ensure user comfort. Related to environmental education-focused regulations, the National Environmental Policy for 2030, developed in 2021, considers the “Reduction of ecosystem goods and services affecting people’s development and environmental sustainability” as a public issue [20]. For efficient recycling, the municipality of Lima has the “Recicla Lima” program, which educates residents on proper solid waste segregation, included in the “En Casa Yo Reciclo” application promoted by the Ministry of Environment [21].

Despite these efforts, the country still faces a significant deficit in educational infrastructure. According to estimates by the Ministry of Education, the deficit of public educational centers amounts to approximately PEN 56 billion. Given the current conditions of public investment, it is projected that around two decades would be needed to close this gap [22]. This results in a global educational crisis, with over 670,000 children not enrolled, many forced into child labor [23], and 35% of children and adolescents living in poverty [24], representing a significant barrier to accessing quality education in the country.

In Peru, the Lima Metropolitan region has the lowest percentage of people with completed or incomplete primary education, at 3% compared to the national average of 9.6%, and compared to each of the other departments. In technical studies, Lima Metropolitan is below Ica, Callao, Moquegua, Tumbes, Junín, Tacna, Cajamarca, and Arequipa, with 15.2% [25]. This situation is due to the number of establishments requiring partial or total repairs and the lack of access to basic services. The 2014 Educational Infrastructure Census (CIE) shows that nearly one-third of buildings were constructed before the implementation of national earthquake-resistant standards in 1998, and 41% were built by parent associations without following proper safety criteria. If considering schools built with extremely vulnerable structures, more than half of the school buildings presented a high risk of collapse in the event of seismic threats [26]. According to 2013 MINEDU data, only 40% of the country’s educational centers had access to all three basic services (water, sewage, and electricity). The remaining 60% lack at least one of these services [27].

This is reflected in Figure 4A, where the damage to roofs, walls, and columns of school buildings in Lima can be seen, many of which are irreversible, leaving complete demolition as the only option. Similarly, in Figure 4B, due to humidity, exposed rebar and pipes pose a permanent danger to students, teachers, and administrative staff [28].

Figure 4. (**A**) State educational center in Lima lacking adequate infrastructure reprinted with permission from Ref. [28]. 2018, Hugo Pérez and El Comercio; (**B**) School with roof damage, reprinted with permission from Ref. [28]. 2018, San Juan de Miraflores Municipality.

This situation gains greater relevance when considering the lack of access to education in districts like Carabayllo, where more than 50% of the school-age population neither works nor studies [29], and according to the district's risk analysis, the age group of 0 to 14 years is identified as the most vulnerable population, exposed to risks ranging from malnutrition to child labor exploitation [30,31]. This educational challenge is magnified in El Progreso, which covers an extensive area of 346.88 km^2 and has a census population of 350,989 people, being recognized as "The Genesis of North Lima" [32,33].

In this sector, the primary school 2025 prevails, with an area of 4810 m^2, which presents deficiencies in its design and infrastructure, not fully meeting the needs of the population and showing a lack of integration with the local climate and environment. This results in clear deterioration, a disconnection of the school, and low accessibility in the area.

The condition of the roads adjacent to the school, such as Jose Santos Chocano Street, features unpaved roads, no sidewalks, and poorly maintained perimeter fences of the school, as shown in Figure 5A. Similarly, on Jr. Isabel Chimpu Ocllo, the situation is even more unsafe due to the adjacent blind walls, as shown in Figure 5B.

Figure 5. (**A**) St. Jose Santos Chocano reprinted with permission from Ref. [34]. 2023, Google Maps; (**B**) Jr. Isabel Chimpu Ocllo reprinted with permission from Ref. [35]. 2023, Google Maps.

This situation is exacerbated by the presence of a largely abandoned and deteriorated park, lacking proper furniture and green areas [36]. This deficiency translates into a limited green space per inhabitant, estimated at only 3.5 m^2 per person [37]. This neglect of green space treatment and its connection with public spaces underscores the fundamental human need to establish a link with the natural environment to contribute to physical and mental health, as well as social well-being. In this context, bioclimatic architecture emerges, which promotes the recovery and utilization of available resources in a rational and well-planned manner, ensuring the preservation of existing ecosystems and avoiding contamination [38].

Therefore, the present research aims to generate comfort for users of the educational center by applying sustainable design strategies, Carabayllo-Peru-2023.

2. Materials and Methods

2.1. Methodological Scheme

The present research is of a basic nature and employs a hypothetico-deductive method of non-experimental design. The development proceeded through four phases, following the process described in the following sections, as observed in Figure 6.

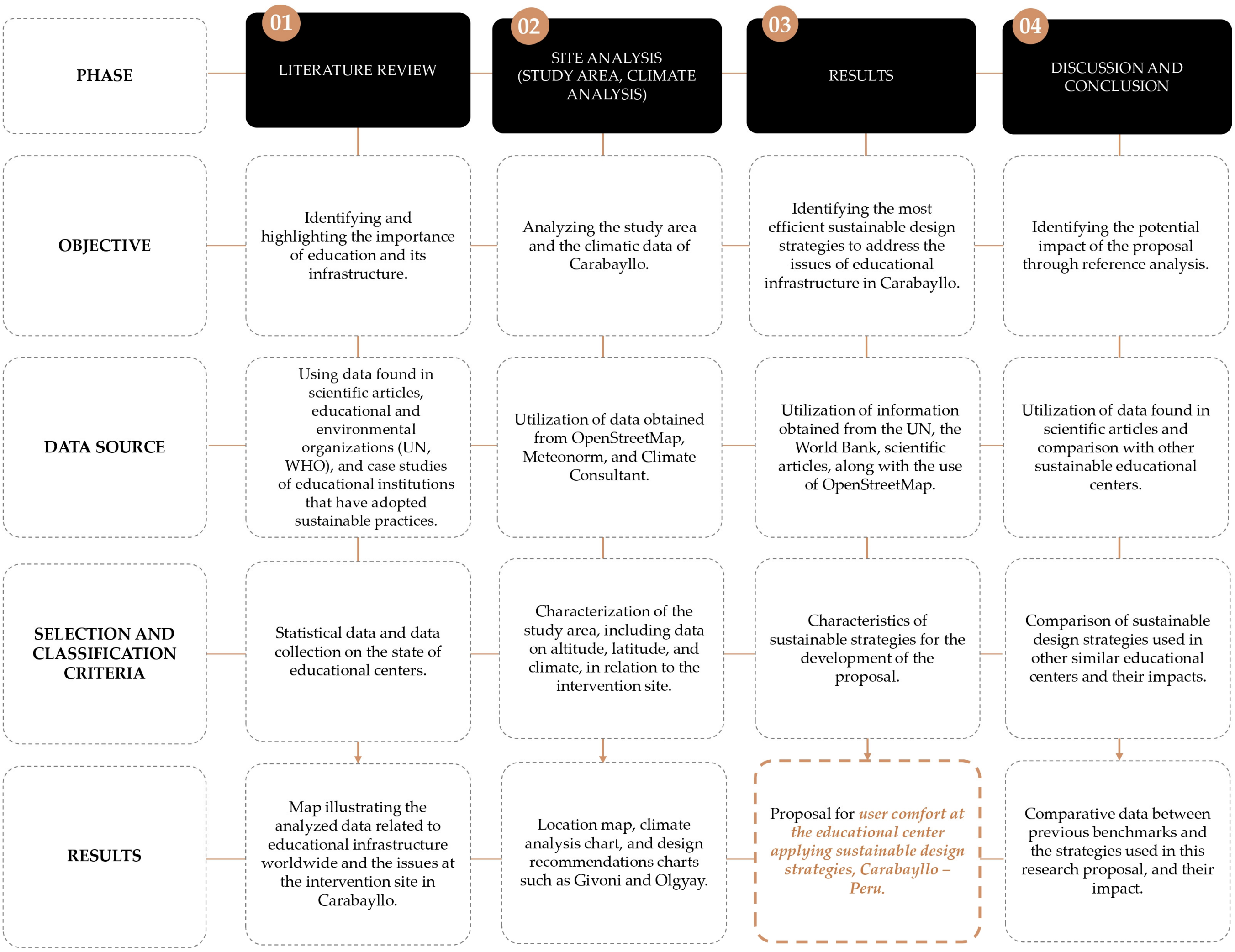

Figure 6. The methodology applied in the research.

2.1.1. Literature Review

In the first phase, a literature review was conducted to gather relevant information contextualized within the study area. This process allowed for the identification of issues and the establishment of parameters to consider as potential solutions. The reviewed sources included articles from academic journals, educational and environmental organizations (UN and WHO), and case studies of educational institutions that have adopted sustainable practices. This bibliographic review was crucial for developing a deep understanding of the factors affecting the quality of education in Carabayllo and for identifying sustainable design strategies that could be applied to enhance educational environments in this district.

2.1.2. Site Analysis

During the second phase, location and data analysis of the intervention site were carried out using the OpenStreetMap tool. This allowed for consideration of potential terrain limitations, specific environmental challenges, as well as existing physical deficiencies and climatological needs in the El Progreso–Carabayllo area. Additionally, climatological data were analyzed, addressing essential aspects such as temperature (maximum, minimum, average), wind (speed and direction), relative humidity (maximum, minimum, average), and precipitation. This facilitated the implementation of sustainable design strategies in educational centers aimed at minimizing environmental impact positively. The following outlines the climatic data acquisition process:

1. In the present study, annual climatic data for the year 2020 were extracted. Data collection (EPW) was conducted using the Carabayllo meteorological station from Meteonorm. The obtained data include temperature (°C), wind (m/s and °), relative humidity (%), and monthly and annual precipitation (mm).
2. The use of Climate Consultant as a graphical viewer of meteorological data and the Givoni chart allows for climate characterization and establishes the strategy to be used.
3. The use of AutoCAD to create the Olgyay chart. Climatic data were utilized to manually graph outdoor climate strategies.
4. Obtaining the Stereographic Solar Chart with Sun-Path from Andrew Marsh's website.
5. An analysis of the results obtained and their influence on the future proposal.

2.1.3. Results

In turn, during the third stage, the key steps for carrying out the proposal using digital tools are described. As a first step, the location of the site was established with coordinates using OpenStreetMap; the second step involved mapping the elements in the immediate project environment (buildings, streets, parks, existing vegetation, etc.) along with project constraints through JOSM in OSM format; the third step involved lifting the environment and topography using Rhinoceros and Grasshopper with the use of the OSM file via the Gismo plugin; for the fourth and final step, a combination of Revit BIM Collaborate and Rhinoceros with Grasshopper was used for modeling the proposed project, as observed in Figure 7.

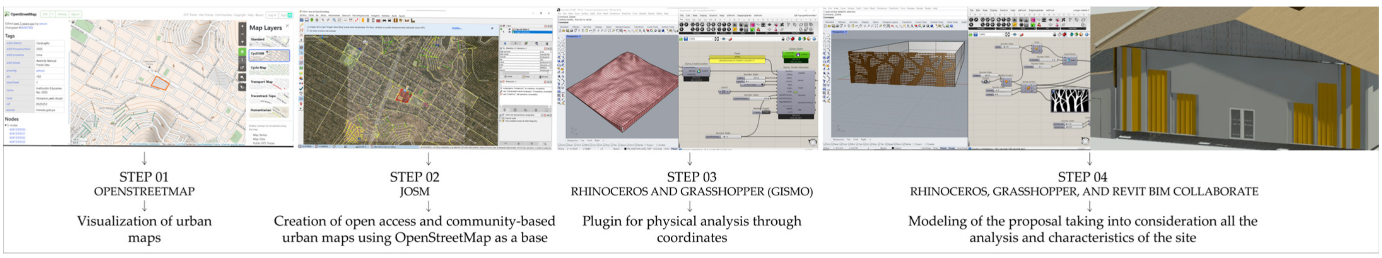

Figure 7. Steps for the implementation of the proposal with digital tools.

Additionally, to conduct solar calculations for each space, a section was made through the openings of the facade. Based on the facade's orientation, the angle of solar incidence was determined. The angle was set from sunrise (6:30 AM) to sunset (6:00 PM) to count the number of hours of direct solar radiation entering the interior of the building. Figure 8A illustrates the facade section of the sports slab with solar incidence angles, showing the period during which solar penetration occurs. As detailed in Table 1, with solar protection in this area, there is no record of daily, monthly, or annual direct solar penetration through the openings. However, without solar protection, there are 11 h daily, 330 h monthly, and 3960 h annually of solar penetration.

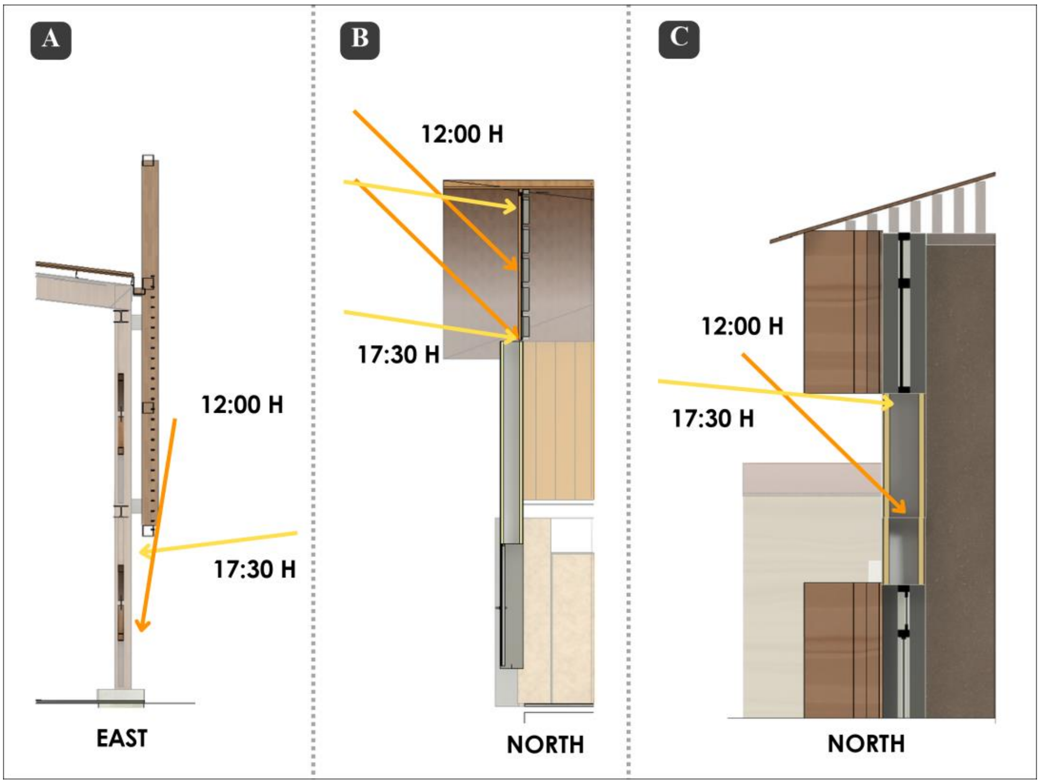

Figure 8. (**A**) A facade section of the sports slab with solar incidence angles; (**B**) a facade section of the administration and multipurpose room with solar incidence angles; and (**C**) a facade section of the educational pavilion with solar incidence angles.

Table 1. The amount of direct solar penetration hours in the openings of the sports slab.

	Hours		
	Daily	**Monthly**	**Annual**
With Solar Protection	0	0	0
Without Solar Protection	11	330	3960

In Figure 8B, the facade section of the administration and multipurpose room with solar incidence angles is detailed, showing the period during which solar radiation enters through the upper windows (openings), as indicated in Table 2. With solar protection on these windows, there is a direct solar penetration of 3.3 h daily, 99 h monthly, and 1188 h annually. In contrast, without solar protection, penetration increases significantly to 8 h daily, 240 h monthly, and 2880 h annually.

Table 2. The amount of direct solar penetration hours in the windows of the administration and multipurpose room.

	Hours		
	Daily	**Monthly**	**Annual**
With Solar Protection	3.3	99	1188
Without Solar Protection	8	240	2880

Finally, Figure 8C illustrates the facade section of the educational pavilion with solar incidence angles, showing the period during which solar penetration occurs, corresponding to Table 3. With solar protection on the windows of the educational pavilion, there are no hours of daily, monthly, or annual direct solar penetration recorded. However, without solar protection, there are 11 h daily, 330 h monthly, and 3960 h annually of direct solar penetration.

Table 3. The amount of direct solar penetration hours in the windows of the classroom pavilion.

	Hours		
	Daily	**Monthly**	**Annual**
With Solar Protection	0	0	0
Without Solar Protection	11	330	3960

In turn, the calculation for obtaining the monthly energy produced by the solar panels uses the following equation [39]:

$$E = P(\text{kW}) \times R\left(\text{kWh/m}^2/\text{day}\right) \times \eta p \times \text{days} \quad (1)$$

In this equation, E represents the total energy generated in kilowatt-hours (kWh), indicating the total electricity produced. P is the nominal power of the solar panel in kilowatts (kW), defining its maximum theoretical capacity under ideal conditions. R is the average daily solar radiation in kWh/m^2/day, reflecting the daily average solar energy received per square meter. ηp is the efficiency of the solar panel system, expressed as a percentage, indicating how much solar energy is effectively converted into usable electricity. Days refer to the total number of days during which the panels are operational and generating power. The multiplication of these factors determines the total amount of kWh of electricity that the solar panels can produce during that specific period.

2.1.4. Discussion and Conclusions

Finally, in the fourth stage, a comparison will be made with previous benchmarks of findings, such as the strategies used in the proposal.

2.2. Study Area

The study area is located in South America in the country of Peru, Lima province, and Lima department, as observed in Figure 9A,B. Additionally, Figure 9C illustrates that the intervention site is situated in the Carabayllo district in the El Progreso sector, on the right bank of the Chillón River, at coordinates 11°52′40.54″ S latitude and 77°00′25.04″ W longitude, at an approximate altitude of 221 m.a.s.l., and with a territorial extension of 346.88 km^2. It borders to the north with the district of Ancón and the province of Canta, to the south with Comas and San Juan de Lurigancho, to the east with the province of Huarochirí, and to the west with the district of Puente de Piedra [40].

2.3. Climate Analysis

The study area is classified as climatic zone E (d) B′, characterized by an annual average temperature of 17.9 °C and an annual temperature range of 4.5 °C. It is warm in the summer with an average temperature of 21 °C and cold in the winter with an average temperature of 15.9 °C. The area experiences light seasonal precipitation, with 5.7 mm in summer and a very light precipitation of 1 mm for the rest of the year. It has a humid climate with an annual relative humidity (RH) of 82.5% and light breeze winds averaging 3.1 m/s predominantly from the NNO direction and occasionally from the SE direction. Additionally, the area has an annual average radiation of 6.0 kW/m^2, as observed in Figure 10 [41].

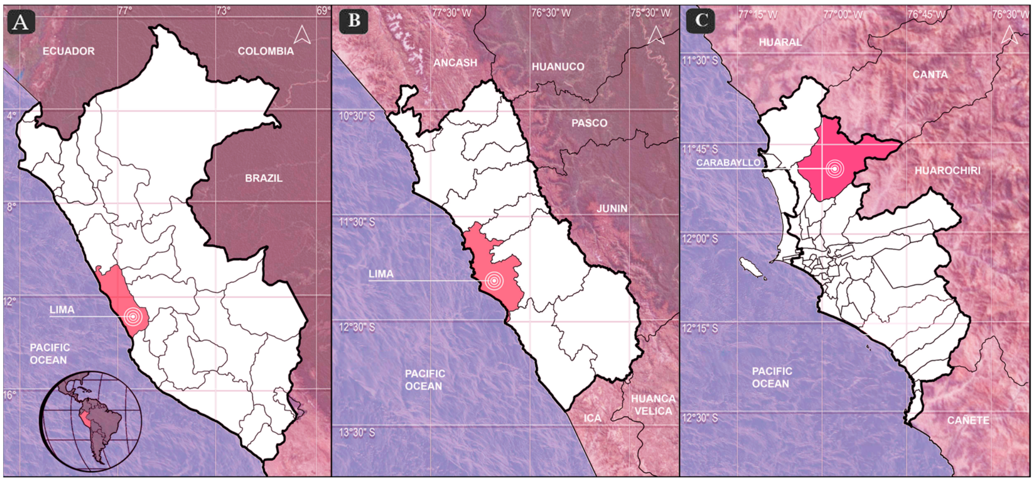

Figure 9. (**A**) A map of the South American continent, country of Peru, and department of Lima; (**B**) a map of the province of Lima; and (**C**) a map of the Carabayllo district.

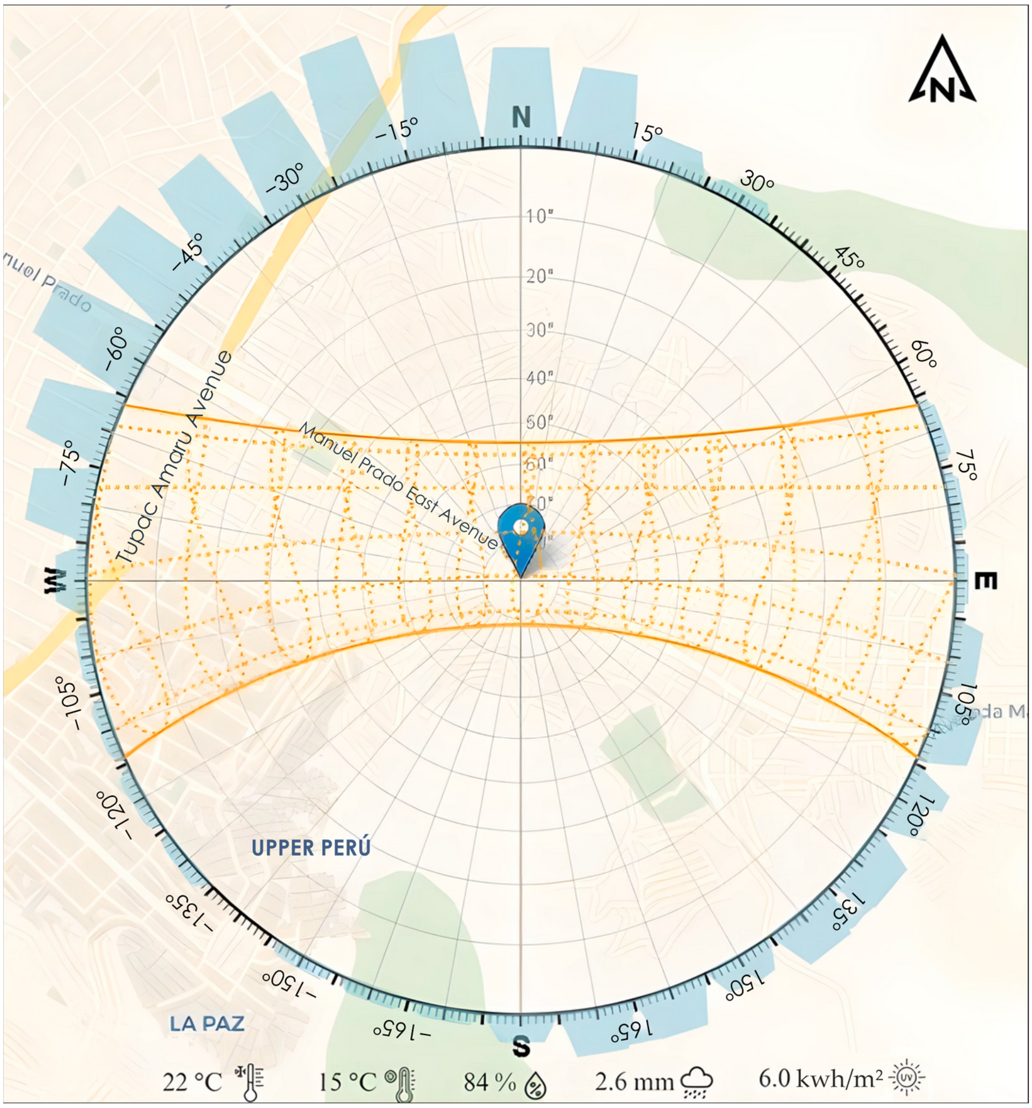

Figure 10. Graphical climatology of study area.

2.4. Design Strategies

The intervention site features a temperate climate, necessitating the implementation of specific strategies for both summer and winter, as illustrated in Figure 11A. In Figure 11B, it is observed that during the summer, with a warm climate of 21 °C, a thermal oscillation of 5.6 °C, and a relative humidity of 80.3%, the effective control of thermal mass and internal gains is crucial. Strategies focus on preventing temperature increases and promoting natural ventilation during the day while conserving heat at night. This includes the use of permanent natural ventilation, shading, and solar penetration prevention, as these elements directly affect heat intake and release. In contrast, during winter, with a cold climate of 15.9 °C, a thermal oscillation of 3.4 °C, and a relative humidity of 84%, the effective control of thermal mass, internal gains, solar protection, and natural ventilation remains essential. An integrated approach is applied to maintain heat preservation (thermal inertia) throughout the day and night, emphasizing the prevention of infiltration and the regulation of space ventilation to control humidity and thermal sensation.

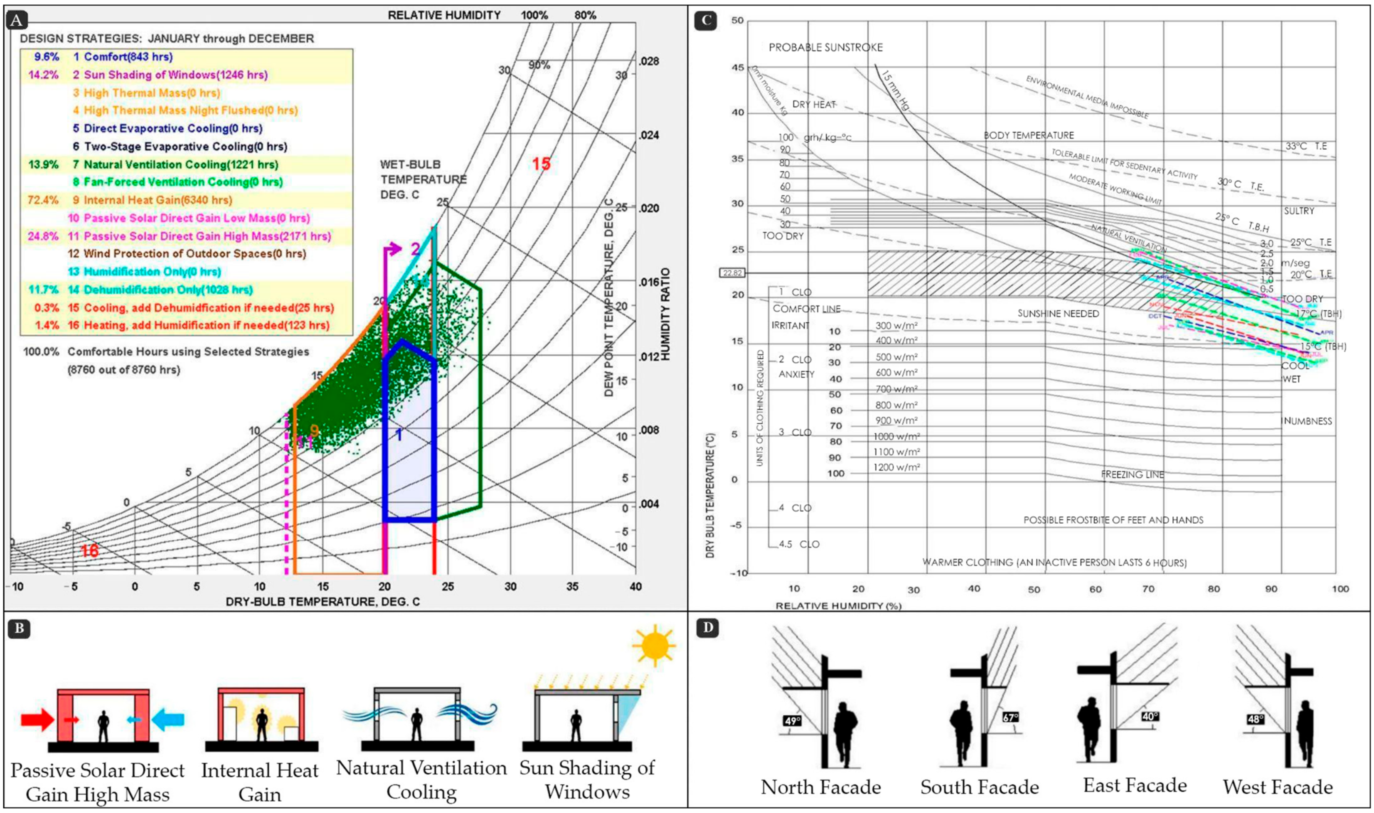

Figure 11. (**A**) Givoni's chart; (**B**) design strategies; (**C**) design angles in spans; and (**D**) Olgyay's chart.

Additionally, Figure 11C depicts other architectural strategies, such as situating the building to maximize climate insulation through material selection and adjustable openings tailored to different facade orientations: 49° on the north, 67° on the south, 40° on the east, and 48° on the west. This design configuration allows the building's slab to function effectively as an eave for solar protection on each facade [42].

Finally, Figure 11D demonstrates the use of the Olgyay chart to derive climate design strategies for outdoor spaces, emphasizing the importance of ensuring shade and ventilation during summer while maximizing solar radiation utilization during winter.

3. Results

3.1. Place of Study and Topography

The exact coordinates of the intervention site are latitude −11.877794° and longitude −77.008594°, with a gentle slope of 9%, as observed in Figure 12A. Additionally, Figure 12B shows the longitudinal section cutting through the intervention site, sloping increasingly from north–northwest to south–southeast [40].

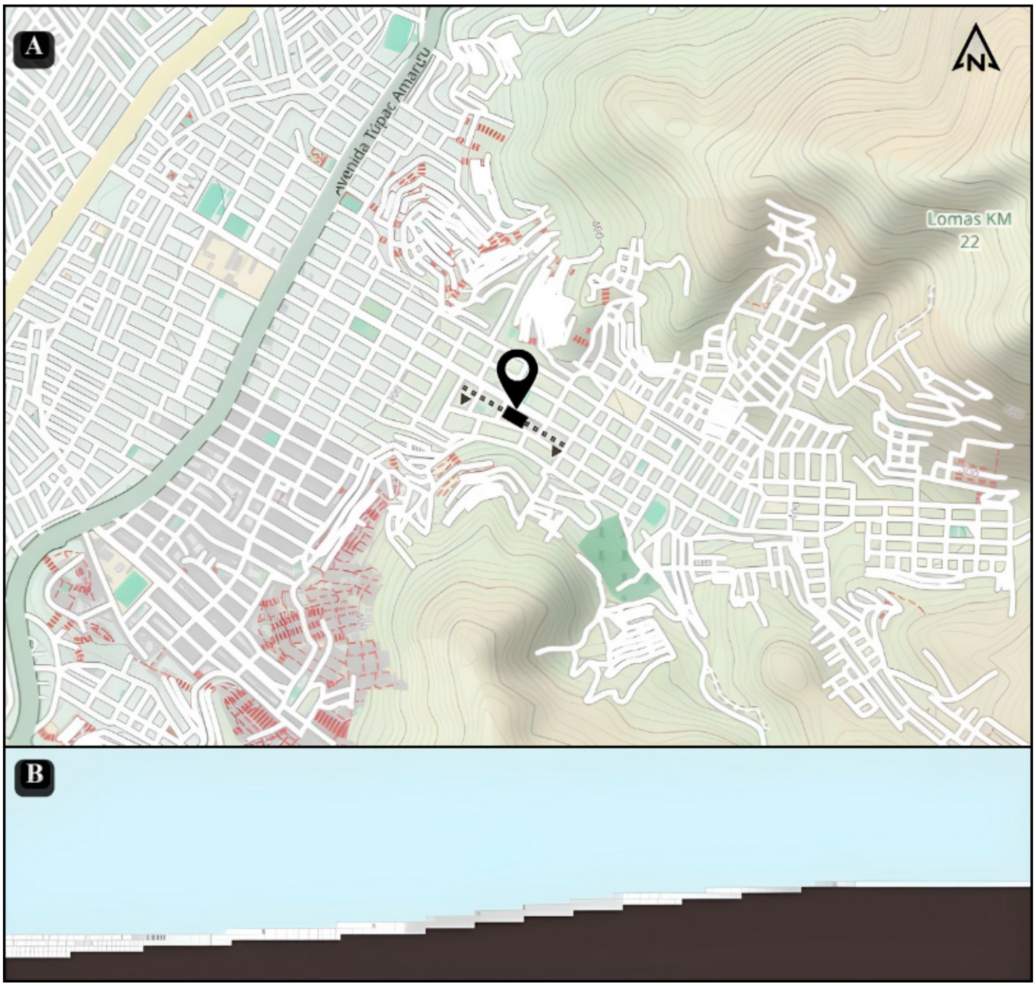

Figure 12. (**A**) Location; (**B**) topography.

3.2. Master Plan and Zonification

The strategic placement of the classroom pavilion and administration, along with the multipurpose room, maximizes natural lighting throughout the year, positioned from east to west relative to the orientation shown on the solar chart. On the other hand, the sports slab, oriented differently than recommended by the solar chart, required additional design strategies to ensure natural lighting and protection against direct solar penetration, considering that the educational center is open from 8 a.m. to 2 p.m. Given the high level of physical activity that occurs once a week in the sports slab area, which influences internal heat gains, an enhanced facade protection strategy was necessary, as observed in Figure 13.

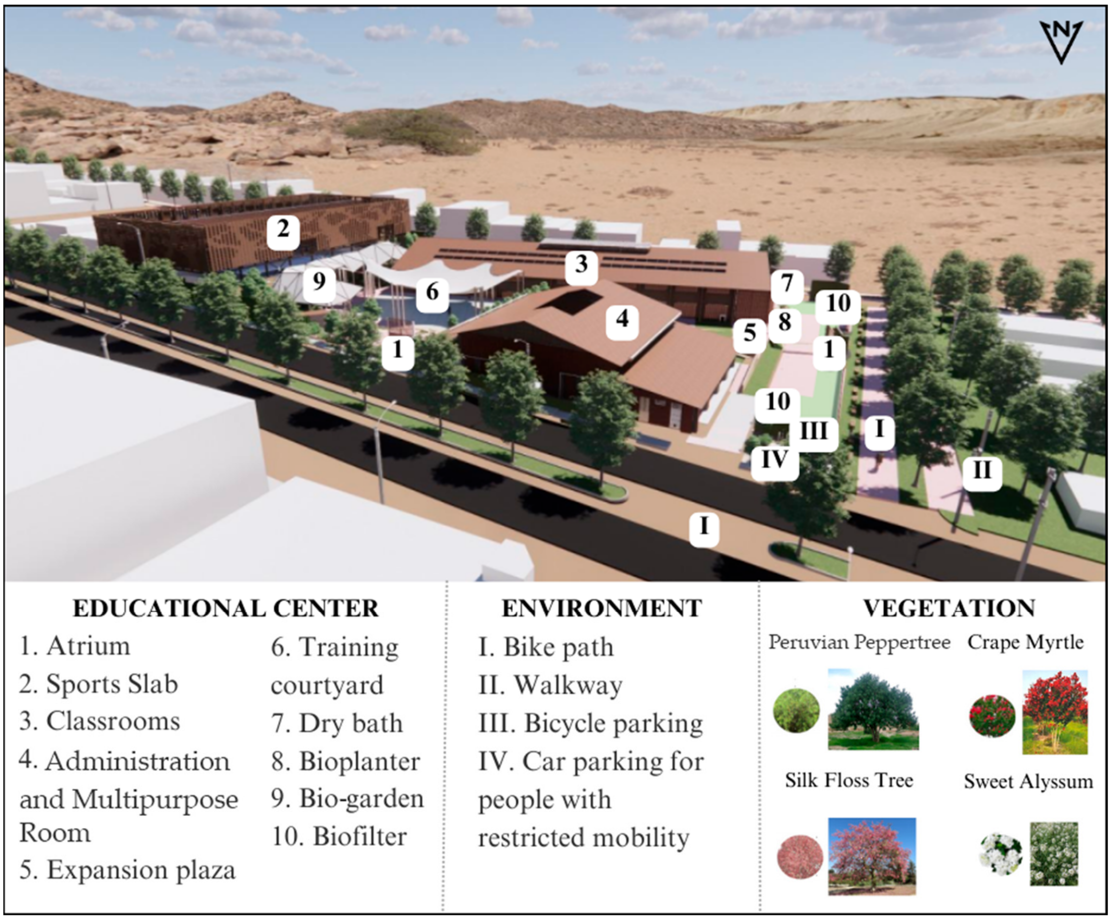

Figure 13. Master plan.

3.3. Proposed Spaces and Strategies Applied

3.3.1. Education Center

As previously mentioned, prioritizing managing and releasing internal gains is crucial for ensuring the comfort and internal temperature regulation of the sports slab, as depicted in Figure 14A. Furthermore, Figure 14B illustrates a double wooden structure with 0.30 cm insulation as support for the external skin, which helps retain heat directly within the wooden panels. This setup allows heat dissipation through subsequent air gaps, functioning effectively as a large insulating wall to reduce temperature increase and thermal exchange, thereby maintaining a protected and cool interior. It also ensures winter comfort with heat generated by physical activities. This facade design also shields against solar exposure while allowing natural light and ventilation through circular openings across the roof. Furthermore, this strategy is complemented by creating a green roof covered with vines, acting as a vegetative cover that reduces heat buildup on roofs due to Lima's nearly perpendicular solar position, further regulating interior temperatures and minimizing radiation. Air renewal in the sports slab occurs through the inflow of air into the spaces, depicted by blue arrows for cold air and red for warm air. This refreshes the internal space while warm air accumulates at the upper part, decreasing due to the thermal insulation effect provided by the green roof above. Graphically illustrating how the internal blue area remains cooler due to air inflow, while the warmer upper part, colored yellow and orange, remains elevated from the activity zone.

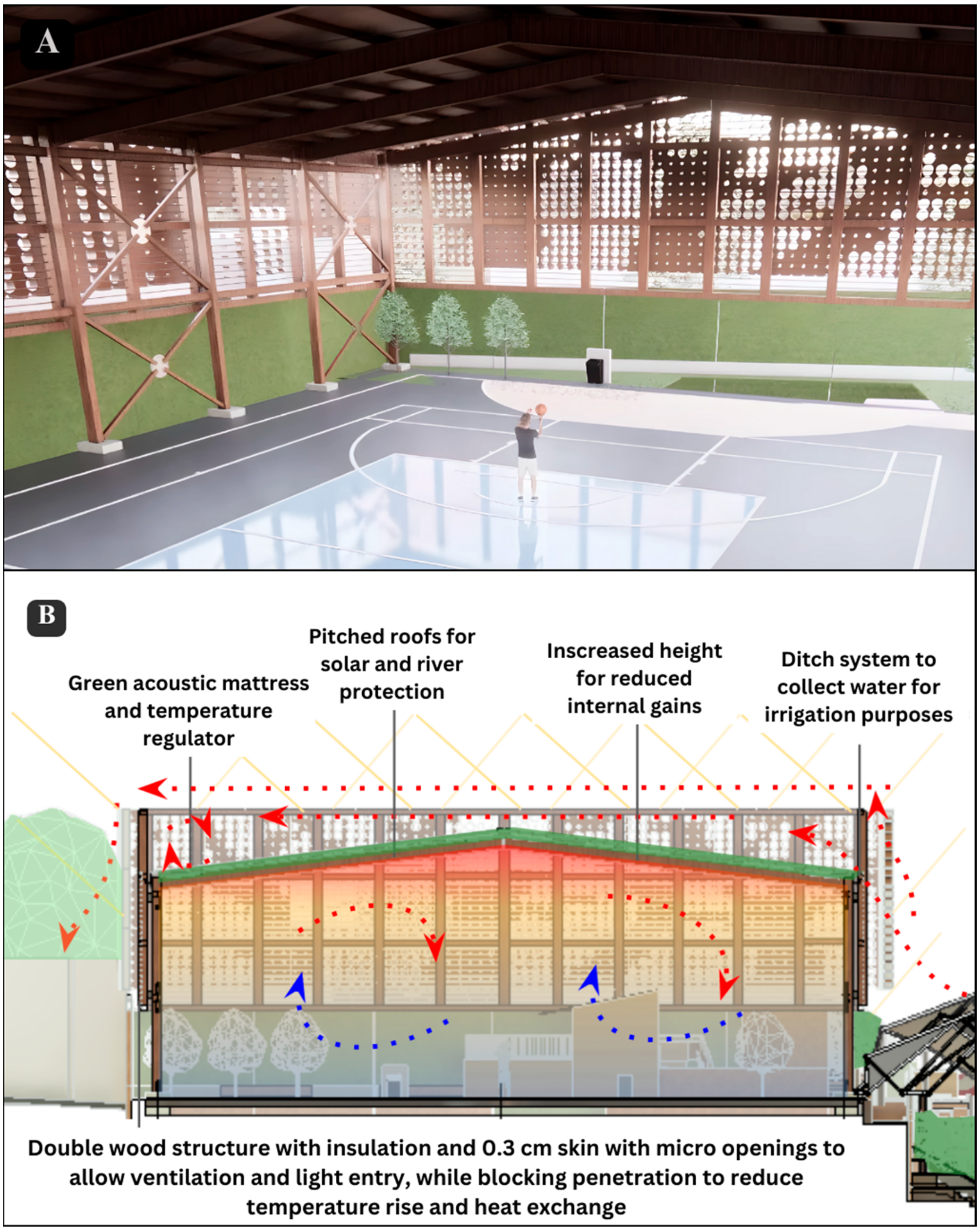

Figure 14. (**A**) The interior of the sports slab with the structure; (**B**) a schematic section with an environmental explanation.

The administration and multipurpose room are equipped with a system of movable windows on the ground floor, designed to adjust according to lighting and protection needs at different times, along with a grid of 0.5 × 0.5 m windows at the upper part to regulate ventilation, as seen in Figure 15A. Additionally, a central skylight is installed to harness zenithal lighting throughout the building and facilitate natural ventilation with a chimney effect. Furthermore, as depicted in Figure 15B, these buildings feature gabled wooden roofs with a 30° pitch and a 2 m projection, providing protection against solar incidence on the facade and roof, as well as rainwater runoff management. Prefabricated adobe walls, 30 cm thick and coated with lime, are used to ensure thermal comfort and prevent air leakage through the walls and openings. The chimney effect occurs when air enters the environment, depicted by blue arrows for cold and red for hot; it cools the internal space while hot air concentrates at the top and disperses through the skylight. This graphic illustrates how the internal space remains cooler (blue) due to incoming air while the upper part is warmer (yellow and orange).

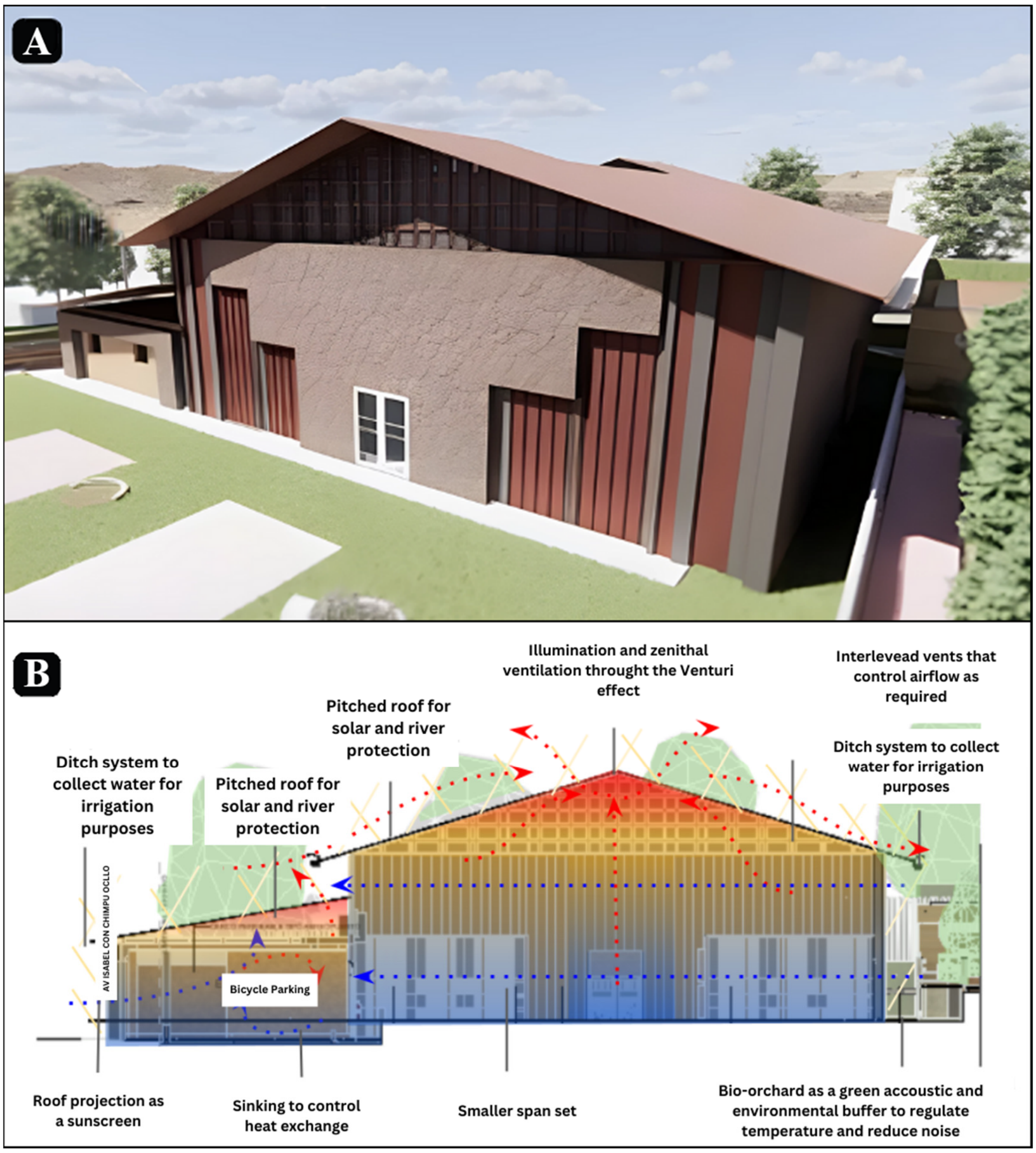

Figure 15. (**A**) Administration and multipurpose Room; (**B**) schematic section with environmental explanation.

The classroom pavilion features a compact design that enhances heat conservation and reduces heat dissipation. Its orientation optimizes natural lighting and ventilation on both floors through the facade. This design is complemented by a skylight for zenithal illumination and interior ventilation using a chimney effect, as depicted in Figure 16A. Figure 16B illustrates how sliding wooden shutters provide meticulous control over sunlight, ensuring effective heat management at openings while adapting to the orientation of each facade. The chimney effect describes how air entering the environment, represented by blue arrows for cold and red for hot, cools the internal space. Meanwhile, hot air gathers at the top and disperses through the skylight. This graphic shows how the internal space stays cooler (blue) from the incoming air, while the upper part becomes warmer (yellow and orange).

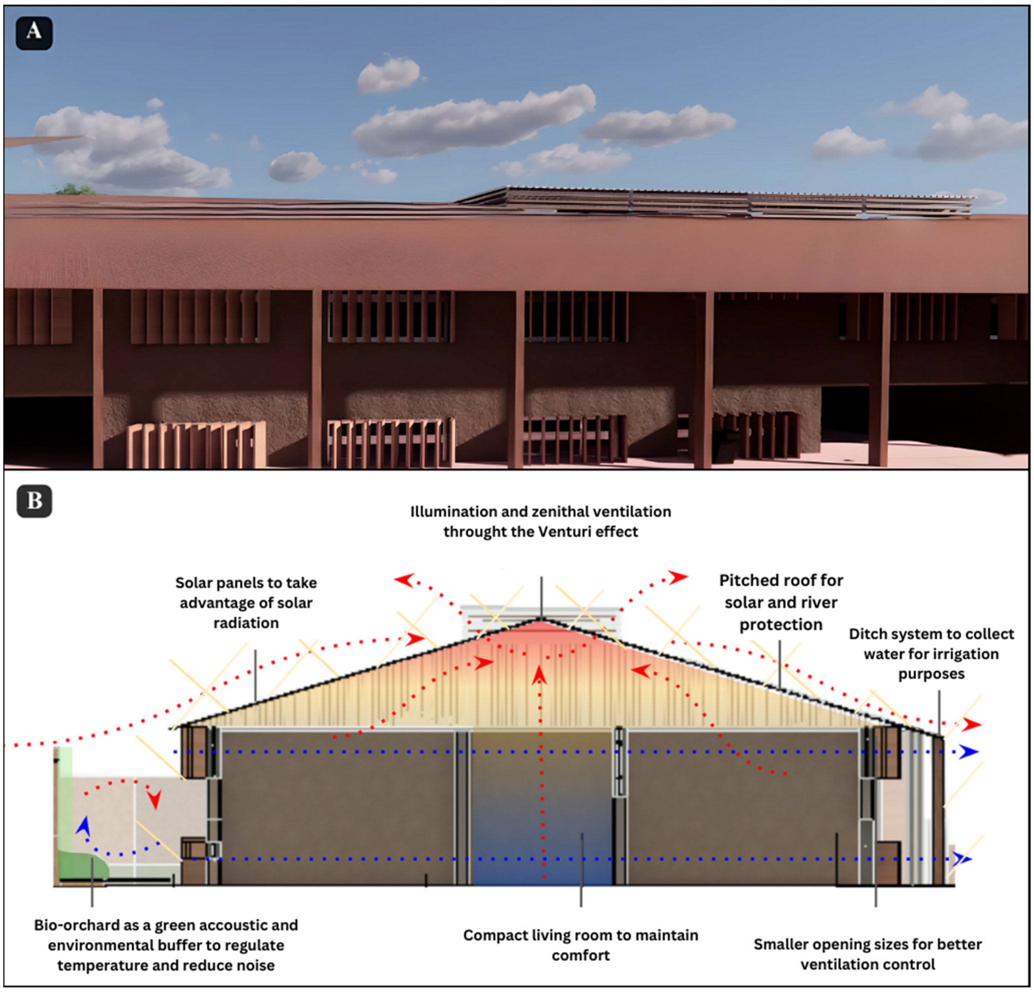

Figure 16. (**A**) Classroom pavilion; (**B**) schematic section with environmental explanation.

Finally, the use of prefabricated adobe walls measuring 40 cm thick, including a plaster coating to ensure thermal comfort and prevent leaks, provides adequate thermal mass, controlling internal gains and exchanges with the exterior. Additionally, gabled roofs with overhangs offer comprehensive protection against solar radiation and rainfall. The combination of these strategies with appropriate materials ensures an optimal thermal transmittance of 2.2 W/m^2K, while also minimizing periodic maintenance, as observed in Figure 17.

All these implementations based on Givoni's recommended design strategies offer the following advantages:

The east-west orientation of the buildings facilitates natural daylighting and enhances airflow for cross-ventilation and air renewal.

The use of thick adobe walls, 30 cm thick and coated with lime, enhances thermal inertia and heat storage capacity, ensuring comfort due to the material and thickness used while promoting construction with biodegradable materials. The lime coating seals adobe against wind-driven infiltrations and helps manage moisture from seasonal rains.

Skylights enable zenithal lighting, particularly effective in Lima due to its solar angle (latitude) of 12°, making sunlight nearly perpendicular and rooftops the areas with the highest solar incidence. This implementation maximizes natural lighting in the educational pavilion and the administration with the multipurpose room. Positioned centrally, skylights allow warm air currents within the building to rise towards the skylight, while cooler air remains lower, facilitating upward airflow due to temperature differences and constant air renewal.

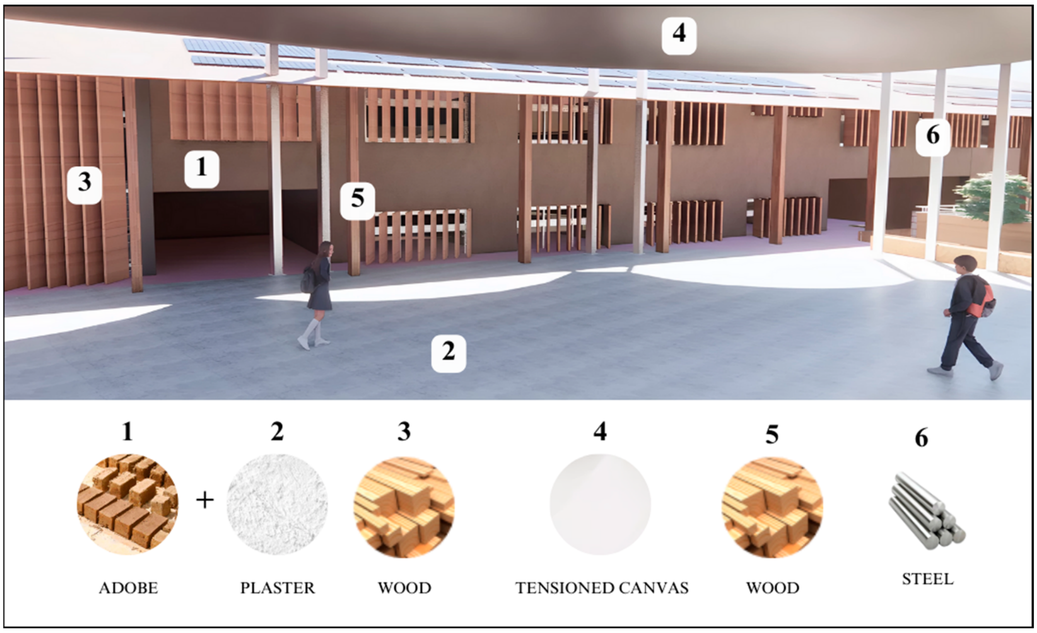

Figure 17. Materiality of classroom pavilion.

Lastly, reducing the size of openings and providing solar shading promotes a decrease in direct solar penetration hours into the building, also known as direct solar gain. This helps prevent the overheating of interior spaces and focuses on heat gain through walls and roofs while preserving indirect solar gain without compromising the natural indirect lighting of the spaces. In Lima, indirect solar gain helps retain warmth longer compared to direct solar heat, which dissipates more rapidly. Therefore, by protecting openings from overheating and concentrating on heating walls and roofs, greater heat conservation is achieved during nighttime and winter.

Additionally, 74 solar panels are installed on the roof of the classroom pavilion to provide the necessary energy capacity for the educational center's operation, including administration, the multipurpose room, the classroom pavilion itself, and the sports slab. These panels are mounted on a pitched structure designed to capture the maximum amount of sunlight throughout the day. Furthermore, they are organized in rows to optimize space efficiency and energy generation and facilitate maintenance access, as observed in Figure 18.

Table 4 details the panels' dimensions, their maximum power of 550 W, and their efficiency of 20.58%. Table 5 shows the solar panel production at the educational center using 74 units, generating 1465.20 kWh monthly and a total annual output of 17,582.40 kWh. Additionally, Table 6 presents the electricity consumption from the electrical grid by the educational center, with figures of 1462.4064 kWh monthly and 17,548.88 kWh annually, which the solar panels fully cover. Finally, Table 7 indicates that the annual cost of traditional energy consumption amounts to PEN 11,944.13. Regarding the cost of the 74 panels, each priced at PEN 675.01 [43], the total cost is PEN 49,950.74. This total cost is incurred once per year, resulting in a total cost over 10 years of PEN 49,950.74 with solar panels, estimated to have a lifespan of 25 years, compared to PEN 119,441.33 with traditional energy.

Table 4. Solar panel characteristics [43,44].

	Manufacturer	City	Country	Distributor	Dimensions (mm)	Peak Power (W)	Efficiency (%)
Solar Panel 550 W 24v Monocrystalline	EcoGreen Energy	Champs-sur-Marne	France	Panel Solar Peru	2102 × 1040 × 35	550	20.58

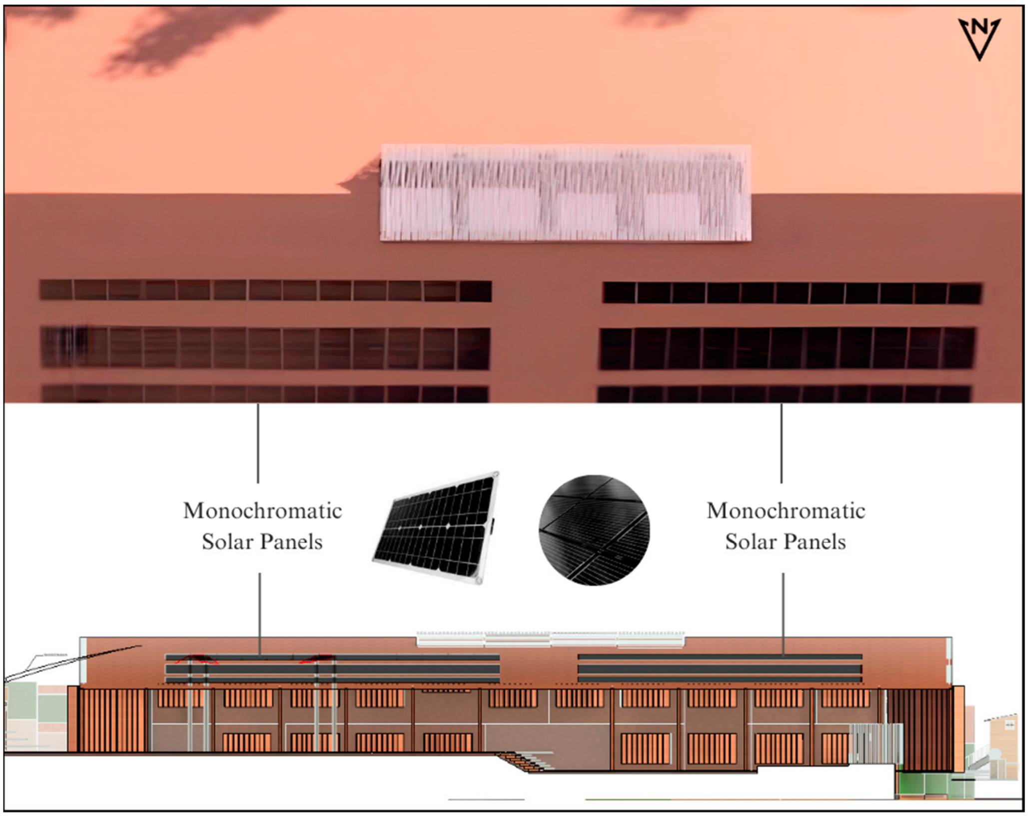

Figure 18. The plan view and elevation of the solar panels located on the classroom pavilion.

Table 5. Solar panel production at the educational center.

	kW Diary per Panel	Diary Solar Radiation	Efficiency (%)	#Panels	N° Days per Month	Total Monthly kWh	Total Annual kWh
Solar Panel	0.55	6.0	20	74	30	1465.20	17,582.40

Table 6. Energy consumption of educational center.

	Total Monthly kWh	Total Annual kWh
Solar Panel	1465.20	17,582.40
Electrical Grid	1462.4064	17,548.8768

Table 7. Cost of traditional energy consumption per year (PEN) and cost of clean energy (solar panels) per year (PEN).

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Total Cost
Cost of Traditional Energy Consumption (PEN)	11,944.13	11,944.13	11,944.13	11,944.13	11,944.13	11,944.13	11,944.13	11,944.13	11,944.13	11,944.13	119,441.33
Cost of Clean Energy (Solar Panels) (PEN)	49,950.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	49,950.74

3.3.2. Bio-Gardens and Compost Area

Orchards with the use of biofilters (recycled water for irrigation), vertical gardens, and biodiverse gardens feature native and xerophytic vegetation, providing climatic, economic, and social benefits. These are achieved through the integration of open classes in these spaces to foster nature-based learning. Additionally, the produce from these gardens serves as a food source for students in the cafeteria. Furthermore, the introduction of this vegetation significantly reduces water usage, gray water treatment, and maintenance costs, thereby promoting an appreciation of natural heritage from a young age, as observed in Figure 19A. Furthermore, Figure 19B shows the cultivation of two main categories of vegetables: the first category includes aromatic and medicinal plants such as basil, oregano, mint, thyme, peppermint, rosemary, tarragon, dill, sage, laurel, coriander, lemon balm, muña, lemon verbena, and chamomile. In addition, floral species such as calendula, geranium, nasturtium, lavender, wormwood, rue, cosmos, borage, and fennel will be implemented [45].

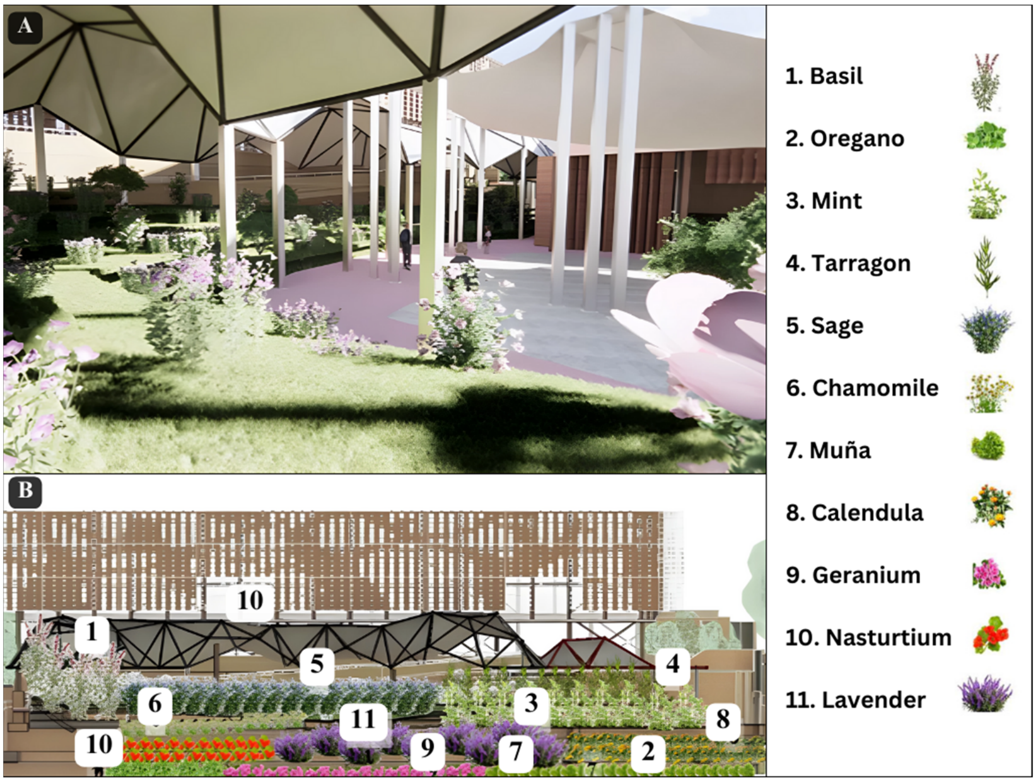

Figure 19. (**A**) Bio-garden; (**B**) section with vegetation marked.

3.3.3. Biofilter

The drainage system of the bathroom sinks is connected to a drainage box that collects gray water. Subsequently, this water passes through a grease trap consisting of two chambers: the first chamber separates water with grease from solid waste, while the second chamber separates grease from gray water. Then, the gray water passes through a biofilter, where wetland plants transfer oxygen to the submerged root zone, enabling the biological degradation of contaminants and organic matter by microbes. Finally, the purified water is stored in a water tank for reuse, as observed in Figure 20A. Similarly, Figure 20B illustrates the components of a biofilter, including the drainage box, the grease trap containing grease, solid waste, and water, and the biofilter itself, composed of sand, gravel, topsoil, and reeds, ending with a water storage container.

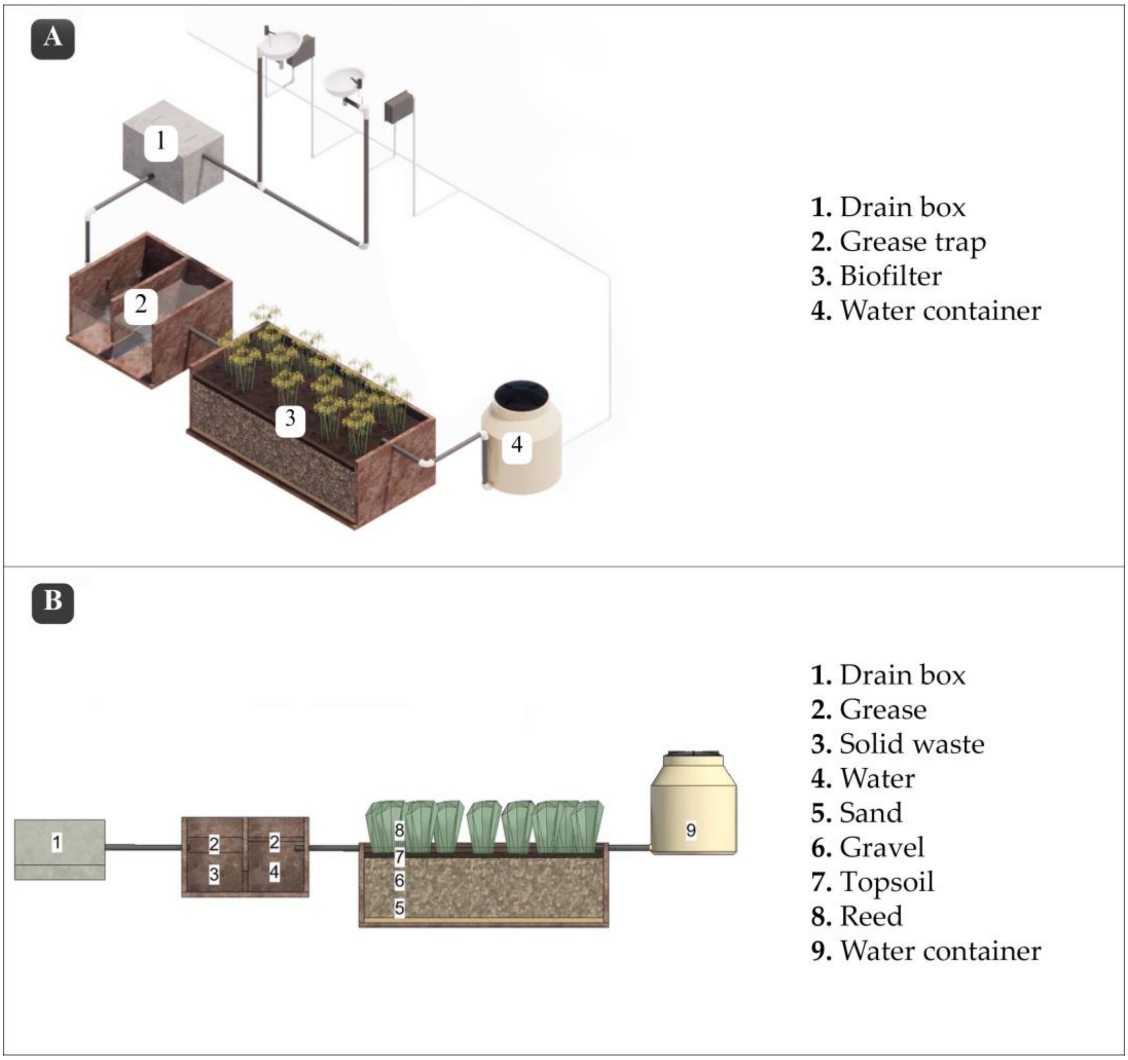

Figure 20. (**A**) Biofilter scheme; (**B**) parts of biofilter.

3.3.4. Dry Bath

The double-dry toilet is designed to treat human excreta through an aerobic process. The organic matter deposited within the chambers, located beneath the dry toilets, must be maintained at a moderate level of moisture, warmth, and oxygenation. Each time the toilet is used, the excreta should be covered with a carbon-rich mixture so that, through an oxidation process, they transform into compost. The decomposition process of the excreta requires a minimum period of six months, during which time one chamber is used while the other undergoes treatment. When the in-use chamber fills up, the treated chamber is emptied, and the cycle restarts [46]. The chambers beneath the urinal are connected to a chamber containing urine. This urine will be used later as fertilizer due to its balanced, quick-action, and nitrogen-rich properties [47].

Similarly, in Figure 21, two sections are observed, one cross-sectional and the other longitudinal, of the double dry bath. These sections include within them the dry toilet, paper holder, urinal, container for covering excreta, sink, the chamber in use, urine chamber, decomposition chamber, windows with mosquito screens, sink drain box, and chamber door.

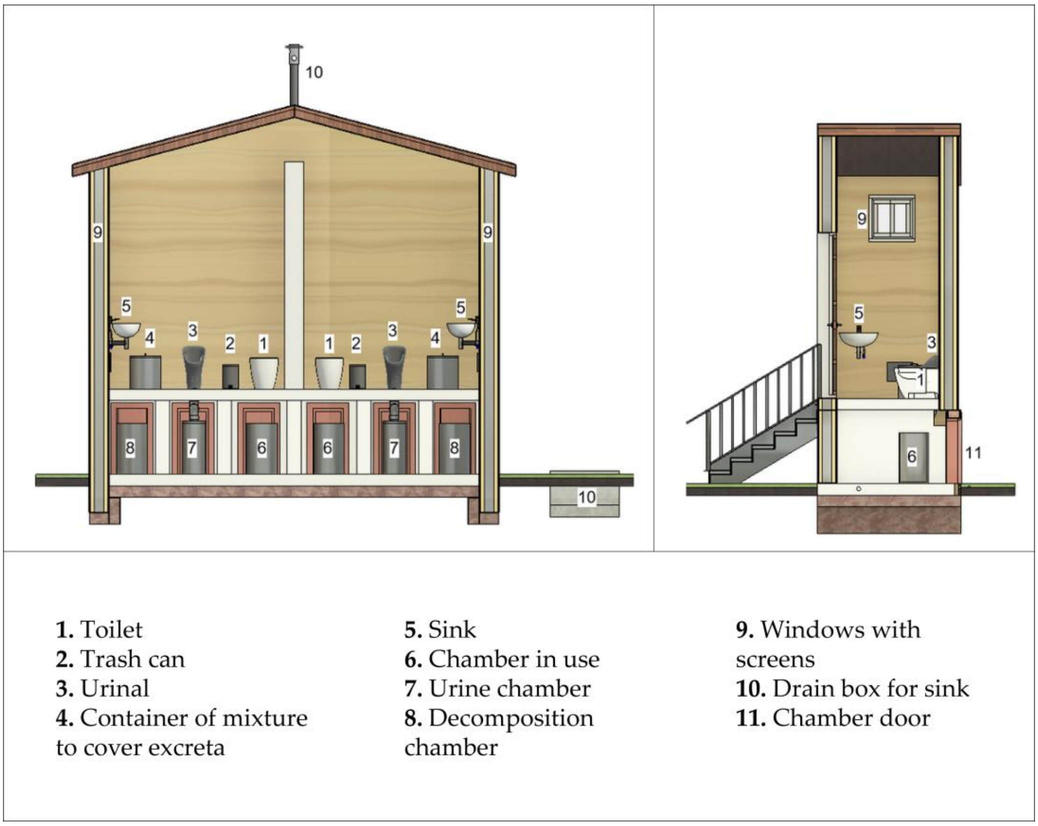

Figure 21. Longitudinal and cross-sectional view of double dry bath.

3.3.5. Bike Path and Walkway

The layout of pathways, pedestrian streets, bike lanes, and green areas is presented as a crucial strategy for creating healthy and suitable public spaces for people, encouraging the use of alternative transportation, and promoting greater activity in public spaces by local residents. In this context, the use of xerophilous vegetation plays a decisive role due to its ability to adapt to low water consumption and the local climate. Therefore, trees such as the Molle Costeño (Schinus molle), Árbol de Júpiter (Lagerstroemia indica), and Palo de Borracho (Ceiba speciosa) are chosen for their broad canopies that provide shade, along with shrubs like Cucarda (Hibiscus rosa-sinensis), Margarita Azul (Felicia amelloides), and Rosa Rugosa (Rosa rugosa). Additionally, ground covers such as Grass Paspalum (Paspalum spp.) are used, which allows for activities on it without incurring high maintenance costs; Gazania (Gazania rigens), Flor de Seda (Aptenia cordifolia), and Lobularia Marítima (Lobularia maritima) are used to complement the vegetation. These elements are combined with eco-friendly materials that can be sourced from local materials and industries, such as clay and crushed concrete pavers, wooden benches, and local stones, along with recycled materials like tires, rubber, wood, ropes, and bottles, which can be used for ground cover as well as benches and playgrounds. Moreover, technological innovations such as photovoltaic pavers and public lighting with solar panels are integrated, promoting community development and environmental awareness through technological innovation, as shown in Figure 22.

The use of photovoltaic lighting systems, detailed in Table 8 with their dimensions and power, not only reduces costs but also generates an annual energy gain of 691.2 kWh, as shown in Table 9. These systems are aligned with Sustainable Development Goal (SDG) 7, promoting a transition towards clean and technological energy in cities by reducing CO_2 emissions and glare (light pollution). Additionally, they contribute to electricity reliability and security by operating independently of the electrical grid, benefiting growing communities by improving accessibility and resilience.

Figure 22. Bike path.

Table 8. Characteristics of public lighting solar panel [48,49].

	Manufacturer	City	Country	Distributor	Dimensions (mm)	Peak Power (W)	Efficiency (%)
FP Series Solar Street Garden Lights with Motion Sensor	Obluesmart	Shenzhen	China	Panel Solar Peru	765 × 665 × 30	80	20

Table 9. Production of solar panels for public lighting.

	kW Diary per Panel	Diary Solar Radiation	Efficiency (%)	#Panels	N° Days per Month	Total Monthly kWh	Total Annual kWh
Solar Street Panel	0.08	6.0	20	20	30	57.6	691.2

4. Discussion

The design of educational infrastructure plays a crucial role in enhancing overall educational quality and the physical and mental health of its users. This approach, aligned with Sustainable Development Goals (SDGs), such as 3 (Good Health and Well-being), 4 (Quality Education), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 13 (Climate Action), provides tailored spaces for both traditional and innovative educational methodologies, integrating areas for extracurricular activities, playgrounds, green spaces, and gardens. In this way, it transforms the educational environment into a multifunctional space that promotes comprehensive well-being and greater connection with the surroundings.

Imagine Montessori School La Pinada in Valencia, Spain, has achieved BREEAM Excellent and Verde 4 hojas certifications. This innovative building reduces energy consumption by 44.8%, primarily through photovoltaic panels that provide up to 48.2% of the annual energy consumed, alongside a cumulative savings of 68.9% compared to conventional buildings. Advanced water management strategies, such as low-consumption plumbing installations and rainwater recovery for irrigation, save up to 20.6% of water annually compared to conventional buildings. Additionally, construction practices like wooden windows and wood fiber insulation have reduced CO2 emissions by 47%, equivalent to 392.37 metric tons of carbon dioxide annually, similar to the positive impact of a 150-hectare forest. With an investment of EUR 4 million, the school has achieved energy savings up to 70% higher than traditional schools thanks to LED technology, continuous insulation, efficient solar protections, adjustable ventilation systems, and sound-absorbing materials that promote a sustainable learning environment [50,51].

In Latin America, "Una Escuela Sustentable" in Jaureguiberry, Uruguay, stands out as a model of free public education with a strong focus on material reuse and the maximization of natural resources such as solar light and rainwater. The school uses 60% recycled materials, including 2000 tires and 5000 glass bottles, alongside 40% traditional materials. Its design includes photovoltaic panels for electricity generation and an indoor garden [52]. Additionally, it features a south-facing retaining wall to enhance thermal inertia and collect rainwater. To reduce pollution, the school has a wastewater treatment system that includes a septic tank and an outdoor wetland [53].

The design proposal integrates eco-friendly materials, including double-layered wooden structures with 0.30 cm insulation, which effectively retains heat within the panels. Additionally, green roofs with vines are implemented for temperature regulation. It also utilizes movable windows and gable roofs for thermal control, solar protection, lighting, and natural ventilation. Prefabricated adobe walls with plaster coating ensure an optimal thermal transmittance of 2.2 W/m^2K. Clean technologies are integrated, including 74 photovoltaic panels in classroom pavilions generating 17,582.40 kWh annually for the educational center's operation, and 20 photovoltaic panels producing 691.2 kWh annually for public lighting, along with photovoltaic pavers, meeting energy needs. Furthermore, the proposal includes using dry toilets for compost production and gray water reuse through biofilters. Vertical gardens with native vegetation reduce water usage and maintenance costs, promoting connection with nature through student-managed cultivation, which also contributes to their nutrition.

5. Conclusions

The proposal develops comfort strategies that allow users to have direct contact with nature through the use of bio-gardens and orchards, promoting a healthier and more pleasant environment. Clean energy strategies are applied, such as the use of photovoltaic panels for natural lighting, taking advantage of the surrounding solar radiation, and achieving significant economic savings. Additionally, the proposal includes passive strategies such as the use of non-polluting materials like wood, thus avoiding climate change impact and creating an ideal learning environment that promotes environmental sustainability. Finally, the use of dry toilets to produce compost and biofilters for gray water reuse contributes to a sustainable and self-sufficient design, improving the quality of life for users, protecting the environment, and reducing operational costs.

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