Evaluation of the impact of the LWS vertical garden prototype on the environmental comfort of a single-family house at 3800 m.a.s.l.

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Abstract In this study, the impact of the implementation of a vertical garden LWS on indoor air quality and thermal comfort in an urban house in Puno City, located in the Collao plateau in the Peruvian Andes, characterized by extreme environmental conditions and low temperatures. The purpose was to evaluate the impact of the LWS vertical garden prototype on the environmental comfort of a single-family house located at 3800 m.a.s.l. A vertical garden prototype was built with five 1.5 m long modular planters, oriented to the northeast and implementing a drip irrigation system. The air quality and thermal behavior of the vertical garden inside the house were compared, demonstrating its positive effect on thermal comfort and air quality. CO2 concentration decreased significantly from 489.37 ppm to 445.10 ppm in the garden. Also, the levels of total volatile organic compounds (TVOC) and formaldehyde (HCHO) were significantly reduced, showing the effectiveness of the garden in absorbing atmospheric pollutants. Likewise, an increase in average temperature from 16.49°C to 18.07°C and an increase in relative humidity from 41.83% to 48.81% was observed, suggesting that the garden contributes to mitigating low temperatures. In addition, the modular augmentation of a planter was found to contribute to improved indoor air quality. These results highlight the viability of this technology as a sustainable solution to optimize the indoor environment. It was also observed how the LWS vertical garden adds an aesthetic and spatial dimension to indoor spaces, enhancing spatial perception through the introduction of vertical vegetation and dynamic interaction with natural light.

Keywords: thermal comfort, vertical garden, air quality

1. Introduction

In an ever-evolving world, human life is facing increasing challenges, including amplified risks, reduced quality, increased stress, and disease proliferation. These problems have been identified as direct manifestations of the excessive increase in pollution (Lartiga, 2016). The construction of housing, without considering the climatic particularities of its location, becomes a crucial factor affecting thermal comfort and internal habitability, negatively affecting the quality of life of residents (Luna, 2016).

Environmental comfort has emerged as a fundamental indicator in any work environment, gaining progressively greater relevance. In this context, air quality is revealed to be an essential component for improving the well-being of building occupants through the implementation of innovative solutions, such as vertical gardens (Molina and Veas, 2012; Perini et al, 2017). Recent research has identified urban morphology and the thermal properties of building materials as primary determinants of microclimate modification (Ordonez & Ximena, 2014).

This study focuses on the critical relevance of air quality in dwellings, especially as urban areas grow and face various environmental challenges (Gil et al, 1997). Indoor environmental quality (IEQ) analysis of buildings focuses on occupant satisfaction, considering key aspects such as thermal comfort and indoor air quality (Lai et al, 2009). In addition, interactions with vegetation have been shown to positively impact thermal comfort, air quality, and resident health, providing noticeable benefits to indoor spaces (Shanahan et al, 2016).

Vertical greening systems have emerged as an ecologically beneficial and environmentally effective response in urban environments. These systems not only improve air quality but also function as absorbent agents of atmospheric pollutants (Wong et al, 2010; Carbajal et al, 2023). Vertical gardens, as contemporary architectural design elements, not only fulfill an aesthetic function but also contribute to energy savings and added value to properties due to their passive approach (George, 2020).
The present project was carried out in a single-family house in the city of Puno, located in Sierra (Andes) of southern Peru, on the border with Bolivia, at the UTM coordinates WGS84 19 L 389926.62 E and 8248418.36 S (Vicuña, 2022). The deterioration of air quality in the region is a result of industrial activities, vehicle smoke emissions, vegetation burning, garbage disposal, and maritime and air traffic (Rodriguez et al., 2013). In recent decades, the city of Puno has faced increasing pollution problems due to the disordered growth of its urban population, which has negatively affected biodiversity, the environment, and people’s health (Quispe et al., 2021; Mamani et al., 2023). The orientation of a dwelling should be aimed at providing maximum comfort to the user, allowing a better quality of life, especially in an era when pollution levels in the environment are high (Ledespema & Carlos, 2020). Housing represents a social need throughout the contemporary world (Garcia, 2005). In this context, the objective of the present study was to evaluate the impact of the LWS vertical garden prototype on the environmental comfort of a single-family house located more than 3800 meters above sea level to mitigate the effects of climate change on a population vulnerable to the transformation of its natural environment.

2. LWS vertical garden design

The Living Wall Systems (LWS) vertical garden prototype is composed of five modular planters made of 4-inch diameter, 5-foot-long PVC pipes. These pipes weigh 1.21 kg and are sealed at the ends with 4-inch pipe plugs that weigh 0.107 kg. This makes them corrosion resistant and lightweight. Each modular planter features eight 3-in. diameter top holes, which are located at 17 cm intervals, as illustrated in Figure 1(a). Lemon balm (Melissa officinalis) seedlings weighing approximately 0.25 kg each were placed in these holes. These plants were selected for their dense vegetation and ease of care. For adequate growth, a special lightweight substrate, composed of sawdust, soil, rice husks, worm castings, and compost at proportions of 2:1:2:2:2:4 was used. Each planter contains approximately 6 kg of this substrate.

The irrigation system adopted was drip irrigation through a gravity system with a flow regulator and a 4-liter water tank (weight without water: 0.2 kg) assigned to each planter. These tanks were attached to the wall using 10 mm × 3 mm stainless steel hooks and 2 mm galvanized wire. In addition, 4 m long irrigation hoses, divided into 1.5 m, 1 m, 0.8 m, 0.50 m, and 0.2 m segments, were used for vertical irrigation. A four-meter long 7 mm hose, divided into 1.4 m segments, was also used for horizontal irrigation, and was located inside each planter, as shown in Figure 1(b).

The prototype was installed on a northeast-facing wall using 20 mm × 3 mm stainless steel hooks anchored to the wall to support the planters. These were placed consecutively at 20 cm intervals, as illustrated in Figure 2(b). After plant maturity, each planter weighed approximately 9.5 kg.

The air quality and thermal comfort of the LWS vertical garden prototype were calculated. To measure the variables, a JD brand instrument with serial number 3002 was used, which had a measurement range of CO₂ from 350 ppm to 2000 ppm, TVOC from 0.000 MG/M to 2000 ppm, and HCHO from 0.000 mg/m to 1.000 mg/m (Diemer, sf). In addition, a Uni-T brand thermohygrometer, model UT333, with a temperature range of -10°C to 60°C, an accuracy of ± 1°C, and a humidity range of 0% to 100% with an accuracy of ± 5% RH was used (Tecnologia Uni-Trend Limited, sf).

The data were collected in two stages: the first took place in summer without the presence of the vertical garden, and the second took place with the LWS vertical garden prototype in the summer and winter seasons. The recordings were made at three-hour intervals, at 6:00, 9:00, 12:00, 15:00, 18:00, 21:00 and 00:00 hours. Measurements were taken at six points at a height of 1.2 m and five points on the first level, plus one point on the second level, as shown in Figure 2. The data were tabulated on log sheets for subsequent digitization in TXT format.

Column headings were assigned to the following variables: day (D), point (P), experiment (E), carbon dioxide (CO₂) (O), formaldehyde (HCHO) (HC), volatile organic compound (TVOC) (TV), temperature (T) and humidity (H). The points were assigned a coding (P-1, P-2, P-3, P-4, P-5, P-6) and the experiments were assigned (1 and 2), where 1 represents the absence of the LWS vertical garden prototype and 2 represents the presence of the LWS vertical garden.

Student’s t test was used to analyze the differences between two sets of small, independent samples that had a normal distribution and equal variabilities (Sanchez, 2015). The process involved several steps: first, data collection; second, coding; third, classification; fourth, data processing or tabulation; and fifth, data presentation. The data were processed using R v4.3.1 software from the R Foundation.
**Figure 1** (a) Design and dimensions of the modular garden module. (b) Composition of the LWS vertical garden prototype.

**Figure 2** Location of monitoring points at the (a) first level and (b) second level.
3. Results and discussion

3.1. Indoor air quality in buildings

A total of 1986 data points were collected, thoroughly tabulated, and categorized for analysis. The development process of the vertical garden prototype was carried out in the interior courtyard space of a single-family house. The implementation of the LWS vertical garden prototype took a period of three weeks, during which precise methodological stages were followed. During the first week, the necessary materials were obtained and meticulously selected according to their specific characteristics.

During the second week, a meticulous assembly process was carried out in which the planters were strategically integrated, considering the principles of spatial distribution and ensuring aesthetic harmonization with the environment. The installation of the irrigation system is vital for the optimal functioning of the prototype, guaranteeing its correct performance and its capacity to provide the right amount of water to the plants.

Finally, in the third week of the process, lemon balm (*Melissa officinalis*) seedlings, which were selected for their adaptability to the study environment, were acquired. A highly specialized substrate was prepared by combining specific components such as sawdust, soil, rice husks, worm humus, and compost in calculated proportions of 2:1:2:2:2:4. The plants were transplanted into the planters, ensuring that the proper environment was provided for their healthy growth and the development of their characteristic dense vegetation. The implementation phase of this vertical garden prototype involved not only a painstaking process but also an effort to obtain reliable and valuable data for subsequent analysis.

The comparison data correspond to (CG) the control group (without the prototype) and (EG) the experimental group (with the prototype). It has been shown that between both groups, there is a significant difference in both groups, with a p value = 0.001 for temperature, CO\(_2\) humidity, TVOC, and HCHO. These results provide valuable insight into the behavior of the LWS vertical garden prototype in a very particular context, the Southern Andes of Peru, a high Andean region where environmental conditions are notoriously harsh due to its altitude and the climatic variability that prevails in the area. It is important to understand that this geographical location, which is characterized by cold and extreme conditions, adds a significant layer of challenge to the adaptation and operation of any system of this type.

In the control group, an average temperature of 16.49°C was observed. This temperature is notably low, suggesting the influence of the cold climate of the high Andean zone. In addition, the average relative humidity under these conditions was 41.83%, indicating a relatively dry environment associated with the climatic characteristics of high altitudes. However, in the experimental group with the LWS vertical garden prototype, an average temperature of 18.07°C was recorded. Although this is still a relatively low temperature, the presence of the prototype contributes to a slight increase in the ambient temperature. This suggests that the vertical garden system can mitigate the effects of the cold weather characteristics of the region. The relative humidity under these conditions reached an average of 48.81%, indicating that the prototype influenced the ambient humidity, contributing to a greater retention of moisture in the air, as shown in Table 1.

In terms of air quality, the average carbon dioxide (CO\(_2\)) concentration was significantly lower in the experimental group (445.10 ppm) than in the control group (489.37 ppm). This reduction is related to the ability of the prototype to absorb CO\(_2\) and improve the indoor air quality. The concentrations of total volatile organic compounds (TVOCs) and formaldehyde (HCHO) were also lower in the experimental group than in the control group, suggesting that the prototype could contribute to a decrease in these substances that can affect air quality, as shown in Table 1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>T</th>
<th>H</th>
<th>CO(_2)</th>
<th>TVOC</th>
<th>HCHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG(^2)</td>
<td>16.49 ± 0.12</td>
<td>41.83 ± 0.41</td>
<td>489.37 ± 6.14</td>
<td>0.12 ± 0.00</td>
<td>0.02 ± 0.00</td>
</tr>
<tr>
<td>EG(^2)</td>
<td>18.07 ± 0.15</td>
<td>48.81 ± 0.33</td>
<td>445.10 ± 3.94</td>
<td>0.06 ± 0.00</td>
<td>0.01 ± 0.00</td>
</tr>
</tbody>
</table>

(1) Control group without the prototype, (2) Experimental group with the prototype.

It is essential to note that these results, obtained in a high Andean area characterized by extreme environmental conditions, provide valuable insights into the potential of vertical garden systems in indoor environments. The prototype's ability to attenuate temperature and humidity variations, as well as to improve air quality, is promising, especially considering the unique climatic adversities of the region. These results underscore the relevance of addressing the adaptation of ecological and sustainable solutions in extreme environmental contexts and highlight the need for future research to deepen the understanding of these effects and their implications in similar regions.

3.2. Increasing indoor air quality in buildings

A second prototype (2P) has been developed, which has been improved by increasing one planter unit, for a total of 5 planters. In comparison, the original prototype (1P) consists of 4 planters. The comparison data between 1P and 2P are as follows. Regarding temperature, the data indicate that no significant difference was observed between the original prototype.
(1P) and the second prototype (2P). The calculated statistical significance is 0.65. This conclusively suggested that the temperature remained at similar levels in both groups, even after the addition of an extra planter unit in the second prototype. On the other hand, the results show that there are significant differences in humidity, carbon dioxide (CO₂) concentration, total volatile organic compound (TVOC) content, and formaldehyde (HCHO) content between the two prototypes. The statistical significance values associated with these indicators are all less than 0.05, indicating that the addition of a planter unit has had a measurable and relevant impact on these parameters.

These results confirm that the incorporation of an additional planter unit in the second prototype (2P) has noticeable effects on the ambient humidity, as well as the CO₂, TVOC, and HCHO concentrations. The environmental conditions in which the green walls are located can vary their impact to a greater or lesser extent. These results confirm that the incorporation of an additional planter in the second prototype (2P) has noticeable effects on the environmental humidity, as well as on the concentrations of CO₂, TVOC, and HCHO due to the environmental conditions in which the green walls are located, which can vary their impact to a greater or lesser extent, as proposed by Charoenkit et al. (2020) and Oquendo-Di et al. (2022). This variation in prototype design has been shown to have a significant influence on the regulation of these environmental factors.

These findings have relevant implications for the optimization of vertical garden prototypes, particularly in situations where humidity control and air quality are relevant aspects, the system also protects indoor thermal conditions as it sustains them Martínez et al. (2023). The results strongly support the notion that the inclusion of more planter units can positively influence the ability of the prototype to modify environmental conditions, improve air quality and contribute to CO₂ reduction. Furthermore, in Table 2, when examining temperature, the data reveal that both prototypes, 1P and 2P, maintain very similar values which, together with the overlapping confidence intervals, indicate that the incorporation of an additional planter unit in prototype 2P has not had a significant effect on the temperature of the indoor environment. The humidity of prototype 2P is greater than that of prototype 1P. This difference suggests that the inclusion of an additional planter unit in prototype 2P influences the humidity regulation of the indoor environment, resulting in higher relative humidity levels. The CO₂ concentration in prototype 2P was slightly lower than that in prototype 1P. This variation in results could be indicative of the potential effectiveness of the 2P prototype in improving indoor air quality. The similarity to the green wall concept proposed by Mazzoli et al. (2013) and Sánchez-Reséndiz et al. (2018) suggests that the 2P design could offer comparable benefits by reducing the concentration of harmful compounds indoors. However, further studies are required to fully evaluate the impact and effectiveness of this design in different environmental settings and for different applications.

Table 2 Prototype 1 and 2 behaviors.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>T</th>
<th>H</th>
<th>CO₂</th>
<th>TVOC</th>
<th>HCHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1P</td>
<td>16.45 ± 0.15</td>
<td>30.54 ± 0.29</td>
<td>444.98 ± 3.92</td>
<td>0.068 ± 0.0</td>
<td>0.019 ± 0.0</td>
</tr>
<tr>
<td>2P</td>
<td>16.55 ± 0.14</td>
<td>41.62 ± 0.41</td>
<td>432.42 ± 3.63</td>
<td>0.055 ± 0.0</td>
<td>0.016 ± 0.0</td>
</tr>
</tbody>
</table>

The results indicate that the design of the prototype, specifically in terms of the number of planters, can have measurable effects on the regulation of the indoor environment, benefiting both humidity and air quality. In addition to the tangible impacts on parameters such as temperature, humidity, and air quality, it is essential to highlight the aesthetic and spatial effects that the LWS vertical garden introduces into the indoor environment, as shown in Figure 3. This technology not only is limited to improving environmental conditions but also significantly influences the visual and spatial quality of the environment, as in an urban landscape Omrany et al. (2016).

The impact of the LWS vertical garden prototype not only encompasses functional and environmental aspects but also considers its effects on the visual and spatial quality of the indoor environment. Through a visual comparison between the previous state without the prototype and the resulting transformation with the inclusion of the LWS vertical garden, its function as a focal point in the environment can be highlighted. The vertical vegetation structure adds a unique dimension that captures attention and creates a visual contrast to traditional surfaces. This green addition not only adds aesthetic value but also connects occupants to nature in an indoor environment.

Notably, even when the LWS prototype is in shadow, it still generates aesthetic visual richness, as shown in Figure 3(a). The vertical vegetation structure creates a play of light and shadow that adds depth and dimension to the environment. The effects of light and shadow on leaf and plant textures generate a dynamic visual palette, enriching the sensory perception of the space. This interplay between vegetation and light contributes to a visually interesting and pleasing environment, even under lower light conditions.

When the prototype is in daylight, this experience is further intensified. The natural light flooding the space interacts with the leaves and plant shapes, creating changing patterns of shadows and highlights. The combination of the verticality of the planters with the daylight reinforces the sense of height and spaciousness in the interior space. This play of natural light adds a poetic and dynamic dimension that transforms the perception of the environment, creating a constantly changing visual environment, as shown in Figure 3(b).
The spatial quality also undergoes a remarkable metamorphosis. The introduction of the verticality of the planters generates a sense of height that enriches the perception of space. The combination of textures and colors of the vegetation contrasts with that of conventional materials, revitalizing and beautifying the place.

![Figure 3](image1.png) Current status of the LWS prototype (a) without natural illumination and (b) with natural illumination.

4. Conclusions

The implementation of the LWS in a vertical garden significantly increased thermal comfort levels and improved indoor air quality. The results conclusively support that this innovative solution has a positive impact on temperature regulation and indoor air purification. Additionally, with the increase in one landscaping unit, the temperature increase is not significant. However, humidity, CO$_2$, TVOC, and HCHO significantly improved. This beneficial effect suggests that the progressive increase in the number of units could lead to a gradual and sustainable optimization of environmental conditions. The incorporation of the LWS vertical garden adds an architectural dimension that goes beyond functionality, becoming an element that revitalizes, beautifies, and gives character to interior spaces. This approach not only responds to the practical needs of air quality and thermal comfort but also introduces a sensory and aesthetic dimension that enriches the user's experience in these environments. The interaction of vegetation with natural light and architectural forms creates a dynamic and constantly changing visual experience.

Ethical considerations

Not applicable.

Conflict of interest

The authors declare no conflicts of interest.

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References


