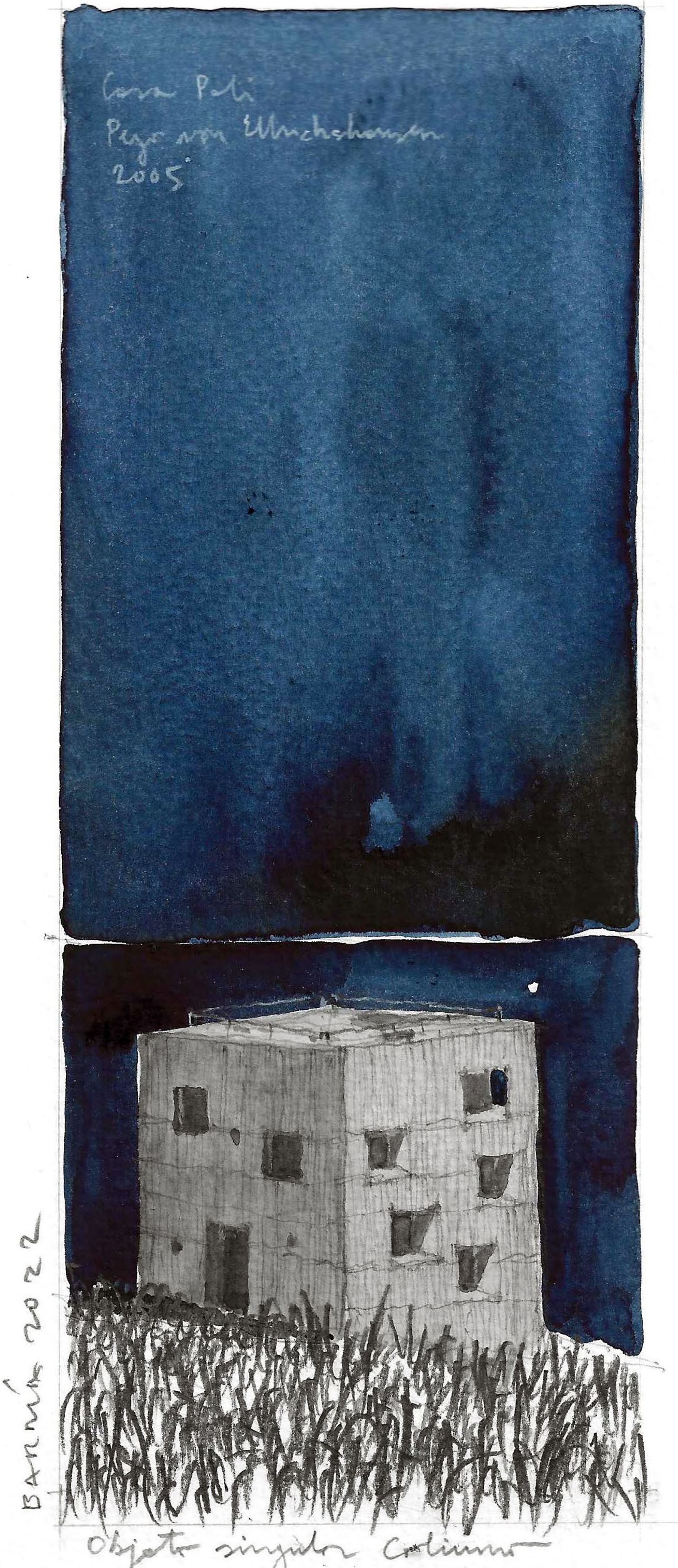

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Revista Hábitat Sustentable

ISSN 0719-0700
Vol. 14 N°. 2
dic
2024

UNIVERSIDAD DEL BIO BIO

HS

Revista
Hábitat
Sustentable

ISSN 0719 - 0700
Vol. 14 N°. 2
diciembre
2024

UNIVERSIDAD DEL BIO BIO

HS REVISTA HÁBITAT SUSTENTABLE V13N2

Revista del Departamento Diseño y Teoría de la Arquitectura
Universidad del Bío-Bío, Concepción, Chile

ISSN 0719-6466 versión online

DIRECCIÓN:
Avda. Collao 1202
CP: 4081112. Concepción, Chile
TEL.(56-41)3111409

Revista **HS** indexada en Scopus, SciELO, ERIHPLUS, Emerging Source Citation Index de Clarivate Analytics, Latindex Catálogo 2.0, Avery Index, DOAJ, Dialnet, Redib, EBSCO, Rebiun, JornalTOcs y ARLA.
HS se adhiere a la Declaración de San Francisco Sobre la Evaluación de la Investigación (DORA).

Revista Hábitat Sustentable es editada por el Facultad de Arquitecturas Construcción y Diseño de la Universidad del Bío-Bío, es financiada por el Fondo de Publicaciones Periódicas de la Vicerrectoría Académica, la Dirección General de Investigación, Desarrollo e Innovación y la Dirección de Postgrado de la Universidad del Bío-Bío junto al Programa de Información Científica Concurso Fondos de Publicación de Revistas Científicas 2018 Proyecto Código: FP180007

Editorial
Rafael Eduardo López-Guerrero, Maureen Trebilcock-Kelly
Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700/ Págs. 04 - 07
https://doi.org/10.22320/07190700.2024.14.02.00

EDITORIAL

En un sur global tan ávido de soluciones prácticas y accesibles, ¿qué tan próximos estamos entre la ciencia que producimos y su aplicación en respuestas tangibles? Si bien esta pregunta podría haber tenido validez en distintos momentos de nuestra historia, en la actualidad reúne nuevas y complejas variables alrededor de sí.

Desde sus inicios, la arquitectura y el ambiente construido se han propuesto fundamentalmente protegernos de riesgos y amenazas, naturales o no, incluidas aquellas asociadas a las inclemencias climáticas esperables cada año. Sin embargo, tal como lo venimos "sorpresivamente" experimentando, estas variables climáticas ya no son tan regulares: el tan famoso cambio climático. Esto nos ha colocado en un escenario de incertidumbre respecto a las soluciones que debemos proponer o adecuar en nuestros edificios. Así, en los últimos años han surgido dos palabras clave frente a este fenómeno: adaptación y mitigación. No obstante, para que el ambiente construido responda a estas directrices, debería diseñarse de manera que interactúe complementariamente con el contexto urbano y socioambiental en el cual está inserto. Esto implicaría mejorar el desempeño individual sin comprometer el de los demás.

Por otro lado, en este mismo contexto global hemos aprendido que no basta con optimizar la operación de los edificios. También debemos comprender y solucionar de mejor manera cómo disminuir los impactos asociados a la construcción a lo largo de todo su ciclo de vida. Pero las variables no hacen más que sumarse. Retomando la motivación inicial planteada en esta editorial, podemos agregar a la lista aspectos relacionados con la sustentabilidad económica y ambiental de nuestro sur global.

En el ciclo postcolonial de nuestro desarrollo social y tecnológico, persisten densas demandas de un hábitat propio, digno, accesible y sustentable, que sea capaz de adecuarse, además, a las solicitudes globales mencionadas anteriormente. En la inmensa heterogeneidad de nuestra región, y considerando el volumen de los posibles beneficiarios, los desafíos apuntan y persisten hacia soluciones concretas que puedan reproducirse de manera rápida y efectiva. Igualmente, las investigaciones dirigidas a la evaluación, solución, recuperación y adecuación del parque edilicio ya construido son nichos que aún precisan ser abordados. Si bien la demanda de nuevos edificios continúa creciendo, los existentes, con su inminente impacto a lo largo de su ciclo de vida, necesitan ser adaptados y preparados para mitigar impactos en el microclima, como el fenómeno de la isla de calor urbana. Conviene, además, priorizar las investigaciones en sectores socioeconómicamente vulnerables, ya que suelen ser los más afectados por un diseño ineficiente de edificios y ciudades.

Esta amplia gama de variables que las condiciones actuales exigen para la construcción de un hábitat sustentable también insinúa la oportunidad del trabajo colaborativo e interdisciplinario. Tramas complejas demandan convergencia de distintas áreas, como la climatología urbana, el trabajo social o los avances informáticos para optimizar procesos, por nombrar algunas. Así, cuando las preguntas de investigación conducen inherentemente al cruce de conocimientos, es probable que se obtengan mejores respuestas a partir de un enfoque interdisciplinario. Esta perspectiva será cada vez más bienvenida ante los enormes desafíos que enfrentamos en el presente siglo.

Asimismo, los rápidos avances tecnológicos que estamos experimentando representan grandes oportunidades de aplicación en nuestro campo. El desarrollo de modelos y el aprendizaje de máquinas como herramientas auxiliares constituyen un salto enorme en la comprensión de distintos fenómenos inherentes o correlacionados con el diseño y la construcción de edificaciones. Su utilización sigue siendo un área importante de exploración para generar soluciones tangibles, como la propuesta de estándares mejor ajustados a las nuevas demandas. Precisamente, esta es una de las áreas con mayores oportunidades en nuestra región, ya que, dentro de la vasta diversidad bioclimática y sociocultural, aún queda mucho trabajo por hacer. Las investigaciones que apunten a evaluar y adaptar estándares existentes o a impulsar la creación de nuevos códigos de edificación no solo son necesarias, sino apremiantes.

El contexto actual nos enfrenta, sin duda, a enormes desafíos para las próximas décadas, más aún considerando que las razones por las cuales hemos llegado hasta aquí todavía se resisten a ser transformadas. No obstante, habitamos una región con enormes potencialidades naturales, culturales y constructivas, llena de oportunidades de investigación aún por descubrir y desarrollar.

Desde la revista *Hábitat Sustentable*, invitamos a seguir pesquisando, innovando y colaborando para construir un sur global más justo y preparado para las demandas actuales y venideras. Reivindicamos nuestras habituales temáticas de interés y reforzamos la invitación a abordar aquellas mencionadas explícita o implícitamente en esta editorial, como los trabajos que beneficien el desempeño del parque edilicio existente, análisis de la relación entre el edificio y el clima urbano, estudios que contribuyan a la evaluación o creación de estándares de habitabilidad, las investigaciones interdisciplinares en el campo, aquellas que combatan la pobreza energética, y el uso de tecnologías informáticas para la optimización de modelos y procesos. Estas temáticas, o incluso el cruce entre ellas, son de especial interés para nuestra próxima edición. Con este llamado, les deseamos búsquedas amenas y productivas, siempre con un espíritu curioso, sensible e imaginativo.

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700/ Págs. 04 - 07
https://doi.org/10.22320/07190700.2024.14.02.00

EDITORIAL

In a Global South so eager for practical and accessible solutions, how close are we between the science we produce and its application to gaining tangible answers? Although this question might have been valid at different times in our history, it currently has new and complex variables.

Since its inception, architecture and the built environment have been fundamentally proposed to protect us from risks and threats, natural or otherwise, including those associated with the inclement weather expected every year. However, as we have been "surprisingly" experiencing, these climatic variables are no longer so regular, thanks to the famous climate change. This has left us uncertain about the solutions we must propose to adapt our buildings. Thus, two keywords have emerged to face this phenomenon in recent years: adaptation and mitigation. However, for the built environment to comply with these guidelines, it should be designed to interact complementarily with the urban and socio-environmental context in which it is inserted. This would imply improving individual performance without compromising that of others.

On the other hand, in this same global context, we have learned that optimizing building operations is not enough. We also need to better understand how to reduce construction impacts throughout their life cycle. But the variables only add up. Returning to the initial motivation behind this editorial, we can add to the list aspects related to our Global South's economic and environmental sustainability.

In the postcolonial cycle of our social and technological development, significant demands remain for a proper, dignified, accessible, and sustainable habitat that can adapt to the aforementioned global requests. In the immense heterogeneity of our region, and considering the volume of potential beneficiaries, the challenges point and persist towards concrete solutions that can be reproduced quickly and effectively. Likewise, research aimed at evaluating, solving, recovering, and adapting the already-built building stock is a niche that still needs to be addressed. Although the demand for new buildings continues to grow, existing ones, with their imminent impact throughout their life cycle, must be adapted and prepared to mitigate the effects of the microclimate, such as the urban heat island phenomenon. It is also advisable to prioritize research in socio-economically vulnerable sectors, since they are usually the ones most affected by inefficient design of buildings and cities.

This wide range of variables, which current conditions demand to build a sustainable habitat, also hints at the opportunity for collaborative and interdisciplinary work. Complex issues demand the convergence of different areas, such as urban climatology, social work, or IT progress, to optimize processes, to name a few. Thus, an interdisciplinary approach will likely yield better answers when research questions inherently lead to an intersection of knowledge. This perspective will be increasingly welcomed for the enormous challenges we will face this century.

Similarly, the rapid technological progress we are experiencing represents excellent opportunities for application in our field. The development of models and machine learning as auxiliary tools constitute a huge leap in understanding different phenomena inherent or correlated with the design and construction of buildings. Its use continues to be an important area of exploration to generate tangible solutions, such as the proposal of standards that better fit new demands. This is one of the areas with the most significant opportunities in our region since there is still much work to be done within the vast bioclimatic and socio-cultural diversity. Research aimed at evaluating and adapting existing standards or promoting the creation of new building codes is not only necessary, but urgent.

The current context undoubtedly confronts us with enormous challenges for the coming decades, even more so considering that the reasons why we have come this far still resist transformation. However, we live in a region with enormous natural, cultural, and constructive potential, full of research opportunities yet to be discovered and developed.

From *Hábitat Sustentable*, we invite you to continue researching, innovating, and collaborating to build a more just Global South prepared for current and future demands. We restate our usual topics of interest and reinforce the invitation to address those mentioned explicitly or implicitly in this editorial, such as works that benefit the performance of the existing building stock, analysis of the relationship between the building and the urban climate, studies that contribute to the evaluation or creation of habitability standards, interdisciplinary research in the field, those that fight energy poverty, and the use of computer technologies to optimize models and processes. These topics, or their transversal nature, are of special interest to our next issue. With this call, we wish you enjoyable and productive pursuits, always with a curious, sensitive, and imaginative spirit.

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700/ Págs. 04 - 07
https://doi.org/10.22320/07190700.2024.14.02.00

EDITORIAL

Em um sul global tão ávido por soluções práticas e acessíveis, qual é a distância entre a ciência que produzimos e sua aplicação em respostas tangíveis? Embora essa pergunta possa ter sido válida em diferentes momentos de nossa história, hoje ela reúne novas e complexas variáveis ao seu redor.

Desde sua criação, a arquitetura e o ambiente construído buscaram, fundamentalmente, proteger-nos de riscos e perigos, naturais ou não, incluindo aqueles associados às intempéries esperadas a cada ano. No entanto, como estamos "surpreendentemente" vivenciando, essas variáveis climáticas já não são tão regulares: a tão discutida mudança climática. Isso tem nos colocado em um cenário de incertezas quanto às soluções que devemos propor ou adaptar em nossos edifícios. Assim, nos últimos anos, duas palavras-chave emergiram diante deste fenômeno: adaptação e mitigação. Entretanto, para que o ambiente construído responda a essas diretrizes, ele deve ser projetado de forma a interagir complementarmente com o contexto urbano e socioambiental em que está inserido. Isso implicaria melhorar o desempenho individual sem comprometer o dos demais.

Por outro lado, nesse mesmo contexto global, aprendemos que não basta otimizar a operação dos edifícios. Também precisamos entender melhor e analisar como reduzir os impactos associados à construção durante todo o seu ciclo de vida. As variáveis, porém, não param de se acumular. Retomando a motivação inicial deste editorial, podemos adicionar à lista aspectos relacionados à sustentabilidade econômica e ambiental do nosso Sul Global.

No ciclo pós-colonial de nosso desenvolvimento social e tecnológico, persistem fortes demandas por um habitat próprio, digno, acessível e sustentável, que também seja capaz de se adaptar às demandas globais mencionadas anteriormente. Na imensa heterogeneidade de nossa região, e considerando o volume de potenciais beneficiários, os desafios continuam apontando para soluções concretas que possam ser reproduzidas de forma rápida e eficaz.

Da mesma forma, pesquisas voltadas para a avaliação, solução, recuperação e adaptação do parque imobiliário existente são nichos que ainda precisam ser abordados. Enquanto a demanda por novos edifícios continua a crescer, os edifícios existentes, com seu impacto iminente ao longo de todo o ciclo de vida, precisam ser adaptados e preparados para atenuar os impactos no microclima, como o fenômeno das ilhas de calor urbanas. Além disso, é importante priorizar pesquisas voltadas aos setores socioeconomicamente vulneráveis, pois eles costumam ser os mais impactados por projetos ineficientes de edificação e urbanismo.

Essa vasta gama de variáveis exigidas pelas condições contemporâneas para a construção de um habitat sustentável sugere, também, a oportunidade de trabalho colaborativo e interdisciplinar. Planos complexos requerem a convergência de diferentes áreas do conhecimento, como a climatologia urbana, o trabalho social ou os avanços da informática voltados à otimização de processos, apenas para citar alguns exemplos. Assim, quando questões de pesquisa conduzem inerentemente ao cruzamento de saberes, as respostas obtidas por meio de abordagens interdisciplinares tendem a ser mais eficazes. Tal perspectiva será cada vez mais bem-vinda frente aos desafios monumentais que enfrentamos neste século.

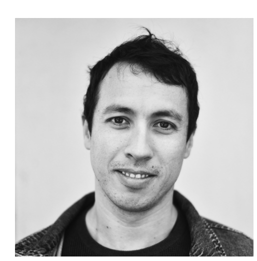
Paralelamente, os rápidos avanços tecnológicos que vivenciamos atualmente oferecem grandes oportunidades de aplicação em nosso campo. O desenvolvimento de modelos computacionais e o aprendizado de máquina (Machine Learning) como ferramentas auxiliares representam um avanço significativo na compreensão de diferentes fenômenos inerentes ou correlacionados ao projeto e à construção de edifícios. A aplicação dessas tecnologias continua sendo uma área fundamental de exploração para a geração de soluções tangíveis, como a proposta de normas mais adequadas às novas demandas. Essa é, justamente, uma das áreas de maior potencial em nossa região, considerando a vasta diversidade bioclimática e sociocultural, que ainda oferece amplas oportunidades de pesquisa e intervenção. Estudos que busquem avaliar e adaptar normas existentes ou fomentar a criação de novos códigos de construção não são apenas necessários, mas urgentes.

O contexto atual nos coloca, sem dúvida, diante de desafios enormes para as próximas décadas, especialmente considerando que as razões que nos trouxeram até aqui ainda resistem a ser transformadas. Contudo, habitamos uma região repleta de potenciais naturais, culturais e construtivos, com vastas oportunidades de pesquisa ainda por explorar e desenvolver.

Em nome da revista *Habitat Sustentável*, convidamos a comunidade acadêmica e profissional a continuar pesquisando, inovando e colaborando para construir um Sul Global mais justo e preparado para as demandas atuais e futuras. Reiteramos nossas temáticas de interesse habituais e reforçamos o convite para explorar os tópicos mencionados explícita ou implicitamente neste editorial, tais como trabalhos que promovam a melhoria do desempenho do parque imobiliário existente, análises das interações entre edifícios e o clima urbano, estudos voltados à avaliação ou criação de padrões de habitabilidade, pesquisas interdisciplinares, que promovam o combate à pobreza energética ou que estimulem o uso de tecnologias computacionais para a otimização de modelos e processos. Estas temáticas, assim como possíveis interseções entre elas, são de especial interesse para nossa próxima edição. Com este chamado, desejamos a todos que suas atividades de pesquisa sejam agradáveis e produtivas, sempre permeadas por curiosidade, sensibilidade e imaginação.

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700/ Págs. 04 - 07
https://doi.org/10.22320/07190700.2024.14.02.00

Rafael Eduardo López-Guerrero
Doctorado en Ciencias de la Ingeniería
Co-Editor Hábitat Sustentable, Profesor Asistente,
Departamento de Ciencias de la Construcción, Facultad de Arquitectura, Construcción y Diseño,
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0000-0002-5941-0421
rlopez@ubiobio.cl



Maureen Trebilcock-Kelly
Doctora en Arquitectura Sustentable
Editora Responsable Hábitat Sustentable, Profesora Titular,
Departamento Diseño y Teoría de la Arquitectura, Facultad de Arquitectura, Construcción y Diseño
Universidad del Bío-Bío, Concepción, Chile
https://orcid.org/0000-0002-1984-0259
mtrebilc@ubiobio.cl

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 08 -19
https://doi.org/10.22320/07190700.2024.14.02.01

THERMAL STUDY OF TRADITIONAL VENTILATED WALLS IN THE TROPICAL CLIMATIC CONDITIONS OF CATATUMBO, NORTE DE SANTANDER, COLOMBIA

Recibido 25/06/2024
Aceptado 16/10/2024

ESTUDIO TÉRMICO DE MUROS VENTILADOS TRADICIONALES EN CONDICIONES CLIMÁTICAS TROPICALES DEL CATATUMBO, NORTE DE SANTANDER, COLOMBIA

ESTUDO TÉRMICO DE PAREDES VENTILADAS TRADICIONAIS NAS CONDIÇÕES CLIMÁTICAS TROPICAIS DE CATATUMBO, NORTE DE SANTANDER, COLÔMBIA

Carmen Xiomara Díaz-Fuentes
Magister en Ciencia y Tecnología de Materiales.
Estudiante de Doctorado Gestión de la Innovación Tecnológica, Nodo de Innovación (UANDES) - Docente, Departamento de Arquitectura (UFPS)
Universidad de Los Andes - Universidad Francisco de Paula Santander, Bogotá - San José de Cúcuta, Colombia
https://orcid.org/0000-0002-8223-5887
carmenxiomaradf@ufps.edu.co

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 08 -19
https://doi.org/10.22320/07190700.2024.14.02.01

RESUMEN

La propuesta de investigación está orientada a identificar una serie de tipologías de muros de cerramiento ventilados tradiciones del mercado de la construcción, como calados, celosías y paneles metálicos con el fin de desarrollar un estudio térmico bajo condiciones climáticas del Catatumbo en Norte de Santander, Colombia. La metodología es teórica a través de simulaciones de transferencia de calor bajo el método de elementos finitos en ANSYS para identificar la relación entre la permeabilidad de superficies y la incidencia en el comportamiento de temperaturas y flujos de calor. Los resultados exponen que las tipologías más permeables, como calados y celosías, registran menos transferencia de energía y temperatura a las tipologías menos permeables, como los paneles metálicos. Además, demostró que existen otros factores como forma y propiedades térmicas de los materiales que conforman las unidades constructivas. Finalmente, el estudio térmico de muros ventilados consolida información técnica de alternativas de cerramiento tradicionales como guía de diseño y planificación de viviendas y edificaciones en zonas de posconflicto, con el fin de promover el confort y la calidad del hábitat en la población mencionada.

Palabras clave
ventilación, transferencia de calor, simulación, materiales de construcción

ABSTRACT

This research proposal aims to identify a series of typologies of traditional ventilated cladding walls of the construction market, such as fretwork, lattice, and metal panels, to conduct a thermal study under the climatic conditions of Catatumbo in Norte de Santander, Colombia. The methodology is theoretical. It uses heat transfer simulations under the finite element method in ANSYS to identify the relationship between the permeability of surfaces and the impact on the behavior of temperatures and heat fluxes. The results show that the more permeable typologies, such as fretwork and lattice, register less energy and temperature transfer than the less permeable typologies, such as metallic panels. It also showed other factors, such as the shape and thermal properties of the construction units' materials. Finally, the thermal study of ventilated walls consolidates technical information on traditional enclosure alternatives as a guide for designing and planning housing and buildings in post-conflict zones to promote comfort and habitat quality in the aforementioned population.

Keywords
ventilation, heat transfer, simulation, building materials.

RESUMO

A proposta de pesquisa está orientada a identificar uma série de tipologias de paredes de revestimento ventiladas tradicionais do mercado da construção, tais como tramas, treliças e painéis metálicos, a fim de desenvolver um estudo térmico sob as condições climáticas do Catatumbo no Norte de Santander, Colômbia. A metodologia é teórica por meio de simulações de transferência de calor com o método de elementos finitos no ANSYS para identificar a relação entre a permeabilidade das superfícies e a incidência no comportamento das temperaturas e dos fluxos de calor. Os resultados mostram que as tipologias mais permeáveis, como tramas e treliças, registram menor transferência de energia e temperatura em relação às tipologias menos permeáveis, como painéis metálicos. Mostraram também que existem outros fatores, como a forma e as propriedades térmicas dos materiais que compõem as unidades construtivas. Por fim, o estudo térmico de paredes ventiladas consolida informações técnicas sobre alternativas tradicionais de fechamento como guia para o projeto e o planejamento de moradias e edifícios em áreas pós-conflito, com o objetivo de promover o conforto e a qualidade do habitat da população mencionada.

Palavras-chave:
ventilação, transferência de calor, simulação, materiais de construção

INTRODUCTION

The incorporation of natural ventilation strategies in architectural projects not only benefits occupant comfort and well-being (Ji, Lomas & Cook, 2009; Pacheco Ochoa, Jiménez Pérez & Ramírez Pérez, 2021), it also has a significant impact on the building's energy efficiency and sustainability (Mercado et al., 2018; Balter, Ganem & Barea, 2020). Natural ventilation refers to the air circulation and flow process in a given space with strategic openings, conditioned by factors such as weather, wind direction, and facade orientation, among others (Giraldo & Herrera, 2017; Mercado et al., 2018; Pacheco Ochoa, Jiménez Pérez & Ramírez Pérez, 2021).

Natural ventilation, by optimizing air quality and comfort through indoor air renewals and temperature regulation, can improve aspects such as users' physical and mental health, achieving high levels of productivity for each space's activities (Pacheco Ochoa, Jiménez Pérez, & Ramírez Pérez, 2021). However, sick building syndrome appears when the design lacks natural ventilation systems. This is a state where a building has comfort issues, ergonomic risks for users, and the prevalence of diseases, among other aspects (Jansz, 2017). In other words, employing optimal ventilation systems in a building is a strategy that can prevent the spread of viral diseases such as coronavirus (Gómez-Porter, 2021; Álvarez Rodríguez, 2022).

However, ventilation is not just limited to openings such as windows or doors. There are geographical contexts with critical climatic conditions that, despite the presence of air inlets and outlets, this solution is insufficient and, therefore, the space is uninhabitable (Atkinson et al., 2009; Batterman et al., 2017; Vartires et al., 2018; Calama-González et al., 2019; Cedeño-Quijada et al., 2022). Faced with these situations, multiple cooling strategies, such as night ventilation, solar chimneys, and ventilated enclosures emerge, providing comfort and energy consumption savings (Giraldo & Herrera, 2017; Mercado et al., 2018; Balter, Ganem & Barea, 2020).

Authors have shown that the advantages vary according to the ventilation strategy implemented in the building. For example, night ventilation with the user intervening by opening windows achieves reductions between 4°C and 5°C depending on the space's height and volume. This translates into 50% energy savings compared to daytime consumption (Mercado et al., 2018). Similarly, building retrofits with ventilated envelopes on the facades reduces energy consumption by up to 32% (Balter, Ganem & Barea, 2020). Another less conventional solution, such as solar chimneys in roof systems, renews the air and reduces thermal loads without affecting the structure of a traditional dwelling (Giraldo & Herrera, 2017).

Although ventilation is a basic need for living, there are areas in the country marginalized by armed conflict and violence where security and life take precedence. Nevertheless, to ensure human rights throughout the country, the State University System—SUE of the Ministry of Education in Colombia—called upon institutions to build peace in post-conflict areas (UFPS, 2017; La Opinión, 2021).

Under this call, Francisco de Paula Santander University participated in sustainable social housing and territorial planning projects. As ventilation is a fundamental component in the architectural composition and considers factors related to the space's function, comfort, sustainability, and efficiency, this research embraces the call by evaluating the thermal behavior of a series of ventilated walls. These consider different construction units, such as fretwork, lattices, and panels. Using the finite element method, low heat transfer simulations were run in the ANSYS software, incorporating the climatic conditions of Ocaña, located in the Catatumbo region in Norte de Santander, Colombia. The aim was to estimate the thermal characteristics of ventilated and traditional construction solutions to provide information for designers, architects, and other professionals in the construction sector. In this way, the research results are theoretical contributions to choosing materials for social housing design and planning processes.

METHODOLOGY

The research methodology for the thermal study of the ventilated walls under the climatic conditions of the theoretical Catatumbo region is divided into three phases. The first phase consists of identifying the types of constructive solutions. The second phase considers the heat transfer simulations in ANSYS, and finally, the third phase analyzes the relationship between the permeability and the thermal performance of ventilated construction solutions.

PHASE I: IDENTIFICATION OF THE TYPES OF VENTILATED CONSTRUCTION SOLUTION

The construction units chosen for the set of traditional ventilated walls in this research are the star fretwork, square fretwork in clay, square fretwork in concrete, brick lattice, metal and cane (gradua) panel, and

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 08 -19
https://doi.org/10.22320/07190700.2024.14.02.01

metal grid panel, as shown in Figure 1. Their choice is linked to the Norte de Santander region's industrial ceramic and clay production. Therefore, most of the products use these materials to promote the use of local resources and the region's identity (Sánchez-Molina, González-Mendoza, & Avendaño-Castro, 2019).

The types of ventilated walls subjected to analysis consist of 1 wall with fired clay fretwork called *Estrella* or Star in the ceramic industry of Norte de Santander (VENT-1) (INDUARCILLA[1], 2020), 2 walls built with square fretwork, one in fired clay and the other in concrete (VENT-2, VENT-3), 3 lattice configurations with solid brick (VENT-4, VENT-5, VENT-6), 1 ventilated panel using *guadua*, a native Colombian plant similar to bamboo, and a metal frame (VENT-7) and 1 ventilated panel with a metal grill and frame (VENT-8), as shown in Figure 2. VENT-1, VENT-2, VENT-3, VENT-4, VENT-5, and VENT-6 are fixed walls, while VENT-7 and VENT-8 are types of enclosure with an access purpose, i.e., they are panel-type doors.

The ventilated walls are 2.40m high and 1.24m wide. The thickness and permeable area of the ventilated walls, recorded in Table 1 and Table 3, respectively, vary depending on the unit's measurements. This standardizes the measurements of the modules evaluated in the research.

PHASE II: HEAT TRANSFER SIMULATIONS IN ANSYS

The heat transfer simulations determine the ventilated walls' temperature distribution and heat flows. In this second phase, the ANSYS software, through the finite element method, requires 3D models in Initial Graphics Exchange Specification (IGES) format, as shown in Figure 2, the thermal conductivity of the materials used, and the climatic conditions of the municipality of Ocaña, Norte de Santander. Although Phase I initially describes the ventilated wall types, Table 1 records the coding and each study element's thickness and thermal conductivity.

As mentioned above, the municipality chosen for the simulation's climatic conditions is Ocaña, Norte de Santander, Colombia. Its geographical location in the Catatumbo region is ideal for setting up the environment, and although other municipalities have climatic conditions with higher temperatures,

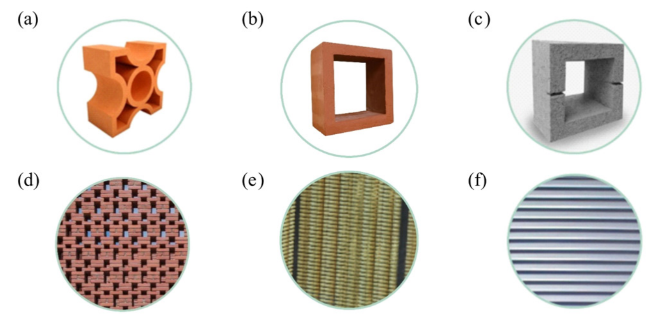


Figure 1. Types of the construction units chosen for the ventilated wall design: (a) star fretwork, (b) square fretwork in clay, (c) square fretwork in concrete, (d) brick lattice, (e) metal and cane (gradua) panel, and (f) metal grill panel. Source: Preparation by the author.

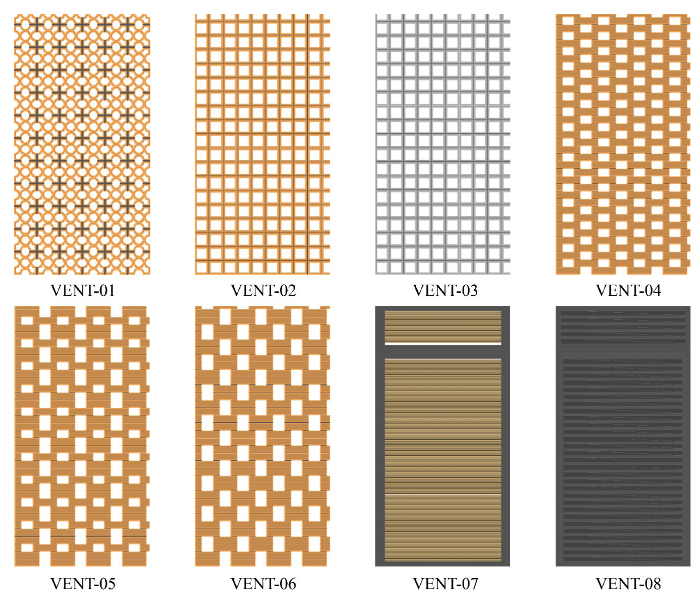


Figure 2. Ventilated wall types. Source: Preparation by the author.

only the data of the aforementioned municipality were obtained. However, thanks to tools such as GoogleEarth and MeteoRED, the climatic and geographical conditions of the municipality of Ocaña and the Catatumbo region can be visualized, as seen in Figure 3.

Below, Table 2 compiles the climatic data of the municipality of Ocaña in the Catatumbo zone of Norte de Santander. The program requires the environmental temperature, wind speed, and solar radiation to calculate the loads applied on the surfaces of the 3D model considering the conditions being simulated.

1 Association of Clay Industrialists of Norte de Santander (INDUARCILLA)

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Table 1. Coding and thermal properties of traditional ventilated wall types. Source: Preparation by the author.

Code	Wall type	Thickness (m)	Conductivity (W/mK)
VENT-1	Traditional fretwork (star)	0.085	0.407 (Vélez-Pareja, 2015)
VENT-2	Square fretwork in clay	0.12	0.407 (Vélez-Pareja, 2015)
VENT-3	Square fretwork in concrete	0.12	0.54 (Vélez-Pareja, 2015)
VENT-4	Brick lattice - Configuration 1	0.1	0.437 (Vélez-Pareja, 2015)
VENT-5	Brick lattice - Configuration 2	0.1	0.437 (Vélez-Pareja, 2015)
VENT-6	Brick lattice - Configuration 3	0.1	0.437 (Vélez-Pareja, 2015)
VENT-7	Ventilated panel with cane	0.076	Structure – 60.50 (Atsonios, Mandilaras & Founti, 2019) Guadua - 0.1417 (Ramírez-Sánchez, 2020)
VENT-8	Door with metal grill	0.076	60.50 (Atsonios, Mandilaras & Founti, 2019)

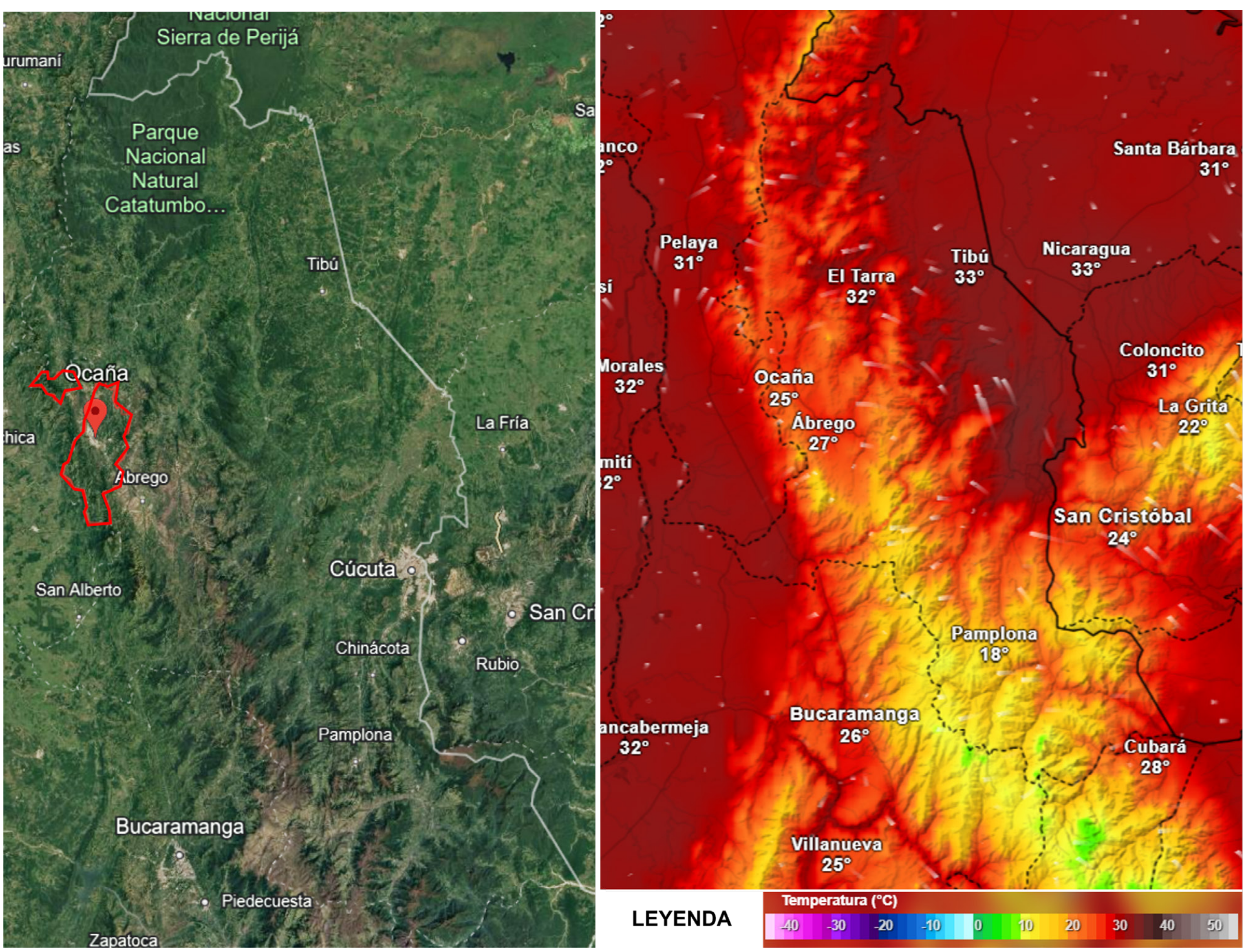

Figure 3. Geographical location of the municipality of Ocaña in the department of Norte de Santander, Colombia (Left) and thermographic map of the municipality of Ocaña and surroundings at noon (Right). Source: Google Earth and MeteoRed (2023)

Table 2. Climate data for the municipality of Ocaña, Norte de Santander. Source: Preparation by the author.

Data	Value
Coordinates	73°19'20.0"W; 8°14'16.0"N
Average temperature	21.8°C (IDEAM[2], 2010)
Wind speed	3 – 3.5 m/s (SUE, 2018)
Wind conductivity	0.26 W/mK (Çengel, 2007)
Incident solar radiation	539.3 W/m2 (Sources-Freixanet, 2013)

Table 3. Permeability of the selected traditional ventilated wall types. Source: Preparation by the author.

Code	Wall type	Non-permeable surface (m2)	Permeable surface (m2)
VENT-1	Traditional fretwork (star)	0.3245	0.6755
VENT-2	Square fretwork in clay	0.3916	0.6084
VENT-3	Square fretwork in concrete	0.3916	0.6084
VENT-4	Brick lattice - Configuration 1	0.6175	0.3825
VENT-5	Brick lattice - Configuration 2	0.6365	0.3635
VENT-6	Brick lattice - Configuration 3	0.6667	0.3333
VENT-7	Ventilated panel with cane	0.84	0.16
VENT-8	Door with metal grid	0.76	0.24

Once the formal parameters (3D models), the thermal characteristics of the materials, and the climatic conditions of the environment have been defined, they are configured in ANSYS through the finite element method. This follows the methodology of Colmenares-Uribe et al. (2023), which starts with the type of analysis system, followed by engineering data, geometry, model, configuration, and solution, and ends with the results of the simulations.

PHASE III: ANALYSIS OF THE RELATIONSHIP BETWEEN AIR PERMEABILITY AND THE THERMAL PERFORMANCE OF THE VENTILATED CONSTRUCTION SOLUTIONS.

The analysis of the relationship between the permeability and the thermal performance of the ventilated construction solutions discusses the impact of natural ventilation on the heat transfer of wall types designed to allow airflow. It compares permeability, heat flows, and temperature distribution.

RESULTS AND DISCUSSION

The results record formal and technical characteristics related to the permeability of the surfaces, thermal behavior, and heat flows of the traditional ventilated wall types selected for the research.

PERMEABILITY OF VENTILATED CONSTRUCTION SOLUTION TYPES

Table 3 compiles the areas of the permeable and non-permeable surfaces of the traditional ventilated wall types from one square meter set up with each construction unit. According to the formal characteristics and the data in Table 3, the surface with the highest airflow is VENT-1, which reaches up to 67.55% permeability. It is followed by VENT-2 and VENT-3, with percentages of 60.84%. To a lesser extent, the configurations of brick lattices (VENT-3, VENT-4, and VENT-5) have permeabilities between 36.35% and 38.25%. Finally, the ventilated panels with metal grills (VENT-8) allow an airflow

2 Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM)

Table 4. Record of maximum, minimum, and average temperatures of traditional ventilated wall types' outdoor and indoor surfaces. Source: Preparation by the author.

Code	Outdoor Temperature (°C)			Indoor Temperature (°C)		
		Minimum	Average	Maximum	Minimum	Average
VENT-1	43.54	38.80	43.58	26.95	22.21	26.71
VENT-2	44.16	41.75	44.16	24.85	22.44	24.42
VENT-3	43.16	40.90	43.16	25.08	22.82	24.72
VENT-4	50.89	45.25	50.89	31.15	25.51	32.40
VENT-5	54.38	44.60	54.38	34.83	25.05	35.53
VENT-6	54.40	44.60	54.40	31.53	24.99	35.56
VENT-7	59.59	42.57	59.59	42.56	28.94	50.75
VENT-8	51.75	49.18	50.41	50.03	44.05	51.73

of 25%, while the worst case is the ventilated panel with cane (VENT-7), which only leaves a margin of 16% ventilation.

TEMPERATURE DISTRIBUTION OF VENTILATED CONSTRUCTION SOLUTION TYPES

The temperature distribution results show maximum, minimum, and average outdoor and indoor temperatures, as shown in Table 4 and Figures 4 and 5. For the outdoor surfaces' temperatures, the maximum values match the averages. In contrast, the average indoor temperatures exceed the maximum values in most cases, except for VENT-1, VENT-2, and VENT-3.

The individual analysis of the thermal behavior examines the maximum, minimum, and average outdoor and indoor temperature differences. The individual analysis shows that VENT-6 has the most significant temperature difference between outside and inside, ranging between 19.60°C and 22.86°C. In second place, VENT-4 registers a difference of 19.74°C, followed by VENT-5 and VENT-2 with 19.55°C and 19.31°C, respectively. In fifth place, VENT-3 and VENT-1 differ by 18.08°C and 16.59°C each. Meanwhile, VENT-7 records temperature differences between 13.62°C and 17.03°C. In last place, VENT-8 registers the lowest values of all wall types between the outside and inside, where the difference only varies between 1.73°C and 5.12°C.

On the other hand, the comparative analysis is focused on identifying the best indoor thermal performances. The ventilated wall types with the lowest indoor surface values are VENT-1 and VENT-2. The thermal benefits offered by VENT-1 range from 0.23°C to 21.84°C. The wall types closest to VENT-1 are the square fretwork in clay and concrete (VENT-2, VENT-3) because the difference in minimum indoor temperatures does not reach 1°C. On the other hand, the solid brick lattices register between 2.79°C (VENT-6), 2.84°C (VENT-5), and 3.80°C (VENT-4) more than VENT-1. However, those with the worst performance compared to VENT-1 are VENT-7 and VENT-8, because indoor temperatures increase by 6.73°C and 21.84°C, respectively.

The second-best thermal performance is from VENT-2, as the comparative analysis of the maximum and average temperatures with the other wall types shows that they exceed it by between 0.23°C and 27.31°C. As in the previous case, VENT-3 registers a minimum difference between 0.23°C and 0.29°C. The similarity of the behavior is related to the shape of the walls' constructive units. The star fretwork comes second, recording an increase of between 2.10°C and 2.29°C in indoor temperatures. The solid brick lattice alternatives vary in temperature increases between 6.30°C and 7.98°C (VENT-4), 9.97°C and 11.10°C (VENT-5), and 6.68°C and 11.13°C (VENT-6). Finally, the metal frame panels are the least advantageous compared to the fretwork and lattice walls. However, VENT-7 has a lower temperature difference (17.71°C and 26.33°C) than VENT-8 (25.18°C and 27.31°C).

HEAT FLOWS OF THE VENTILATED CONSTRUCTION SOLUTION TYPES

The heat flow simulations of ventilated masonry walls show the energy concentration in the walls formed with fretwork, lattices, and grids that allow airflow. Figure 4 illustrates the heat flows obtained. In addition, Table 5 records the maximum and minimum values of the outdoor and indoor surfaces.

The analysis of the heat flows in Figure 6 and Table 5 shows that the flows with the highest concentration are the areas corresponding to the mortar joints and outdoor surfaces; on the contrary, the heat flows are concentrated mainly on the indoor surfaces of the construction units.

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 08 -19
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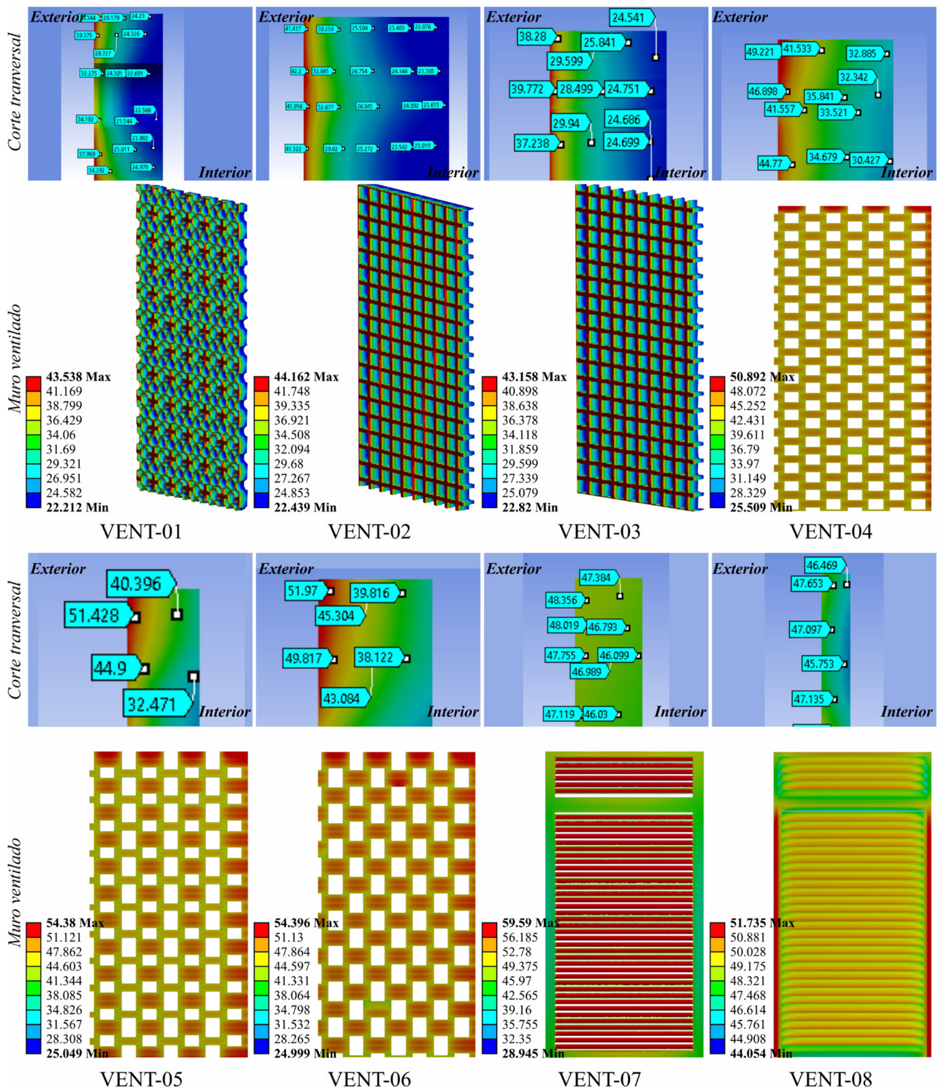

Figure 4. Temperature distribution (°C) of the selected traditional ventilated wall types. Source: Preparation by the author.

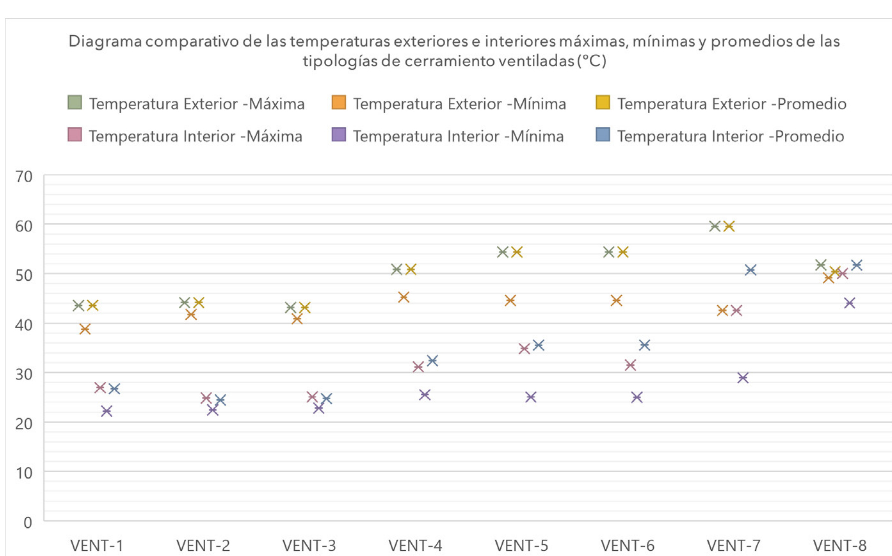

Figure 5. Comparative diagram of the ventilated enclosure types' maximum, minimum, and average outdoor and indoor temperatures (°C). Source: Preparation by the author.

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 08 -19
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Table 5. Record of maximum and minimum heat flows (W/m2) of the selected ventilated wall types. Source: Preparation by the author.

Code	Maximum heat flow (W/m2)	Minimum heat flux (W/m2)
VENT-1	325.78 – 365.78	1.91 – 42.34
VENT-2	267.55 – 343.03	3.38 – 22.25
VENT-3	290.35 – 325.98	5.32 – 23.1346
VENT-4	218.46 – 379.48	17.18 – 37.31
VENT-5	165.41 – 352.17	25.05 – 31.57
VENT-6	204.06 – 297.18	17.81 – 64.37
VENT-7	1231.20 – 3689.20	2.24 – 22.00
VENT-8	2105.50 – 3508.50	354.12 – 1405.60

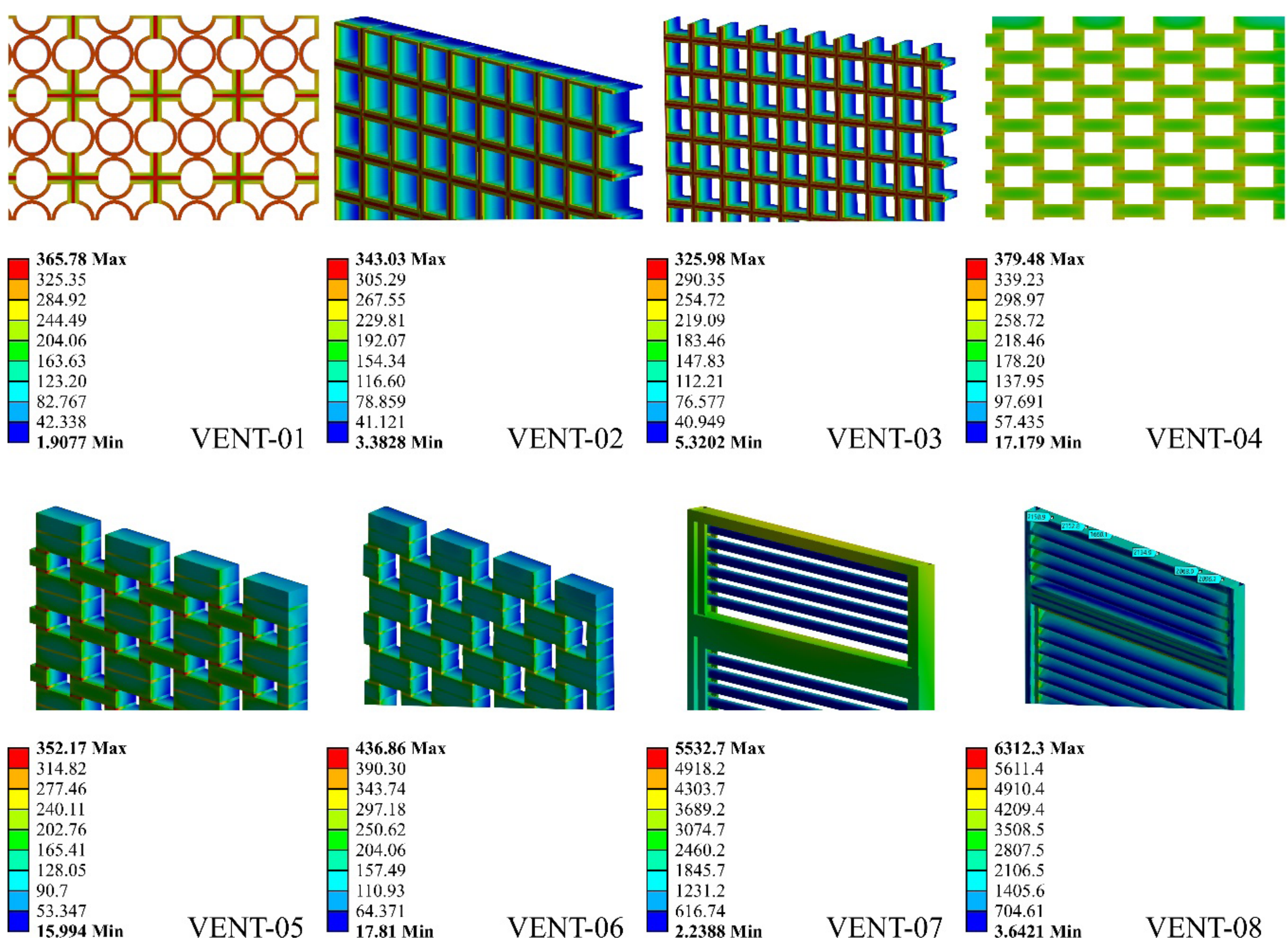

Figure 6. Heat flows (W/m2) of traditional ventilated wall types. Source: Preparation by the author.

The analysis of the maximum heat flows agrees that the areas with materials such as mortar in the joints and steel in the metal frames concentrate between 297.18 W/m^2 and 379.48 W/m^2 and between 1231 W/m^2 and 3689 W/m^2, respectively. Meanwhile, the outdoor surfaces with clay material concentrate between 10.93% and 53% less than those with higher energy.

Although the ventilated walls have common permeable areas for air circulation, this study observes three types of heat flow behaviors that vary according to the shape of the construction units. As mentioned above, the minimum heat flows are located on the indoor surfaces; however, the formal and material composition of the wall types varies as follows: In the case of the fretwork walls VENT-1, VENT-2, and VENT-3, the wall surfaces that connect the outside and inside dissipate between 88.43% and 93.51% of the heat, while the indoor surfaces dissipate almost all of the energy, namely 98.37% and 99.48%.

The second case recorded in the minimum heat flows is the solid brick lattice walls, VENT-4, VENT-5, and VENT-6. These register two zones with minimum values in the construction units' mortar joints and indoor surfaces. Although the mortar joints concentrate the heat flows with the highest concentration on the outside, the dissipated behavior of between 78.34% and 91.04% is reflected on the inside. Meanwhile, indoor surfaces increase heat absorption by between 92.89% and 95.47%.

Finally, the VENT-7 and VENT-8 panels show that the metal structure concentrates the most significant heat flows. However, the indoor surfaces of the frames dissipate between 59.94% and 89.91% of the energy. On the contrary, the horizontal elements of the *guadua* completely dissipate the heat concentration (99.41% and 99.34%).

RELATIONSHIP BETWEEN AIR PERMEABILITY AND THERMAL PERFORMANCE OF THE VENTILATED CONSTRUCTION SOLUTIONS

The thermal study of the selected ventilated wall types shows an inversely proportional relationship between the types' permeability and thermal behavior. Considering the data in Tables 3 and 4, the percentage of permeable surfaces affects the temperature decrease of the indoor surfaces.

The first example to demonstrate this statement is VENT-1, which has the highest percentage of permeability (67.55%) and, in turn, records the lowest indoor surface temperatures (between 22.21°C and 26.95°C). On the contrary, one of the ventilated panels with the lowest permeated surface, such as VENT-8 (24%), doubles the minimum temperatures of VENT-1.

Similarly, the square fretworks in clay and concrete (VENT-2 and VENT-3) also demonstrate that permeability influences the thermal benefits that a ventilated surface can obtain. In fact, with a lower permeability range, it reaches minimum temperatures similar to VENT-1 and even maximum and average indoor temperatures lower than VENT-1.

Although the least permeable typology is VENT-7, with just 16%, it shows that there are other factors in thermal performance, such as the material composition and its conductive properties. Considering the material properties (Table 1) and the heat flow analysis (Figure 4), the conductivity of the materials in the construction units also affects the thermal behavior because the capacity of the *guadua* to dissipate up to 99% of the energy concentrated on the indoor surfaces, allows it to achieve minimum temperatures similar to the minimum and average temperatures of the wall types with double (VENT-4, VENT-5, VENT-6) and up to quadruple (VENT-1) the permeability.

Similarly, the lattice configurations (VENT-4, VENT-5, VENT-6) reflect another factor to be considered in the wall design and thermal performance. Unlike VENT-1, VENT-2, and VENT-3, the lattices comprise a set of solid baked clay bricks joined by mortar joints, which implies that the brick, being a compact volume, concentrates more energy flow. On the contrary, the fretworks are constructive units designed exclusively to allow the flow of air and the entrance of light. Their volume comprises walls that generate the shape of the holes or perforations; therefore, the volume through which the energy is conducted is significantly reduced. For this reason, the lattice configurations only decrease the heat transfer on indoor surfaces by between 92.89% and 95.47%. At the same time, the fretwork types dissipate heat flows by between 98.37% and 99.48% compared to surfaces exposed to solar radiation.

CONCLUSIONS

In conclusion, incorporating natural ventilation strategies into architectural projects has multiple benefits. Apart from promoting occupant comfort and well-being, natural ventilation significantly impacts building energy efficiency and sustainability. The optimization of air quality and comfort through natural ventilation also improves users' physical and mental health.

The initiative of the State University System – SUE of the Ministry of Education in Colombia to build peace in post-conflict areas is an accelerator for the approach of research aimed at solving social problems. The relevance of the research is the commitment to set a precedent to explore new types of ventilated enclosures and evaluate the thermal behavior of different construction units from a specific context, to provide technical information that serves as a basis for choosing systems according to users' needs.

Thanks to the simulations, it is possible to understand the behavior of the heat transfer through the shape of constructive units. Considering the relationship of the comparative diagram between outdoor and indoor temperatures of Figure 5, the wall types with the best thermal performance are the VENT-1, VENT-2, and VENT-3 fretworks, followed by the solid brick lattices that increase their indoor temperatures by between 2.79°C and 3.80°C, compared to the VENT-1 fretwork. However, the metal frame types increase the indoor surface temperatures by between 6.73°C and 21.84°C compared to VENT-1 due to the high conductivity of their structures.

The types of ventilated walls selected with the highest percentage of permeability, i.e., fretwork walls and configurations with lattices, tend to show better thermal behavior and more efficient heat dissipation between the outside and inside. However, it is important to consider other factors, such as the shape and the materials used, to fully understand the impact of the permeability percentage on the ventilated walls' thermal behavior.

CONTRIBUTION OF AUTHORS CrediT

Conceptualization, C.X.D.F.; Data curation, C.X.D.F.; Formal analysis, C.X.D.F.; Acquisition of financing C.X.D.F.; Research, C.X.D.F.; Methodology, C.X.D.F.; Project management, C.X.D.F.; Resources, C.X.D.F.; Software. C.X.D.F.; Supervision, C.X.D.F.; Validation, C.X.D.F.; Visualization, C.X.D.F.; Writing - original draft, C.X.D.F.; Writing - revision and editing, C.X.D.F.

ACKNOWLEDGEMENTS

The author would like to thank Francisco de Paula Santander University's Research Group in Architecture and Alternative Materials (GRAMA) for supporting the proposal of constructive solutions for Rural Housing in Catatumbo.

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 20 -31
https://doi.org/10.22320/07190700.2024.14.02.02

COMPARISON AND CALIBRATION OF COMFORT INDICES FOR THE WARM SEASON IN A SEMI-ARID CITY OF NORTHWESTERN MEXICO

Recibido 24/06/2024
Aceptado 20/10/2024

COMPARATIVA Y CALIBRACIÓN DE ÍNDICES DE CONFORT PARA LA TEMPORADA CÁLIDA EN UNA CIUDAD SEMI-ÁRIDA DEL NOROESTE DE MÉXICO

COMPARAÇÃO E CALIBRAÇÃO DE ÍNDICES DE CONFORTO PARA A ESTAÇÃO QUENTE EM UMA CIDADE SEMIÁRIDA DO NOROESTE DO MÉXICO

Hiram Eduardo Urias-Barrera
Doctor en Ciencias
Profesor Investigador, Centro Universitario de Arte, Arquitectura y Diseño
Universidad de Guadalajara, Jalisco, México
https://orcid.org/0000-0003-0809-8842
Hiram.urias@cuaad.udg.mx

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 20 -31
https://doi.org/10.22320/07190700.2024.14.02.02

RESUMEN

El análisis sobre modelos de confort y el efecto de las condiciones microclimáticas extremas es importante para determinar la relación entre las afectaciones de salud en personas que realizan actividades en áreas abiertas. El trabajo propone un modelo psicofisiológico regional, para individuos con actividades físicas intensas (deportivas) en espacios públicos exteriores en clima cálido seco extremoso (Mexicali, Baja California), el que se contrastó con el Universal Thermal Climate Index con el propósito de calibrarlo y así establecer una base comparativa para formular pruebas de hipótesis que evalúen su aplicabilidad. Se encontró que el modelo regional alcanzó un 67% de aciertos en comparación del Universal Thermal Climate Index que obtuvo 31% de aciertos no calibrado y 53% de aciertos calibrado. Como conclusión de este proceso se destaca la pertinencia, precisión y eficiencia en la utilización de modelos específicos regionales sobre aquellos que tienden a generalizar las condiciones de la percepción térmica.

Palabras clave
modelo psicofisiológico, confort térmico, actividad intensa, calibración de escala.

ABSTRACT

The analysis of comfort models and the effect of extreme microclimatic conditions is vital to determine the relationship between health affectations in people who perform activities in open areas. This work proposes a regional psychophysiological model for individuals with intense physical activities (sports) in outdoor public spaces in an extremely hot dry climate (Mexicali, Baja California), which was contrasted with the Universal Thermal Climate Index to calibrate it and thus establish a comparative basis to formulate hypothesis tests to evaluate its applicability. It was found that the regional model achieved 67% accuracy compared to the Universal Thermal Climate Index, which obtained 31% accuracy when not calibrated and 53% accuracy when calibrated. The conclusion of this process highlights the relevance, accuracy, and efficiency of using specific regional models over those that tend to generalize the thermal perception conditions.

Keywords
psychophysiological model, thermal comfort, intense activity, scale calibration.

RESUMO

A análise dos modelos de conforto e o efeito das condições microclimáticas extremas são importantes para determinar a relação entre as complicações de saúde em pessoas que realizam atividades em áreas abertas. O artigo propõe um modelo psicofisiológico regional para indivíduos com atividades físicas intensas (esportivas) em espaços públicos externos em clima quente e seco extremo (Mexicali, Baja California), que foi contrastado com o Universal Thermal Climate Index para ser calibrado e, assim, estabelecer uma base comparativa para formular testes de hipóteses para avaliar sua aplicabilidade. Verificou-se que o modelo regional alcançou uma taxa de precisão de 67% em comparação com o Universal Thermal Climate Index, que obteve 31% de precisão sem calibração e 53% de precisão com calibração. A conclusão deste processo destaca a relevância, a precisão e a eficiência do uso de modelos regionais específicos em relação àqueles que tendem a generalizar as condições de percepção térmica.

Palavras-chave:
modelo psicofisiológico, conforto térmico, atividade intensa, calibração de escalas.

INTRODUCTION

Nowadays, thermal comfort and its effect on health is a concern (Peng et al., 2019), especially the thermal perception of individuals doing sports activities in outdoor public spaces. As mentioned by Nikolopoulou and Lykoudis (2006) and Manavvi and Rajasekar (2022), this is a feature that contributes to the quality of the urban environment, helps increase occupancy levels and use, and supports leisure, recreation, and health-related activities (Lai et al., 2020).

Thermal comfort can be understood in different ways. On one hand, it is the individual's mental satisfaction with the thermal environment. On the other hand, it can also be their physiological and psychological satisfaction with this environment (ISO 7730, 2006; Nikolopoulou & Lykoudis, 2006; Manavvi & Rajasekar, 2021). In this sense, the convergence of the subjective and objective parts of thermal perception and the search for comfort are determined in the adaptive processes. Even so, thermal comfort is a complex process to define, evaluate, and study, making it difficult to establish an appropriate concept (Dashrath-Khaire et al., 2021).

Hence, researching the effects climates have on individuals' health is essential today (González-González, 2021). New trends have focused on understanding the relationship between weather conditions and individual's thermal perception in outdoor public spaces and, as in the case presented, for intense sports activities (metabolic rate 600w/m^2) and in extreme dry hot climates (de Dear, 2011; Candido et al., 2012; Fernández García et al., 2012; Tumini et al., 2015; Jiaqi et al., 2022; Liu et al., 2023).

The literature reviews list up to 140 comfort indices (Epstein & Moran, 2006; Carlucci & Pagliano, 2012; De Freitas & Grigorieva, 2015). Hence, the relevance of studies that develop and compare indices that aim to establish, measure, and validate people's thermal responses.

It is important to mention that there are different types of comfort models: univariate ones such as those developed by Martínez-Bermúdez y Rincón-Martínez (2024), Nuñez et al. (2024), Martín del Campo et al. (2020), Rincón et al. (2020), López-Cañedo et al. (2021), and Bojórquez et al. (2014) that consider the correlation between a meteorological variable and thermal sensation. On the other hand, there are multivariate models and temperature indices, such as the Actual Sensation Vote – ASV - (Nikolopoulou & Lykoudis, 2006), the Standard Effective Temperature, -SET-, Predicted Mean Vote – PMV and the Universal Thermal Climate Index (UTCI), developed to link meteorological conditions with thermal sensation (Fang et al., 2019). These are based on the user's thermal balance with the surrounding environment, the processes of human thermoregulation (physiological aspects: metabolism, sex, age, health status), and psychological aspects (adaptation, tolerance, expectation, and experience, in some cases).

Numerous indexes have evaluated comfort in indoor spaces. However, only a few can be used to evaluate thermal perception and comfort in outdoor spaces. There are fewer still on people who do sports or intense activities in their different magnitudes - as is the case of the model in this work - making studies more complex due to the alteration of people's metabolic, thermoregulation, and thermal balance issues. Thus, developing a comfort index or model is further complicated by the specific characteristics of open urban spaces and the users' conditions (Johansson, 2006), given the different aspects of the sensation and thermal comfort process (expectation, experience, adaptation, clothing, exposure time, etc.) involved. Psychological and cultural aspects have also begun to be considered for their development. (Jendritzky, de Dear & Havenith, 2012).

UTCI is one of the most widely used indices and is currently a reference for developing other physiological adaptation models to generate equivalent temperature indices (Jendritzky, de Dear & Havenith, 2012). Studies such as those of Tumini and Pérez (2015) and more recent ones like Jing et al. (2024), Liu et al. (2023), Boussaidi et al. (2023), Manavvi and Rajasekar (2023), and Ghani et al. (2021), Barcia-Sardiñas et al. (2020), and Marchante y González (2020), have compared it with other similar indices to demonstrate its reliability and applicability by correlating its results and thus establishing its efficiency when applied. In some cases, comparisons and calibrations have been made, such as those by Monteiro and Alucci (2009), establishing the indices' applicability or efficiency.

Thus, based on the aforementioned works, to compare the indices, it must be considered that both are calculated using meteorological variables that affect thermal comfort in outdoor spaces and that both can evaluate the thermal sensation using a numerical value associated with a qualitative scale of perception and quantitative meteorological variables.

Hence, this article aims to establish the reliability of applying a physiological-rational adaptation model

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 20 -31
https://doi.org/10.22320/07190700.2024.14.02.02

Figure 1.- Mexicali, Baja California. Source: Preparation by the author.

and a psychophysiological-empirical adaptation model by comparing both under intense sports conditions in a hot, dry climate. To determine how applicable the UTCI is under these characteristics and establish its reliability in similar conditions, the study was run using TSV (Thermal Sensation Vote) simulations with the indices and a comparative analysis of the results obtained to determine the accuracy of each one. In addition, the discussion was reinforced with statistical analyses to validate the results.

METHODOLOGY

The comparison of both thermal comfort indices is based on an understanding of the region and the climatic conditions. For this, the UTCI model was described and characterized, and a description of the regional model was generated. Finally, the simulation process and statistical analysis of the data were detailed.

LOCATION OF THE APPLICATION AREA

Mexicali is located in northwest Mexico (Figure 1), at 32.65° N and -115.45° W. According to the Köppen-García classification, its climate is extremely hot and dry [BW (h") hs (x") (e")]. Its average annual temperature is higher than 23.0 °C and lower than 18.0 °C in the coldest month. The characteristics of the warm period are: normal maximum average temperature of 42.0 °C and extreme highs above 50.0 °C; the relative humidity of the period ranges between 10% and 65%; wind speed ranges between 0.10 m/s to 4.0 m/s, and there is an average Solar Radiation of 937 W/m^2 in July.

UTCI INDEX

The UTCI is a physiological adaptation model that can be applied to diverse regions. It was developed from non-acclimatized subjects in outdoor spaces and under variable meteorological conditions. Its purpose is to provide information to avoid adverse climatic effects on health and as a tool to see the impact of climate change on aspects of population morbidity and mortality (Jendritzky, de Dear & Havenith, 2012).

It is established as an "equivalent temperature" (ET) index of the reference environment, under a physiological response criterion with exposures of 30 and 120 minutes, and expressed in degrees Celsius (°C) equivalent on the thermal stress values scale (Table 1) (Bröde et al., 2012). It uses the meteorological variables of air temperature (°C), mean radiant temperature (°C), relative humidity (%) or water vapor pressure (hPa), and wind speed (m/s).

The index is calculated using a multiple linear regression model (Błażejczyk & Kunert, 2011), whose expression is shown in Equation 1.

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Table 1.- Equivalent temperature scale of the UTCI index. Source: Taken from the UTCI Assessment Scale: UTCI categorized in terms of thermal stress

UTC range (°C eq)	Stress Category
Above +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	Without heat stress
+9 to 0	Slight cold stress
0 to -13	Moderate cold stress
-13 to -27	Strong cold stress
-27 to -40	Very strong cold stress
Below -40	Extreme cold stress

Note: °C eq means equivalent degrees Celsius

$$UTCI^* = 0.84 \cdot ta + 0.246 \cdot Tmrt - 2.45 \cdot v + 0.204 \cdot vp - 0.01$$

(Equation 1)

Where:
UTCI* = equivalent temperature index (°C)
DBT = air temperature (°C).
MRT = mean radiant temperature (°C).
WS = wind speed at 10 m above ground level (m/s).
VP = ambient vapor pressure (hPa).

REGIONAL PSYCHOPHYSIOLOGICAL MODEL (VSTAI)

The VSTai (Thermal Sensation Vote- Intense Activity) uses the ISO 10551 standard as a reference. This latter establishes thermal sensation votes using subjective and objective perception scales linked to climatic variables through statistical correlation analysis (Pearson). These scales are dry bulb temperature (DBT), Relative Humidity (RH), Wind Speed (WS), Solar Radiation (SR), and Mean Radiant Temperature (Mrt) (Table 2). Using them, a multivariate mathematical statistical model is developed (Jiaqi et al., 2022; Sarhadi & Rad. 2020).

The calculated sample consisted of 300 surveys, with a reliability of 95%. The season analyzed is the warm season (May-September). 332 observations were collected, providing data for the model's generation. In total, 10% more surveys were taken than planned, providing sufficient margin to discriminate those that did not have the necessary data quality while retaining a representative sample.

For the field data collection, an instrument was prepared using the criteria of the current comfort regulations

Table 2.-Correlations of meteorological variables with the thermal sensation. Source: Preparation by the author.

Meteorological variable	Coeficiente Pearson
Ta	0.53
Hr	0.23
V	0.16
Rs	0.07
Trm	0.52

Sample, collection, and analysis of data to develop the model

(ISO 10551, 2019; ISO 7730, 2006; ISO 7726, 1998; ISO 9920, 2007), creating a questionnaire with an eight-part structure: Control data, thermal perception, light and acoustic perception, thermal history, physiological data, insulation by clothing, meteorological variables and characteristics of the built environment. In total, the instrument has 59 reagents (Table 3).

In the meteorological data collection, the instruments were placed within no more than 10 meters of the surveyed individuals (Figure 2) to comply with the provisions of ISO 7730. Readings of the analyzed variables (DBT, RH, WS) were taken, and these complied with the regulations of ISO 7726 (Table 4). Complementary tools were used to collect the individuals' physiological data, such as scales, tape measures, infrared skin and ear thermometers, and blood pressure monitors, which were collected to calculate the metabolic rate and heat production. Although these data were important in the study, they were not directly input into the VSTai model.

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Table 3.- Questions of the instrument to collect thermal perception data. Source: Preparation by the author.

Section	Type of question	Response scale (qualitative and numerical)						
		1	2	3	4	5	6	7
Thermal perception	How are you feeling right now?	Very cold	Cold	Slightly cold	Neither hot nor cold	Slightly hot	Hot	Very hot
	How would you prefer to feel right now?	Much colder	Colder	A little colder	Unchanged	A little warmer	Hotter	Much hotter
	How are you feeling right now regarding the humidity?	Very wet	Wet	Slightly wet	Normal	Slightly dry	Dry	Very dry
	What would you prefer regarding humidity at the moment?	Much wetter	Wetter	A little wetter	Unchanged	A little drier	Drier	Much drier
	What do you feel the wind is like at the moment?	No wind at all	Some wind	Pleasant wind	Slightly strong	Very strong		
	How would you prefer the wind to be at the moment?	Less windy	Unchanged	Windier				
	What do you feel the solar radiation is like on your skin right now?	No radiation at all	Some radiation	Pleasant radiation	Somewhat strong radiation	Very strong radiation		
	How would you prefer the solar radiation to be on your skin right now?	Less radiation	Unchanged	More radiation				
	What do you feel the climate is like in this place?	Generally acceptable	Generally unacceptable					
	How tolerable does the weather seem to you at the moment?	Perfectly tolerable	Tolerable	Between tolerable and intolerable	Intolerable	Extremely intolerable		

Table 4. Meteorological instrument specifications. Source: Preparation by the author.

Equipment characteristics	Equipment used		
	ExTech 30 thermal stress monitor	A10 one-way anemometer	Dr. Meter SM206 Radiometer
Parameter -unit	Dry bulb temperature (DBT, °C) and relative humidity (RH, %)	Wind speed (WS, m/s)	Solar radiation (SR W/m2)
Measuring range	DBT: 0 to 50 °C, ± 1°C; RH: 0 to 100%.	WS: 0.1 to 20 m/s	SR: 1-3999 W/m2
Accuracy	DBT ±0.1°C; RH: ±3%	±3%, ± 0.30.	0.1 W/m2, ±5%
Recording frequency	All take 1 sample per second.		

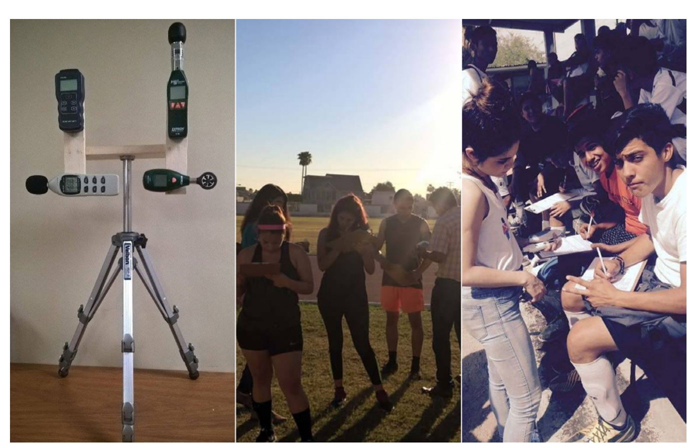

Figure 2.- Setup of instruments for meteorological data collection and survey process. Source: Preparation by the author.

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Two spaces were chosen, with diverse physical activities and extended operating hours, such as the Autonomous University of Baja California sports unit and the Municipal Sports complex, "Ciudad Deportiva" (Figure 2). The fieldwork was set up considering representative days of the warm period (July 23rd to August 8th for this case), which was characterized by the following climatic conditions: DBT 30.1 °C to 40.8 °C, RH 13% to 57%, WS 0.1 m/s to 2.88 m/s, MRT (calculated) 31.2 °C to 97.6 °C.

The study population, which fluctuated between 17 and 60 years old, was selected deterministically and with an intense activity level. The survey was applied one by one or in a group (to make the process efficient), considering the type of sports activity done individually. For the thermal perception analysis, a numerical scale of 7 levels was used, ranging from very cold (1) to very hot (7) (Table 5).

Table 5. Study's Thermal Sensation Votes. Source: Preparation by the author.

ISO 10551 Thermal Sensation Vote Valorization	
7	very hot
6	hot
5	slightly hot
4	neither hot nor cold
3	slightly cold
2	cold
1	very cold

The data analysis was carried out in the Statistica 12 program. This began with Pearson correlation tests to determine the significant variables (Table 2). Then, a residual study was performed to adjust the sample's normality (those answers outside ±2 standard deviations were discriminated; a total of 3% was left out). Subsequently, the multiple linear regression model was generated (Equation 2). In it, radiation was discarded as the one with the lowest coefficient compared to the TS.

$$VSTai = 0.27 \cdot ta + 0.068 \cdot hr - 0.092 \cdot v + 0.0047 \cdot Trm - 5.95$$

(Equation 2)

Where:
VSTai = Thermal Sensation Vote in intense activity (without unit)
DBT = air temperature (°C).
MRT = mean radiant temperature (°C).
WS = wind speed at 10 m above ground level (m/s).
RH = relative humidity (%).

COMPARATIVE PROCESS OF INDICES

The comparative analysis started by transforming the VSTai model into an ET index with degrees Celsius equivalent to heat stress levels. Thus, a determined index was generated with an equivalent temperature in intense activity (ET,re, Equation 3) (Monteiro & Alucci, 2009), with the assumption of a reference environment characterized by MRT = DBT; RH = 50% and WS = 0.1 m/s; When considering this, the relationship between the air temperature of the reference environment and the perception of thermal sensation is the following:

$$Ta,re = 3.64VSTai + 9.2827$$

(Equation 3)

Where:
ET, re = reference air temperature (°C).
VSTai = Thermal Sensation Vote in intense activity.
Equation 2 is substituted in equation 3, obtaining the equivalent temperatures in intense activity model:

$$TE,ai = 0.98 \cdot ta + 0.25 \cdot hr - 0.34 \cdot v + 0.017 \cdot Trm - 12.378$$

(Equation 4)

Where:
ET,ia: temperature equivalent in intense activity (°C).
DBT = air temperature (°C).
MRT = mean radiant temperature (°C).
WS = wind speed at 10 m above ground level (m/s).
RH = relative humidity (%).

This was conceptualized as a thermal sensation scale that presented numerically equivalent values to the UTCI. This allowed the homologation of both indices and established the equivalent temperature ranges in intense activity for the VSTai scale.

A total of 332 observations collated in the database were used. The TSV was calculated with both models. The simulation was established based on the characteristics of thermal sensation in the region's warm season, subjects with intense sports activities, and extreme meteorological variables.

The calculated equivalent temperature was then associated (Equation 1 and Equation 4) to have a comparative base of the indices. Subsequently, using the empirical extrapolation of each index's stress level ranges, the numerical scale was determined to the resulting ET values of the UTCI, a standardization was generated, and a comparison was made (Table 6).

Table 6. Standardized scales between VSTai and UTCI. Source: Preparation by the author.

UTCI stress category	VST	ISO 10551 scale
Intense and/or extreme heat stress	7	very hot
Strong heat stress	6	hot
Moderate heat stress	5	slightly hot
Thermal comfort	4	neither hot nor cold
Slight cold stress	3	slightly cold
Moderate to severe cold stress	2	cold
Intense and/or extreme cold stress	1	very cold

Table 7. Comparison of model and value simulations for hypothesis testing. Source: Preparation by the author.

	Observations	Total Answers	Mean	Variance	F critical	F Calculated	Z critical	Z Calculated
TSV	332	1853	5.58	1.07	-	-		
VSTai	332	1873.31	5.73	0.18	3.86	3.36	±1.96	-1.84
UTCI eq	332	2361.1	7.11	0.59	3.86	473.19	±1.96	-21.78
UTCI eqcal	332	2111.8	6.46	0.18	3.86	463.10	±1.96	-18.63

To establish the study's relevance, comparative statistical analyses of the models were performed for the TSV. A Pearson and Spearman linear correlational analysis was conducted to establish how the results are associated quantitatively. Both coefficients were calculated to have a comparison point, which anticipated that the Spearman coefficient is robust in the presence of atypical data and thereby obtained greater certainty of the sample's normality.

On the other hand, the ANOVA variance analysis and Z-tests allowed the author to compare the group means (the TSVs and those calculated by the indices). This determined that at least some of them differed significantly between the groups. With this process, the author sought to validate the hypotheses raised about the efficiency and applicability of each model in the regional conditions.

RESULTS

The model for the city of Mexicali (VSTai) and the ET,ia index that was developed specifically for the region, were more efficient when calculating the TSV, which generally coincided with Barcia-Sardiñas et al. (2020) and Monteiro and Alucci (2009). The process results showed that a non-regional model tended to overestimate the TS (see the TSV averages in Table 7). On the other hand, the VSTai calculated a more accurate TSV, as its mean only differed by 3% compared to the responses observed in the databases.

The differences observed when calculating the TSV with the VSTai model and the UTCI are significant. The variability demonstrates greater homogeneity in the regional model by obtaining better calculations than the other index. This can be visualized when establishing the predicted means and comparing them with the TSVs collected from the subjects, where they have a difference of only 0.15 (VSTai) and 1.53 compared to the equivalent TSV for the UTCI. Even with the calibrated UTCI index, the value of its predictions continues to be very far from that of the observed votes, which is 0.86 points of the thermal perception (Table 7). This confirms the variance analysis, where the difference in the means between the TSV and the UTCI was determined and strengthened with the Z-test, which, with the calculated parameter of -1.84, corroborated the reliability of the regional model since it accepts the hypothesis of homogeneity of the mean between the TSV and the TSV that it calculated.

This is all part of regional models' greater efficiency. This corroborates what Monteiro and Alucci (2009) found, who mention that a regional model with an adaptive approach, even with fewer determination coefficients, is better at calculating the comfort vote.

It was also seen that the Pearson correlation is higher between the VSTai and the TSVs compared to the

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Table 8. Correlation between the models' TSV and TS predictions. Source: Preparation by the author.

	Pearson Correlation	Spearman Correlation	Success %	Index calibration		
				Pearson Correlation	Spearman Correlation	Success %
VSTai	0.31	0.32	67	-		-
UTCI eq cal*	0.12	0.14	31	0.18	0.21	53

Note: UTCI eq cal refers to the empirical calibration made to the Universal Thermal Climate Index

Table 9. Empirical calibration of the UTCI compared to the VSTai. Source: Preparation by the author.

UTCI (°C) calibrated range	Stress Category	ISO 10551 scale	
Above +36	Extreme heat stress	7	very hot
+31 to +36	Strong heat stress	6	hot
+28 to +31	Moderate heat stress	5	slightly hot
+24 to +28	Thermal comfort	4	neither hot nor cold
+20 to 24	Slight cold stress	3	slightly cold
+17 to 20	Moderate to severe cold stress	2	cold
Below +17	Intense cold stress	1	very cold

calibrated UTCI (Table 9). The psychophysiological model's prediction effectiveness was detailed, with a success percentage of 67%, while the UTCI only had 31%. When comparing the results of the calibrated UTCI, 53% of the votes were successful, indicating that the regional model continues to obtain better statistical parameters and adapt better to the conditions.

Similarly, Spearman correlations are better in the VSTai, which validates the VSTai's reliability in the region compared to the other model and establishes greater efficiency in predicting the thermal sensation.

As a result, the calibration made to the UTCI index (Table 8) provided a better correlation with the empirical data collected and, consequently, a higher percentage of correct predictions. With this, it is inferred that using the model with a higher correlation between TSV and its predictions is appropriate. This substantiates the results found since, even when the UTCI model was calibrated, it continued with a lower success rate than the VSTai model, which, as mentioned above, matches what Monteiro and Alucci (2009) found.

On the other hand, the ET,ia Index has the best correlation between the model's parameter and the subject's responses, which also leads to improved predictions when performing its simulations. Therefore, the estimates of a thermos-physiological equilibrium and adaptation model that needs several iterations to provide reliable results (VSTai) have better results and reflect the importance of the subjects' adaptation and acclimatization to the region's meteorological conditions.

CONCLUSIONS

The comparison between the two ET indices - UTCI and ET,ia - showed that developing comfort models and indices is important when predicting the thermal perception of subjects in an outdoor environment. The VSTai model with a thermal sensation measurement scale (numerical only) is not enough, so equivalent temperature ranges must also be reflected for better application and interpretation, as used in this research, to be able to generate these comparison points (Błażejczyk et al., 2000; Monteiro & Alucci, 2011; Błażejczyk et al., 2012).

The comparative empirical study done with the UTCI allowed the results to be verified, to validate the model developed, and to establish its effectiveness through statistical hypothesis tests. This coincides with the aforementioned research, where regional models are more suitable when calculating ET and TSV (Monteiro & Alucci, 2009) and partially with that of Tumini and Pérez (2015), where the UTCI, even though it was compared with another model, did not have the same measurement scale. This contributes to strengthening researchers' interest in generating models and indices that help understand microclimatic variables' effects on people's health.

Therefore, its applicability and reliability were determined by performing a mean-variance comparison of the VSTaí results with a predictive model (even calibrated). This coincides with Monteiro and Alucci (2009), who calibrated several indices from a regional model, which showed that people's TS was still overestimated.

This work's main contribution was to provide an equivalent temperature index (ET,ia) derived from a psychophysiological model (Equation 4) that is easy to use, intuitive, and reliable and helps to evaluate thermal comfort in outdoor spaces. This work provides an understanding of how comfort can affect health in extreme climates and how the high metabolic rate, acclimatization, adaptation, and psychological aspects affect environmental perception and serve as a basis for generating early warning systems in the region.

Prospectively, it is necessary to consider:

1. Due to the limits within which the model was developed and the validation of the proposed ET,ia, it cannot be applied in other regions with other climates. It would overestimate or underestimate the thermal sensation due to the region's characteristics, people's activity levels, and urban conditions.
2. The number of observations needs to be increased to corroborate the effectiveness of the model and the ranges proposed in ET,ia
3. It would be a good idea to conduct work in different climates to the study to corroborate the model's behavior under different conditions.
4. Determine how the subjective aspect of comfort influences the increased reliability of models that are developed.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, H.E.U.B.; Data curation, H.E.U.B.; Formal analysis, H.E.U.B.; Acquisition of financing; Research, H.E.U.B.; Methodology, H.E.U.B.; Project management, H.E.U.B.; Resources; Software, H.E.U.B.; Supervision, H.E.U.B.; Validation, H.E.U.B.; Visualization, H.E.U.B.; Writing – draft original, H.E.U.B.; Writing – revision and editing, H.E.U.B.

ACKNOWLEDGMENTS

To the National Council of Humanities, Sciences, and Technology, in addition to the Institute of Engineering of the Autonomous University of Baja California, for the support provided to the doctoral research entitled "Thermal Comfort in Outdoor Public Spaces for Intensive Sports Activities: in extremely hot dry climate" ded number CVU 556780, from which this work emerges.

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https://doi.org/10.22320/07190700.2024.14.02.03

COST-BENEFIT ANALYSIS OF ENERGY EFFICIENCY STRATEGIES FOR HOUSING, APPLYING THE CURRENT REGULATIONS IN NORTHWEST MEXICO

Recibido 29/08/2024
Aceptado 05/11/2024

ANÁLISIS COSTO-BENEFICIO DE ESTRATEGIAS PARA EFICIENCIA ENERGÉTICA EN VIVIENDA, APLICANDO LA NORMATIVIDAD VIGENTE EN EL NOROESTE DE MÉXICO

ANÁLISE DE CUSTO-BENEFÍCIO DE ESTRATÉGIAS PARA EFICIÊNCIA ENERGÉTICA EM RESIDÊNCIAS, APLICANDO AS REGULAMENTAÇÕES ATUAIS NO NOROESTE DO MÉXICO

Cecilia Galindo-Borbón
Magíster en en Ciencias Ambientales
Profesora de asignatura, Departamento de Arquitectura y Diseño
Universidad de Sonora, Hermosillo, México
https://orcid.org/0000-0002-9637-7173
cecilia.galindo@unison.mx (Autora de Correspondencia)

Ana Borbón-Almada
Doctora en Ciencias
Profesora de tiempo completo, Departamento de Ingeniería Civil y Minas
Universidad de Sonora, Hermosillo, México
https://orcid.org/0000-0002-7781-2571
ana.borbon@unison.mx

José M. Ochoa-de-la-Torre
Doctor en Arquitectura
Investigador de tiempo completo, Departamento de Arquitectura y Diseño
Universidad de Sonora, Hermosillo, México
https://orcid.org/0000-0001-6035-1249
josemanuel.ochoa@unison.mx

Irene Marincic-Lovriha
Doctora en Ingeniería de Caminos, Canales y Puertos
Profesora de tiempo completo, Departamento de Arquitectura y Diseño
Universidad de Sonora, Hermosillo, México
https://orcid.org/0000-0002-8609-2748
irene.marincic@unison.mx

RESUMEN

El cambio climático ha afectado de manera desproporcionada a los sectores más vulnerables, y la eficiencia energética en edificaciones emerge como clave para mitigar y adaptarse a estos efectos. En México, los climas cálidos secos predominan en el 53% del territorio, especialmente en el norte, y aunque existe normativa para la eficiencia energética en la edificación, ésta tiene un impacto limitado. El estudio evalúa los costos y beneficios de dicha normativa que considera viviendas comunes en distintos climas de un estado del norte de México donde se analizaron 180 modelos y se concluyó que cumplir con la normativa aumentaría el costo de la vivienda en 1.93%, reduciría el consumo eléctrico en 26% y disminuiría las emisiones de CO2e en 16.95%. Estos beneficios se obtuvieron sin cambiar los sistemas constructivos más utilizados y se priorizó sistemas de sombreado. Los resultados podrían orientar a políticas públicas más adecuadas a los contextos locales.

Palabras clave
cambio climático, vivienda, energía eléctrica, normalización, consumo de energía.

ABSTRACT

Climate change has disproportionately affected the most vulnerable sectors, and energy efficiency in buildings is essential for mitigating and adapting to these effects. In Mexico, hot, dry climates predominate in 53% of the country, especially in the north, and although there are energy efficiency regulations for buildings, they have a limited impact. This study evaluates the costs and benefits of these regulations considering ordinary dwellings in different climates in a state in northern Mexico, analyzing 180 models and concluding that complying with the regulations would increase the cost of housing by 1.93%, reduce electricity consumption by 26%, and decrease CO2e emissions by 16.95%. These benefits were obtained without changing the most commonly used construction systems, although shading systems were prioritized. The results can guide public policies that are more appropriate to local contexts.

Keywords
climate change, housing, electric power, standardization, energy consumption.

RESUMO

As mudanças climáticas afetam desproporcionalmente os setores mais vulneráveis, e a eficiência energética em edifícios surge como uma das chaves para mitigar e adaptar-se a esses efeitos. No México, os climas quentes e secos predominam em 53% do território, especialmente no norte, e, embora existam regulamentações para a eficiência energética em edifícios, elas têm impacto limitado. O estudo avalia os custos e benefícios de tais regulamentações considerando residências comuns em diferentes climas em um estado do norte do México. Ele analisou 180 modelos e concluiu que a conformidade com a norma aumentaria o custo da moradia em 1,93%, reduziria o consumo de eletricidade em 26% e reduziria as emissões de CO2e em 16,95%. Estes benefícios foram obtidos sem alterar os sistemas de construção mais comumente usados e os sistemas de sombreamento foram priorizados. Os resultados podem orientar políticas públicas mais adequadas aos contextos locais.

Palavras-chave:
mudança climática, habitação, energia elétrica, padronização, consumo de energia

INTRODUCTION

The sixth report of the IPCC (2023) says that the effects of climate change have been more severe than anticipated, affecting natural systems and socio-economic sectors, especially the most vulnerable ones. These impacts include physical and mental health problems, the result of phenomena such as extreme heat waves, which increase mortality and morbidity. The report highlights the need for governments to address these challenges through adaptation and resilience policies, where the importance of energy diversification, decentralization of generation and demand management, with a particular focus on the energy efficiency of buildings to mitigate and adapt to climate change, stand out.

According to the latest report by the International Energy Agency, IEA (2023), the building sector accounts for 30% of the world's total final energy consumption. This is mainly due to the energy demand for thermal comfort in spaces, where heating is one of the first energy end-use demands, and cooling is the fastest-growing end-use in recent decades. Predictions for a rise in built-up areas worldwide are also around 20% from 2021 to 2030, of which 80% would be in emerging market economies, aggravating the growing effects of climate change (IEA, 2022).

In Mexico, the construction sector, considering residential, commercial, and public buildings, represents 18% of the total end energy consumption, and the primary energy source used is electricity (Ministry of Energy [SENER], 2023). However, energy consumption is mainly determined by climate characteristics that condition habitability to using cooling systems (A/C), and, therefore, the distribution of consumption in the national territory is not uniform. In general, humid and dry hot climates predominate in 89% of the Mexican territory, particularly arid hot climates (very dry, dry desert, dry and semi-dry) that represent 53% of the total area and are located in the northern region of the country (Ministry of Environment and Natural Resources [SEMARNAT], 2024b).

Household energy expenditure comprises fuel, gas, and electricity, and through this expenditure, the energy demand that identifies the energy source can be described, as well as its consumption level (Rodriguez et al., 2022). Notably, the northern states invest most in energy expenditure (Figure 1), and electricity can exceed 60% or up to 70% of that expenditure (Rodriguez et al., 2022).

Nationally, the end-uses of electricity in the residential sector are as follows: cooling comprises 30% of the total, food refrigeration 20%, the use of household and other appliances 15%, entertainment, specifically television, has a demand of 13%, lighting 8%, laundry 6%, water heating 5%, heating 2%, and pumping 1% (Contreras et al., 2022). It is necessary to emphasize that these data are national averages and that the end-use percentage from cooling would be higher in areas with higher temperatures. There is no exact information, but in tropical climate zones, 14% more electricity is consumed than in temperate climate zones, while in northern states with dry climates, this consumption is 29% higher than in those with temperate climates (Rodriguez, 2018; INEGI, 2022). This difference is assumed to be mainly related to the increased energy used for cooling due to the temperatures.

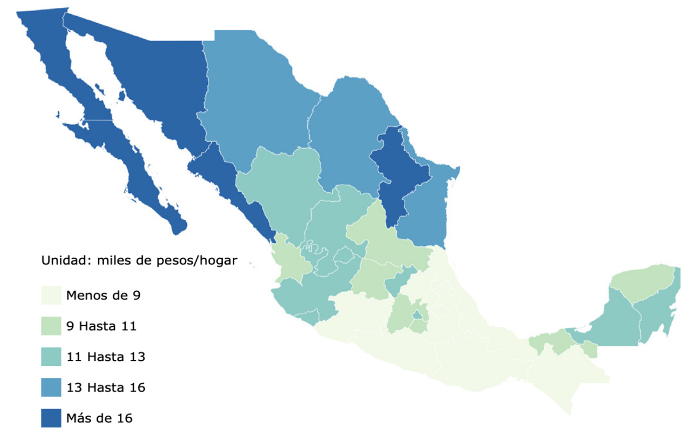

Figure 1. Energy expenditure per household in Mexico. Source: Image taken from the Ministry of Energy [SENER] and National Commission for the Efficient Use of Energy [CONUEE] (2024), MEX$19.80/Dollar for August 2024.

It should also be considered that it is highly likely that energy needs for thermal comfort will increase. To evaluate the uncertainty, according to the National Atlas of Vulnerability to Climate Change (INECC, 2022), for the northern states of Mexico, in a medium-term and an RCP4.5 scenario of average stabilization, the anomaly in the average temperature would be 1.9°C, and for a high emission RCP8.5 scenario, it would be 2.4°C (López-Díaz et al., 2022).

This problem is aggravated further when it is acknowledged that achieving thermal comfort requires sufficient economic and energy resources, especially when a population sector is vulnerable due to limited access. In the last decade, interest in this topic has grown, with research on the phenomenon of energy poverty (Siksnelyte-Butkiene et al., 2021). It has been argued that this depends not only on access to energy but is also

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 32 - 47
https://doi.org/10.22320/07190700.2024.14.02.03

determined by the territory's characteristics, the temporal context, and the specific socio-technical and socio-cultural conditions.

In this regard, income levels (García Ochoa, 2022; Méndez et al., 2021; Panca & Calatayud, 2021), energy prices, and subsidies (Durán & Condori, 2021; Méndez et al., 2021) are important factors, but other elements also have an impact, such as weather conditions (García Ochoa, 2022; Santillán et al., 2020), regulations on the quality of housing and its installations (García Ochoa, 2022; Hernández, Aguayo & Duque, 2018; Méndez et al., 2021; Garcia Ochoa, Ávila-Ortega & Cravioto, 2022; Panca & Calatayud, 2021), as well as the affordability of energy technologies (Hernández, Aguayo & Duque, 2018; García Ochoa, 2022; Garcia Ochoa, Ávila-Ortega & Cravioto, 2022).

In this context, the uncertainty about the capacity of buildings and conditioning systems to guarantee thermal comfort, together with the economic limitations of governments and individuals, poses a public policy challenge with an impact on health (IEA, 2022). This is where the importance of this research lies, as energy efficiency is identified as the strategy to provide these living conditions, at least to some extent.

In Mexico, there is a specific regulatory structure for energy efficiency in buildings, with a series of Official Mexican Standards (NOM) that regulate several technical aspects, such as the labeling of air conditioners, household appliances, glazing systems, and the thermal envelope of buildings. However, the regulations for the thermal envelope, specifically NOM-008-ENER-2001, Energy Efficiency in Buildings, Non-Residential Building Envelope and NOM-020-JAN-2011. Energy Efficiency in Buildings, Residential Building Envelope, established to rationalize energy use in air conditioning systems, considering a reference building as a base, have not had the expected impact despite being mandatory. Diverse factors, including logistical and technical aspects, explain why these regulations have not had the expected impact.

Among the logistical details, it is highlighted that neither standard is integrated into local construction regulations. There is also a lack of coordination by the three levels of government; there is no technical capacity of professionals for their implementation, it is not mandatory in programs run by credit and housing entities, or in any case, only optional criteria are sought and, there is an objection from the construction sector, precisely because it entails an additional cost (Rodriguez, 2018; Martin-Domínguez et al., 2018)

Among the technical details for the calculation methodology, an overestimation of the solar absorption of the building envelope is identified (Martin-Dominguez et al., 2018). The heat capacity of the materials is also omitted, as the calculation model does not consider variations in ambient temperature over time (Huelsz et al., 2014), which leads, in essence, to an over-dimensioning of the insulation. In addition, the meteorological data needs to be updated to respond to the phenomenon of climate change, and the standard does not provide a comfort model (Guízar Dena et al., 2021).

The application of energy efficiency regulations in buildings in Mexico is unavoidable and urgent, especially in homes in the country's northern regions, given the critical conditions of climate change, the increase in energy demand, and the high economic and social costs. Given this urgency, it would be important to maximize the potential of the current regulations, as their application could generate significant results, especially when considering this region's climate.

This study focuses on the application of NOM-020-JAN-2011 - Energy Efficiency in Buildings, Residential Building Envelope methodology, and the aim is to identify combinations of strategies that maximize the impact on the assessment of regulatory compliance with the least economic investment. This would allow defining benefits in terms of energy savings and emissions reduction, as well as the cost of achieving the level of compliance, at least at its minimum level. In addition, the region's most common designs and construction systems and, finally, the results that could contribute to guiding public policies that best adapt to local contexts are considered.

METHODOLOGY

In this exercise, localities in a northern state of Mexico, specifically Sonora, were analyzed, where 95% of the region has a hot and dry climate (INEGI, 2024) and as of 2017, 71% of households had A/C (National Commission for the Efficient Use of Energy [CONUEE], 2024).

This study considered the analysis of 9 housing models in the four orientations and five types of climates in the State for a total of 180 analyzed models. An initial evaluation was carried out without considering efficiency conditions, and based on the results, strategies were implemented to achieve the desired efficiency level, quantifying the costs and possible savings.

Table 1: Localities included in NOM-020 for Sonora, the corresponding electricity tariff, and climate. Source: Prepared by the authors, with information from CFE (2024), NOM-020 (2011), INEGI (2024).

Locality	Latitude	Tariff	Description of the Tariff	Climate	Consumption level
Hermosillo	29.10N	1F	Domestic service for localities with an average minimum summer temperature of 33°C	Very dry, very warm	The first level is from 1 to 1,200kWh, the second is from 1,201 to 2500kwh, and the rest is surplus.
Obregón	27.49N	1F		Dry very warm	
Guaymas	27.92N	1E	Domestic service for localities with an average minimum summer temperature of 32°C	Very dry, very warm	
Navojoa	27.07N	1E		Dry very warm	
Nogales	31.31N	1A	Domestic service for localities with an average minimum summer temperature of 25°C	Semi-dry temperate	The first level is from 1 to 300kWh, the second from 301 to 1200kWh, and the third from 1201 to 2500kWh; the rest is surplus.

For the analysis, NOM-020-JAN-2011 - Energy Efficiency in Buildings, Residential Building Envelope (2011) was used, which, from now on, will be referred to as NOM-020. This is applied in homes located in cities whose electricity supply has the following electric tariffs: 1C, 1D, 1E, and 1F (NOM-020-JAN-2011 Resolution, 2016).

The Federal Electricity Commission sets these rates (CFE, 2024) and they are defined according to a minimum average summer temperature classification. The tariffs range from 1A to 1F, and a high consumption domestic tariff (DAC). The 1F tariff is for the highest minimum average temperature and applies to the highest subsidy for the summer season. Consumption levels structure the subsidies, and each has an increase in cost per kWh. Given the high temperatures recorded in 2023, electricity users in the State of Sonora recorded consumption far higher than those in other regions of the country, leading to an extraordinary level of social clamor for support. In this context, the Collaboration agreement for tariff support for the State of Sonora (2024) was prepared, which outlines a larger subsidy that benefits the entire State, covers the months of April to October, considers adjustments in consumption levels, standardizes the 1E and 1F tariffs, and improves the conditions for the rest of the tariffs. See Table 1.

NOM-020 includes values in its tables to calculate the heat flow through the envelope for specific cities. Sonora considers only five localities: Hermosillo and Ciudad Obregón for the 1F tariff, Guaymas and Navojoa with 1E, and Nogales with 1A (see Table 1). Although NOM-020's resolution indicates that Nogales is not subject to the verification of the standard, the analysis will be made to expand upon the possible observations.

Some of the representative characteristics of social housing design in the hot, dry climate are usually unique for the area and are deployed on one of the property's boundaries. This means the dwelling does not share walls or have insulation systems. Although they may vary in their distribution, they comprise a common area (living room, dining room, and kitchen), one or several bedrooms, and a bathroom. The facades also lack solar protection (Romero Moreno et al., 2020), and the largest proportion of windows are located on the main and rear facades. In terms of construction area, 58% of the housing in the state of Sonora is between 46 m^2 and 150 m^2 (INEGI, 2020), and regarding the most commonly used construction systems, 92% of the homes in the state have brick, block, cement or concrete walls (INEGI, 2022), particularly 0.12m thick concrete block walls (Romero Moreno et al., 2020). Finally, concrete ceiling slabs or joists are found in 72% (INEGI, 2022), where particularly 0.15m thick joist slabs predominate (Romero Moreno et al., 2020).

Nine housing model projects were chosen for this analysis, considering the characteristics described in the previous paragraph. The information on the projects was provided by different property developers, who will remain anonymous. These one—and two-floor models range from 43m^2 to 126 m^2. In Table 2, each model's information is detailed, including, among other data, the wall-to-window (%) of the houses. The table also includes a nomenclature to identify each model in the following figures.

The calculation method of NOM-020 estimates the heat gain by conduction and radiation of the projected building and compares it with a reference building. To comply with the regulations,

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the projected building's heat gains must be equal to or less than those of the reference building. The results are presented as a percentage of savings from the difference in thermal load (W) between the projected and reference buildings. For compliance, at least 0% savings or more must be achieved. A negative number represents spending and non-compliance with the standard.

Table 3 outlines the construction systems used in the initial evaluation. Regarding the floor slab, according to NOM-020, the portion of the envelope directly above the ground is considered a zero-heat gain; therefore, it was not included.

The conductivity values of each material were taken from the tables available in NOM-020 (2011) and NMX-C-460 (2009). The values not available in these lists were taken from the commercial product's technical data sheet, see Table 3.

The U reference values established by the Mexican regulations may imply a high level of thermal insulation. This entails using materials with very low thermal conductivity, such as insulators, to meet the requirements. However, according to the standard's methodology, it is possible to optimize the envelope's thermal behavior by adopting different construction strategies, such as using lightweight materials, new geometries, and innovative solutions. In addition, combining these approaches with efficient glazing technologies and shading systems makes it possible to reduce the demand for insulation. Similarly, having more accurate information on the thermal conductivity values of locally produced materials is essential, as it would facilitate adapting construction solutions to the region's specific conditions.

In the first analysis, the results describe the level of compliance with the current state of housing, namely, without additional strategies for compliance with NOM-020. The results are described by relating some design characteristics, such as the WWR and orientation, as well as the impact of the climate, with the results of NOM-020.

A second analysis applies energy efficiency strategies that impact the NOM's calculation. The strategies were applied to those dwellings that did not comply in the first analysis. The intention was to achieve compliance with NOM-020, at least at its minimum level. The criteria for selecting the strategies consider not modifying the original design; they must use common materials available in the market and should represent the lowest possible cost. A unit price analysis was made to determine these costs, considering material,

Table 2: Characteristics of the analyzed models: 9 models in 4 orientations in the 5 climates available in NOM-020, totaling 180 models. Source: Preparation by the Authors.

Number of floors	Built area (m2)	WWR ratio (%) and without shading	Nomenclature
1	43.00	12.08	1N_43
1	54.00	9.43	1N_54
1	61.00	9.21	1N_61
1	66.00	8.60	1N_66
1	78.00	5.65	1N_78
2	97.00	6.62	2N_97
2	104.00	8.45	2N_104
2	113.00	8.19	2N_113
2	126.00	7.40	2N_126

Table 3: Description of the construction systems and values used to calculate the initial evaluation. Source: Preparation by the Authors.

System	Description	Conductivity (λ) W/mK	Source of λ values	Thickness (m) as per the project
Hollow concrete block walls	Cement sand mortar	0.17	NMX-460	0.015
	Concrete block with 2 or 3 holes	1.11	NMX-460	0.120
Joist slabs	Reinforced concrete	1.74	NOM-020	0.040
	Expanded nominal density polystyrene 12 kg/m3 (Polystyrene joist)	0.04	Commercial product technical data sheet	0.090
	Reinforced concrete joist	1.74	NOM-020	0.090
	Flattened plaster	0.372	NOM-020	0.01
Windows without shading	Single glazing, shade coefficient (SC) 1.00	0.93	NOM-020	0.006

Table 4: Description of the constructive systems and values used to calculate the evaluation with improvement strategies. Source: Preparation by the Authors.

Improved System	Description	Conductivity (λ) W/mK	Source of λ values	Thickness (m) as per the project
Hollow concrete block walls	Cement sand mortar (outside)	0.17	NMX-460	0.015
	Expanded nominal density polystyrene - 12 kg/m3 (Outer plate)	0.04	Commercial product technical data sheet	0.025
	Concrete block with 2 or 3 holes	1.11	NMX-460	0.120
	Cement sand mortar (inside)	0.17	NMX-460	0.015
Joist slab	Reinforced concrete (compression layer)	1.74	NOM-020	0.040
	Expanded nominal density polystyrene - 12 kg/m3 (Polystyrene slab)	0.04	Commercial product technical data sheet	0.090
	Reinforced concrete (Joist)	1.74	NOM-020	0.090
	Flattened plaster (inside)	0.372	NOM-020	0.01
Single-glazing with film	Single glazing with solar control film and a shading coefficient (SC) of 0.40	0.93	NOM-020	0.006

labor, and equipment with current costs to 2024. In addition, the total direct cost of housing was determined using a parametric analysis of the project items and the estimated cost per m^2 of affordable housing in 2024. With this information, the economic cost overrun of complying with the standard was estimated.

The strategies used are detailed below:

- Horizontal window shading: In all cases where the project did not comply with the regulations, horizontal window shading was implemented as a first strategy. The criterion for defining the element's longitude was to consider the city's latitude, as indicated in Table 1. An overheating period spanning from May to October was also considered using the available climatological databases and the window's vertical dimension. This results in an ideal shading system that protects from radiation in critical periods and allows heating during colder periods.

If the shading systems do not comply with the standard, wall insulation is added, or the quality of the windows is improved.

- Insulation in one or two walls with 0.025m expanded polystyrene on the outside. The criteria for defining the wall to be insulated were as follows: if the main facade is north- or south-facing, the west wall is insulated. The south wall is insulated if the main facade is east or west-facing. In some cases, it was necessary to insulate a second wall, adding the south or west wall, as appropriate. The configuration of the improved construction systems is shown in Table 4.
- Improvement of windows. The strategy consists of improving the windows with one of the following two options: If the house measures less than 100 m^2, a solar control film with at least a shading coefficient value of 0.4 (CS) is used, or if the house measures more than 100 m^2, a double-glazing system with Double Low-E film and a shading coefficient (CS) of 0.64 is included. The criterion for one option or the other depends on the cost of the strategy vs the housing cost, with the intention of not having an excessive impact on the final cost. The configuration of the improved construction systems is shown in Table 4.

In critical cases, wall insulation was used, and the quality of the windows was improved. A critical case is those models that require all the strategies together to reach the minimum level of the standard.

To calculate the energy consumption in kWh, the thermal load results were taken along with A/C use from April to October, corresponding to the subsidy period defined in the Collaboration Agreement for tariff support for Sonora (2024) and an 11-hour daily usage that corresponds to the daily A/C average use in housing in the state (INEGI, 2018).

To define the energy cost, the consumption calculated for A/C plus the proportion of electricity consumption by other devices described in the introduction was considered, in addition to the current subsidy tariff scheme of the collaboration agreement for tariff support for the State of Sonora (2024).

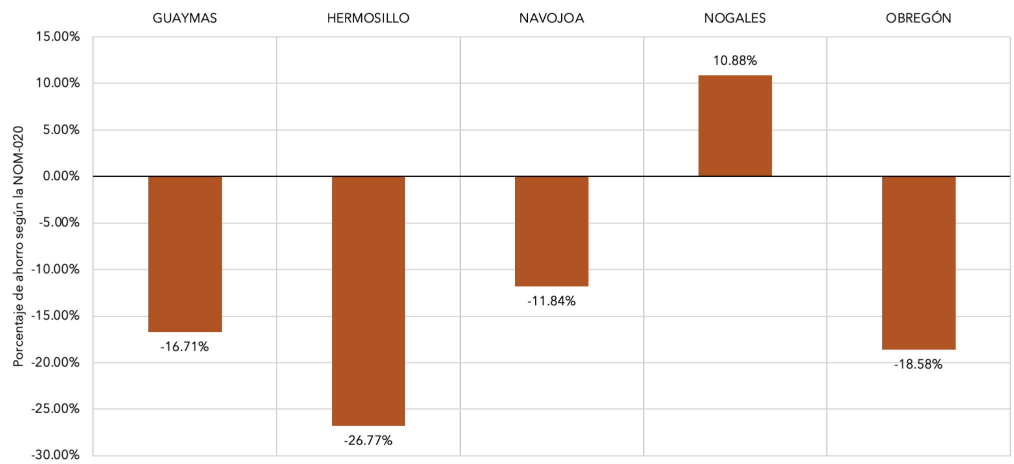

Figure 2. Average savings of all the models per city in all orientations according to NOM-020, without energy efficiency strategies. Source: Preparation by the Authors.

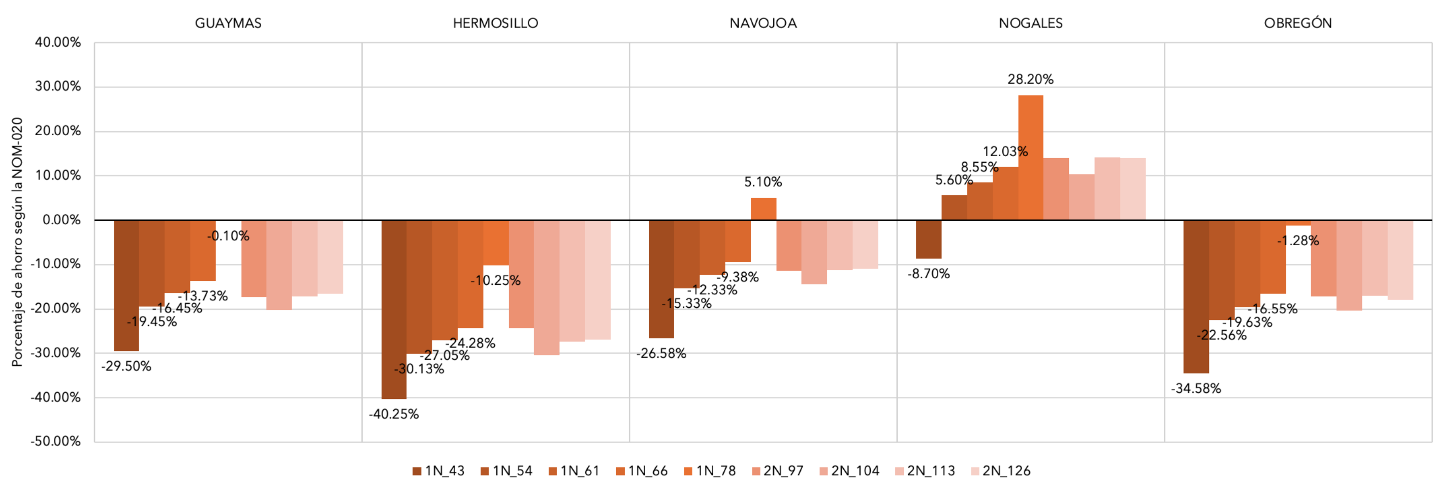

Figure 3. Average savings for each model in all its orientations by city according to NOM-020, without energy efficiency strategies. Source: Preparation by the Authors.

Finally, an estimate of the potential savings in CO_2 emissions is made, considering the emission factor of the National Electricity System, which represents the calculation of indirect greenhouse gas (GHG) emissions from electricity consumption for 2023 (SEMARNAT, 2024a).

RESULTS

FIRST ANALYSIS

Figure 2 shows the average savings of all the models analyzed in 4 orientations for each city without considering any energy efficiency strategy. The models with the highest expenditure or that are further from complying with NOM-020 are those located in Hermosillo, with -26.77%, followed by Obregón, Guaymas, and Navojoa, with -18.58%, -16.71%, and -11.84%, respectively. In the case of Nogales, the models' average savings level complies with NOM-020, with an average savings level of 10.88%.

Figure 3 shows the average savings per model in its four orientations per city. This shows the impact of the specific design variations of each model. In Guaymas, Hermosillo, and Obregón, all the percentages are negative, and the model with the lowest savings is 1N_46, which is the one with the lowest m^2 and highest percentage of glazing, reaching up to -40.25% savings in Hermosillo. In Nogales, all models, on average, have a positive percentage, but the 1N_46 model is still negative with -8.70%. In Navojoa, all the models have negative savings on average except for 1N_78 with 5.10%. In fact, this model is the best evaluated in all localities, either with a negative percentage closer to zero or with a savings percentage of up to 28.20% in Nogales.

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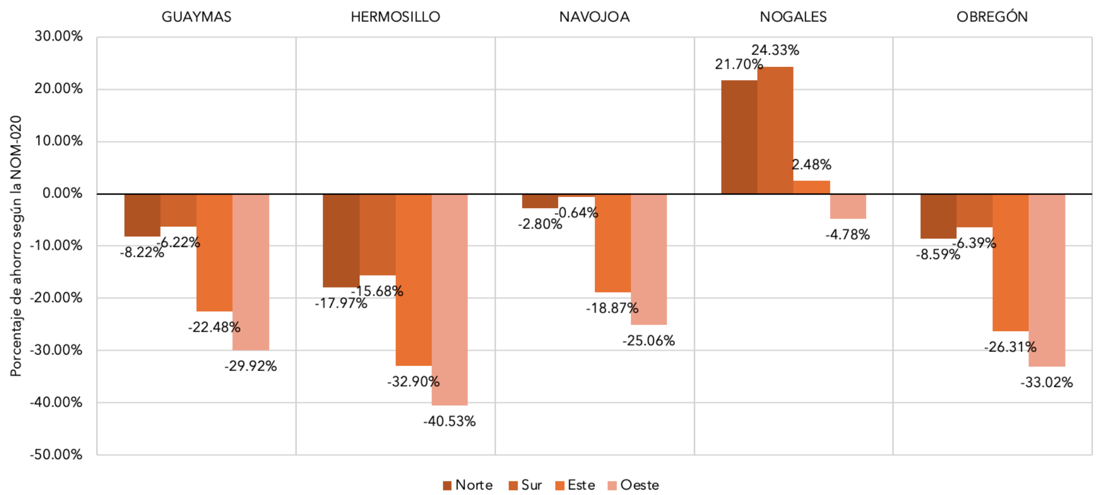

Figure 4. Average savings of all models by orientation per city according to NOM-020, without energy efficiency strategies. Source: Preparation by the Authors.

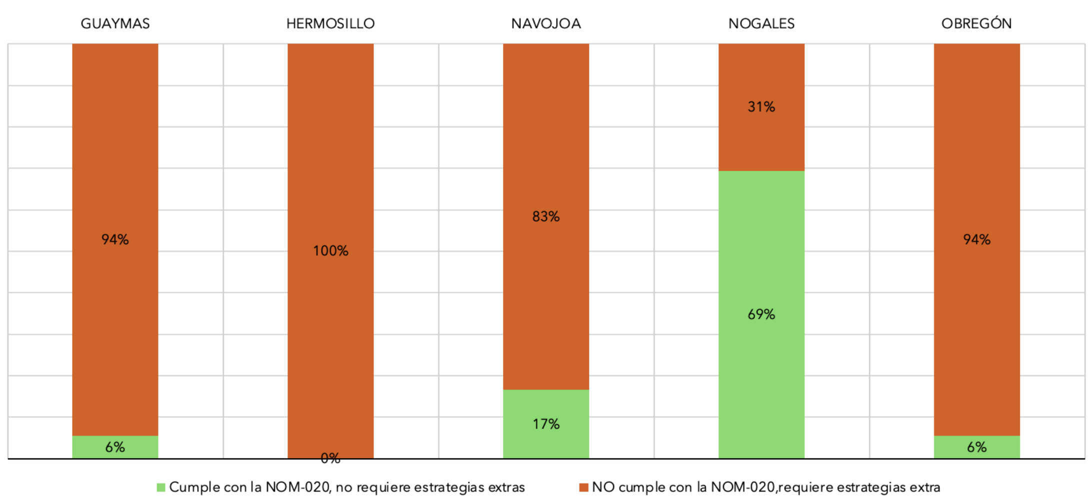

Figure 5. Percentage of cases by city that require additional strategies to comply with NOM-020. Source: Preparation by the Authors.

Figure 4 shows the savings averages of all the models analyzed by orientation and city. This allows us to visualize the impact that orientation has on any model. The most unfavorable orientations are east and west, with negative values in almost all cities, reaching up to -40.53% in the west orientation in Hermosillo. North and south facing are also negative in almost all cities, but closer to savings than the previous ones. The exception is Nogales, with positive values in the north, south, and east, although the west orientation remains negative at -4.78%.

Finally, Figure 5 shows the percentage of cases that would require energy efficiency strategies by city. That is to say, of all the models analyzed in Guaymas, Navojoa, and Obregón, 94%, 83%, and 94%, respectively, need energy efficiency strategies to comply with NOM-020. In Hermosillo, 100% of homes require it, and in Nogales, only 31%.

SECOND ANALYSIS

Figure 6 shows the average savings of all the models in 4 orientations per city, with and without strategies. The most significant impact was in Hermosillo, where the average savings percentage went from -26.77% to 6.39%, representing 33.16 percentage points. This was followed by Obregón, with a difference of 25.29; Guaymas, with 21.5; Navojoa, with 18.78 percentage points; and finally, Nogales, where although the average savings was positive, with 10.88%, it increased savings to 17.39%, representing 6.51 percentage points.

To achieve compliance with NOM-020 with the

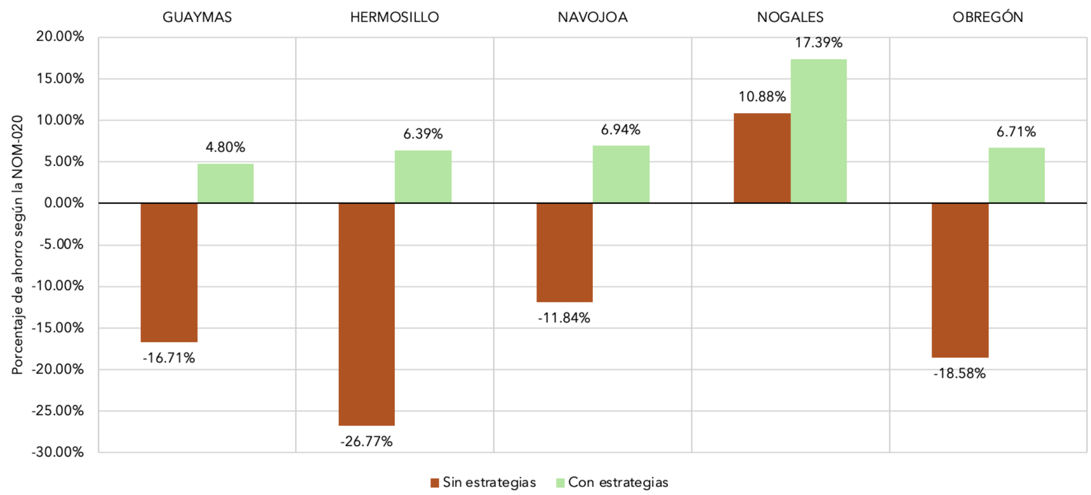

Figure 6. Comparison of the average savings of the models by city according to NOM-020, with and without energy efficiency strategies. Source: Preparation by the Authors.

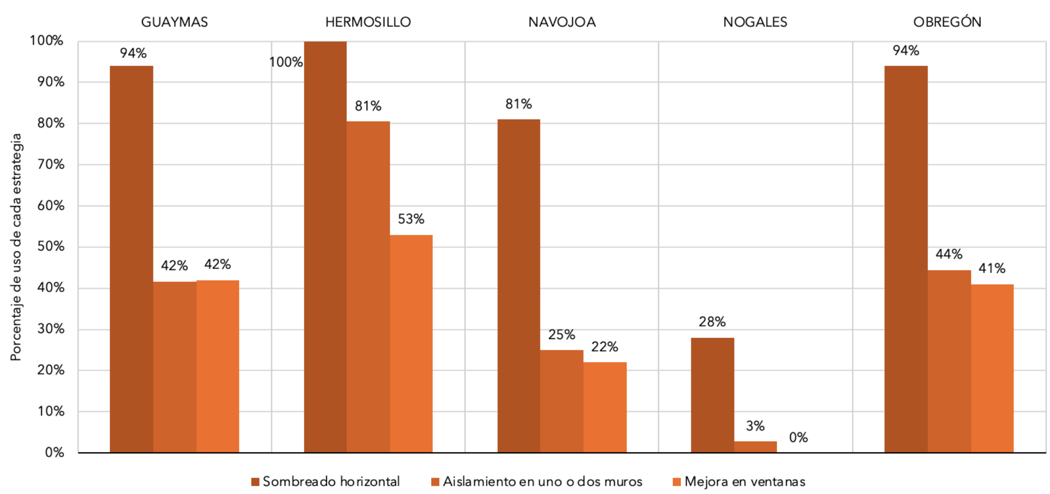

Figure 7: Percentage of use strategies implemented by city to comply with NOM-020. Source: Preparation by the Authors.

savings levels plotted in Figure 6, Figure 7 shows the percentage of each strategy used by city. That is, the percentage of each strategy represents the proportion of times the particular strategy was used relative to the number of models analyzed. To comply with NOM-020, 100% of the houses in Hermosillo were horizontally shaded, 81% required insulation on at least one wall, and 53% of the models had the window quality improved either with film or a double-glazed window. Obregón and Guaymas are very similar, where about 94% of the models included shading, and about 40% required insulation and/or improvement in windows. In the case of Navojoa, 81% required shading, while only about 20% of the models required wall insulation and or window improvement. Finally, in Nogales, the shading strategy was applied to 28%, only 3% required insulation, and the strategy of improving windows was not used.

COST OF IMPLEMENTING THE STRATEGIES TO COMPLY WITH NOM-020

Implementing the above strategies increased direct housing costs, as shown in Figure 8. Hermosillo has the highest cost overruns to achieve compliance with NOM-020, with an average of 2.95%. Obregón and Guaymas follow, with similar average cost overruns of 2.23% and 2.17%, respectively. In Navojoa, the average cost overrun is 1.61%; finally, Nogales has a 0.68% average cost overrun.

ESTIMATION OF SAVINGS

The difference between the first and second analyses generates estimates of possible savings in electricity consumption and costs and GHG reductions in CO_2e.

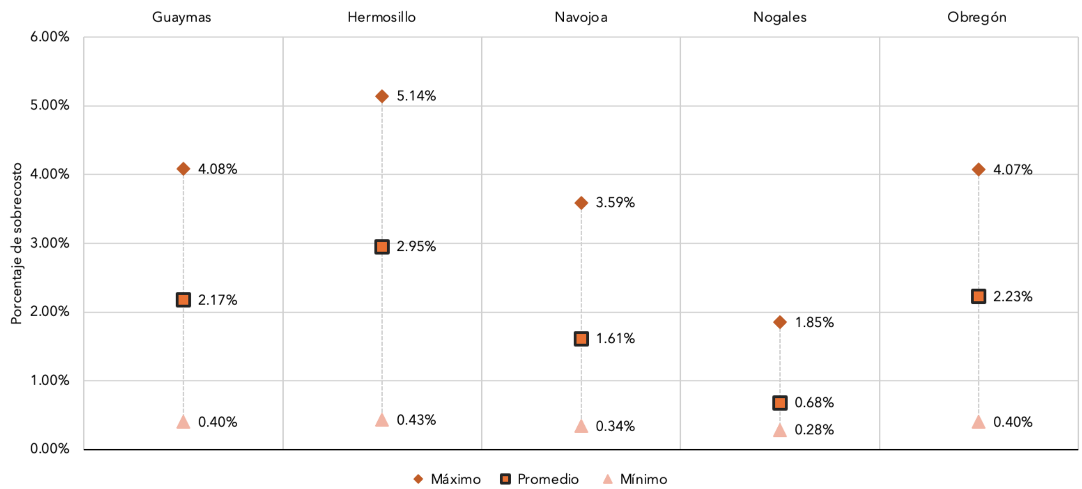

Figure 8: Cost overruns by implementing strategies for compliance with NOM-020 by city. Source: Preparation by the Authors.

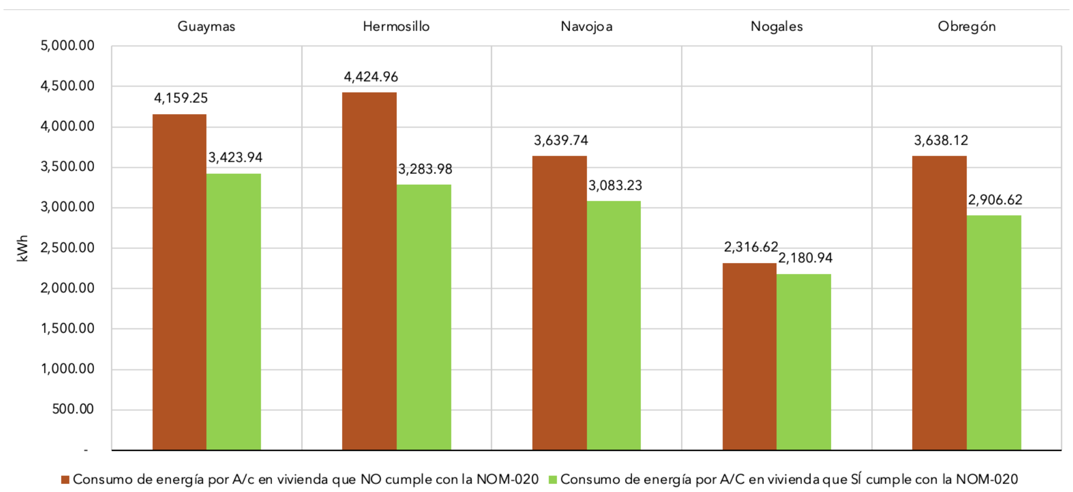

Figure 9: Estimated average A/C energy consumption in kWh of all models by city that do not comply with NOM-020 against the estimated energy consumption of those that do comply with NOM-020. Source: Preparation by the Authors.

Figure 9 shows the estimated average energy consumption in kWh of all homes by city that do not comply with NOM-020 against the estimated energy consumption of the homes that do. These consumption values are from April to October, with an average A/C use of 11 hours a day (INEGI, 2018). The calculation is limited only to A/C consumption, i.e., it does not consider the energy consumption by other devices. The most significant impact is in Hermosillo, with a 25.43% decrease in energy consumption, followed by Obregón and Guaymas, with 20.22% and 17.53%, respectively. The case with the least impact is Nogales, with 6.04%.

In Figure 10, the estimate of the total expenditure for energy consumption of the dwelling that does not comply with NOM-020 is presented against the total expenditure of the dwelling that does. For the calculation, it was estimated that air conditioning, as described in the introduction, represents 60% of the total energy consumption. The calculations contemplate the subsidy of the current CTE tariff scheme (Collaboration Agreement For Tariff Support For The State of Sonora, 2024) and are the accumulated expenditure during the season from April to October. According to the results, in Hermosillo, on average, $20,168.95 Mexican pesos would be allocated for the subsidized season in housing that does not comply, against $13,149.07 Mexican pesos in housing that does comply with NOM-020, a 35.32% savings. In Obregón, the average savings was 30.95%, Guaymas 25.10%, Navojoa 24.27%, and Nogales 15.80%. It is worth emphasizing that the subsidy percentage could reach up to 75% if compared with the regular tariff and that this percentage varies because it depends on the level of consumption.

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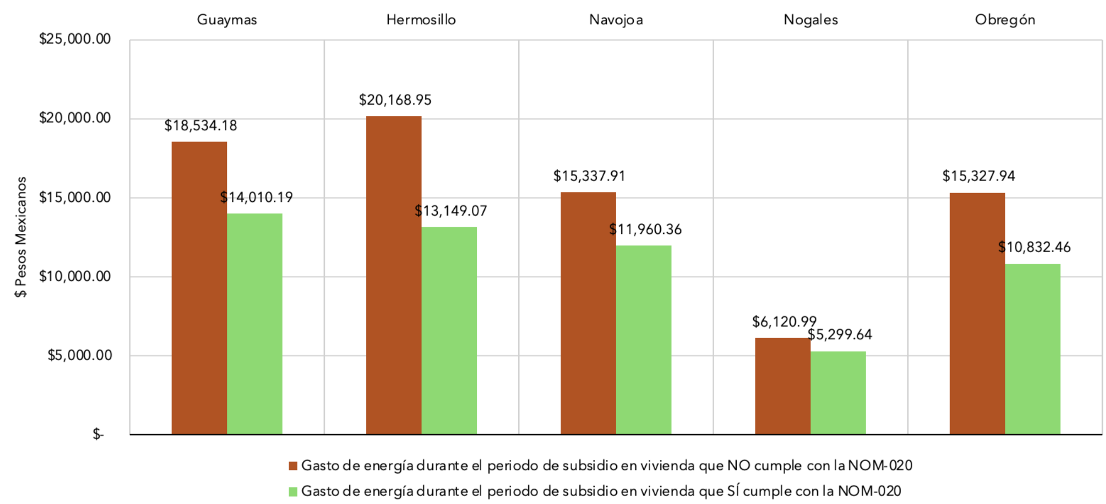

Figure 10: Estimated average energy expenditure from April to October, in Mexican pesos, of all dwellings by city that do not comply with NOM-020 against the energy expenditure of dwellings that do. 19.80 $MEX/dollar for August 2024. Source: Preparation by the Authors.

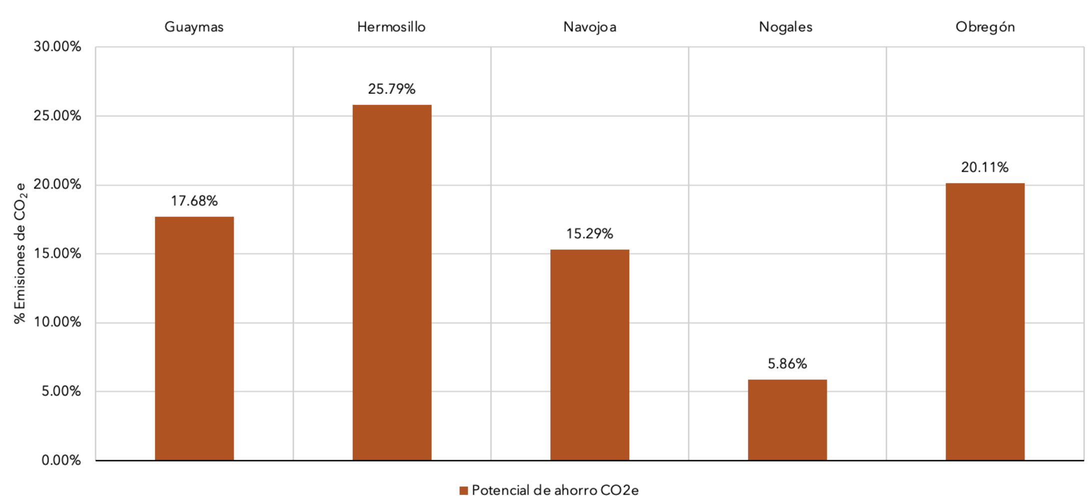

Figure 11. Potential CO2e savings per A/C season of the housing that complies with NOM-020 by city. Source: Preparation by the Authors.

Finally, the estimated CO_2 e saving potential of the dwelling that complies with NOM-2020 for the A/C use season is presented with the following values: Hermosillo 25.79%, Guaymas 17.68%, Navojoa 15.29%, Nogales 5.86% and Obregón 20.11%.

ANALYSIS AND DISCUSSION OF THE RESULTS

This study analyzes housing models located in a specific context, which considers particular climatic conditions, constructive characteristics typical of the region, and a specific energy tariff scheme. These factors vary considerably between regions, and consequently, energy poverty depends not only on the availability and cost of energy but also on the structural and cultural constraints that condition its efficient and safe use in each context.

This study considered housing of 43, 54, 61, 66, 78, 97, 104, 113, and 126 m2 to cover various areas according to the data of INEGI, (2020). Given its predominance in the region, the joist slab is used as a baseline (Romero Moreno et al., 2020). In addition, the study prioritizes shading strategies, limits insulation to 1 or 2 walls to a maximum of 1 inch, and uses up-to-date construction prices. These characteristics, together with the special tariff scheme for the State, represent the main differences compared to the analysis conducted by CONUEE (2017); no comparable study was found.

This study argues that although the current regulations require significant improvements in the calculation methodology, if applied today, at least at its minimum level, benefits would be obtained, and it is possible to achieve the energy efficiency range specified in the standard by combining various strategies.

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Since the same models were used for all the cities analyzed, Figure 2 shows the impact of climate on the efficiency level according to the calculation method, where Hermosillo is the most critical case. The case of Nogales suggests that, on average, homes in their initial state meet the efficiency level. This compliance would only apply to the efficiency of air conditioning, but there is no way to evaluate the efficiency conditions in the period with low temperatures. In Figure 3, the 1N_43 model has the smallest area and the highest WWR percentage, being the worst evaluated in all cities, even having negative percentages in Nogales. However, NOM-020 would not apply in Nogales according to the resolution of NOM-020 (2016). The 1N_43 model exemplifies a housing segment requiring summer efficiency strategies, especially for the more vulnerable.

On the other hand, in Figure 3, the 1N_97 model is the best evaluated as it complies in Navojoa, Nogales, and the rest of the cities. Although it has a negative value, the values are closer to zero. What can be seen from this is that this model has the lowest WWR (see Table 2).

When it comes to orientation, as expected, the east or west-facing houses are the most critical, but a significant change is observed when the same models face north or south. For example, in Hermosillo, the west-facing models have an average of -40.53%, but the same models facing south achieve an average of -15.68, obtaining a difference of 24.85 percentage points; see Figure 4. It should be clarified that some of the analyzed models had a higher WWR on the rear façade. Therefore, houses with a south-facing main façade get a better evaluation than the north-facing one. Thus, a fundamental strategy to comply with the regulations would be to modify designs to minimize transparent surfaces in unfavorable orientations, regardless of where the main façade is.

As already mentioned, NOM-020 would not be mandatory for Nogales. However, 31% of the homes analyzed required improvements (Figure 5), most solved with shading systems. In very few cases, walls used insulation (Figure 7), representing an average cost overrun of 0.68% (Figure 8).

In the case of Navojoa, 83% of the analyzed models required strategies (Figure 5), where most cases were solved with shading systems, and about 20% would require insulation and window improvement (Figure 7), with an average cost overrun of 1.61% (Figure 8).

Guaymas and Obregón required improvements in 94% of the evaluated cases (Figure 5). The strategies to achieve this include shading in all the improved models. About 40% of the cases required insulation in one or two walls and improving the window characteristics (Figure 7), representing an average overrun of about 2% per dwelling (Figure 8).

Finally, the most critical case is Hermosillo, where all the models evaluated required strategies; 100% were shaded, 81% required insulation on one or two walls, and 53% required window improvements. This city represents the largest average overrun with 2.95%, but also represents the greatest savings in energy consumption and expenditure (Figures 10 and 11). It should also be considered that Hermosillo is the most populous city in the state of Sonora, so energy savings by applying the standard would potentially have more impact than in other cities.

It is important to highlight the impact of the tariff scheme on energy expenditure, as the subsidy can cover up to 75% of the total bill depending on the level of consumption, where the cost of the surplus kWh can be up to five times higher than that of the first level. Although this measure is not sustainable in the long term for the treasury or the environment, it is effective and benefits a large part of the population. Without this government support, most households would find the estimated energy costs unaffordable. In the absence of energy efficiency in housing, energy subsidies have worked as a temporary solution to alleviate this economic burden.

CONCLUSIONS

Complying with the minimum level of NOM-020 in the State of Sonora would represent, on average, an overrun of 1.93% in construction, benefiting from a potential economic savings of 26% for electricity from April to October and a decrease of 16.95% in CO_2e emissions. This was achieved without needing to change the construction systems commonly used in the region's housing or using excessive insulation. Also, priority was given to shading systems, and insulation was limited to 1 inch on a wall for a maximum of 2 walls.

The most critical cases are homes with a smaller surface area because the WWR is higher and considerably impacts the calculation, especially if the windows are placed in critical orientations, especially in extreme climates like Hermosillo. On the other hand, models were identified that required additional improvements in cooler climates, such as the case of Nogales. However, these could have been avoided if an orientation and adequate window protection for the hot season had been considered from the design stage. In no case is the efficiency of the envelope during the cold season known. Implementing efficiency strategies to "correct" these models considerably impacts the housing cost due to the ratio of the investment cost versus the housing cost.

In addition, with the analyzed data, the following appropriate configurations are proposed for each analyzed locality:

- For Nogales, shading windows during the hottest season can be effective in complying with regulations, as can avoiding west-facing windows or, where appropriate, placing the smallest windows on this side.
- For Navojoa, besides the shading strategy in the hottest season, it is important to avoid east—and west-facing windows or place the smallest windows on these sides. In some cases, the wall insulation strategy is required.
- For Guaymas and Obregón, apart from the shading strategy in the hottest season, insulation on one or two walls and/or an improvement in the window quality is relevant, depending on the dwelling's specific design. It is important to avoid, as far as possible, east—and west-facing windows. If needed, smaller ones must be used on these sides.
- Finally, for Hermosillo, the shading strategy is essential in the hottest season. The vast majority of cases require insulation on one or two walls, and an improvement in the window quality has a considerable impact depending on the specific design of the house. Avoiding east- and west-facing windows as far as possible, particularly in the west, is imperative.

Habitability of spaces is guaranteed through a regulatory framework that integrates building regulations and energy efficiency standards, aligned with their objectives, and adapted to the specific context, requiring developers and builders to comply with minimum standards of quality, accessibility, and sustainability in the context of climate change. However, in reality, this is not the case. In this sense, it would be advisable for municipalities to include a series of best local design practices in the building regulations that consider specific temperature conditions and minimum and maximum window-to-wall ratios by orientation without neglecting the issue of ventilation and daylighting. In addition, it could also be established in the regulations that the base construction systems analyzed here, or similar, are considered as minimum constructive characteristics for urban housing.

Although improving the current calculation method of NOM-020 and considering the municipality's and architecture and construction professionals' implementation capabilities are necessary, its application must begin immediately. Applying the current regulations represents an opportunity to improve living conditions; in the meantime, the work on improving the current regulations must continue.

In future research, it would be essential to conduct more accurate projects on the thermal conductivity values of locally produced materials to facilitate the adaptation of constructive solutions to the region's specific conditions. Also, since the tariff scheme is based on consumption levels, it would be relevant to develop innovative strategies that allow users to monitor and manage their consumption to maximize the benefits of this tariff structure.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, C.M.G.B., A.C.B.A., J.M.O.de la T., I.M.L.; Data curation, C.M.G.B.; Formal analysis, C.M.G.B., A.C.B.A., J.M.O.de la T., I.M.L; Acquisition of financing, J.M.O.de la T.; Research, C.M.G.B.; Methodology, C.M.G.B., A.C.B.A., J.M.O.de la T., I.M.L.; Project management, J.M.O.de la T.; Software, C.M.G.B.; Supervision, A.C.B.A., J.M.O.de la T., I.M.L.; Validation, C.M.G.B.; Visualization, C.M.G.B.; Writing - original draft, C.M.G.B.; Writing - revision and editing, C.M.G.B., A.C.B.A., J.M.O.de the T., I.M.L.

ACKNOWLEDGEMENTS

The article comes from the Project funded by the University of Sonora. Code - USO318009160. Benefits of compliance with NOM-020-ENER-2011 in hot dry climate.

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https://doi.org/10.22320/07190700.2024.14.02.04

Recibido 26/07/2024
Aceptado 15/11/2024

ANALYSIS OF EVOLUTIONARY MORPHOLOGIES WITH CFD: IMPROVING NATURAL VENTILATION IN CENTRAL COURTYARD HOUSING, IN SEMI-WARM AREAS OF LATIN AMERICA

ANÁLISIS DE MORFOLOGÍAS EVOLUTIVAS CON CFD: MEJORAR LA VENTILACIÓN NATURAL EN VIVIENDA DE PATIO CENTRAL, EN ZONAS SEMI CÁLIDAS DE LATINOAMÉRICA

ANÁLISE DE MORFOLOGIAS EVOLUTIVAS COM CFD: MELHORIA DA VENTILAÇÃO NATURAL EM HABITAÇÕES DE PÁTIO CENTRAL EM ÁREAS SEMI-QUENTES DA AMÉRICA LATINA

Diego Rodríguez-de-Ita
Magíster en Arquitectura
Estudiante de Doctorado, Profesor del Departamento de Arquitectura y Diseño Industrial, Facultad de Arquitectura
Universidad Autónoma de Nuevo León, San Nicolás de los Garza, México
https://orcid.org/0009-0001-2796-6484
diego.rodriguezdt@uanl.edu.mx (Autor de Correspondencia)

Liliana Beatriz Sosa-Compeán
Doctorado en Filosofía de la Arquitectura y Asuntos urbanos
Profesora Investigadora en la Facultad de Arquitectura y Jefatura de Investigación en Diseño Industrial
Universidad Autónoma de Nuevo León, Monterrey, México
https://orcid.org/0000-0001-8811-3218
Liliana.sosacm@uanl.edu.mx

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 48 -59
https://doi.org/10.22320/07190700.2024.14.02.04

RESUMEN

Este estudio busca reducir la demanda energética en la arquitectura mediante el uso de estrategias pasivas, específicamente enfocadas en la ventilación natural interior. Se realizaron simulaciones computacionales (CFD: Computational Fluid Dynamics) y se utilizó algoritmos paramétricos en Grasshopper, en que se aplicó una metodología basada en el diseño evolutivo. El objetivo es optimizar el diseño de viviendas unifamiliares de patio central con ventilación cruzada, al evaluar cómo la morfología de las viviendas influye en su desempeño en términos de ventilación natural. A través de procesos de morfogénesis y diseño evolutivo; se generaron más de 200 variaciones morfológicas (muestras), cuyos resultados permitieron seleccionar los modelos con mejor desempeño. Los genes más exitosos se combinaron en nuevas generaciones para repetir las evaluaciones, lográndose finalmente un modelo de vivienda que optimiza la ventilación hasta 2.5 veces más que el modelo tradicional de casa con patio central.

Palabras clave
diseño evolutivo, ventilación natural, arquitectura sustentable, CFD en vivienda de patio central.

ABSTRACT

This study aims at reducing energy demand in architecture through passive strategies, specifically focusing on natural indoor ventilation. Computational simulations (CFD: Computational Fluid Dynamics) were conducted, and parametric algorithms in Grasshopper were employed, applying a methodology based on evolutionary design. The aim is to optimize the design of single-family courtyard houses with cross-ventilation by evaluating how their morphology influences their performance in terms of natural ventilation. Through morphogenesis processes and evolutionary design, more than 200 morphological variations (samples) were generated, whose results allowed the selection of the best-performing models. The most successful genes were combined in new generations to repeat the evaluations, ultimately achieving a housing model that optimizes ventilation up to 2.5 times more than the traditional courtyard house model.

Keywords
evolutionary design, natural ventilation, sustainable architecture, CFD in courtyard housing.

RESUMO

Este estudo tem por objetivo reduzir a demanda de energia na arquitetura por meio do uso de estratégias passivas, com foco específico na ventilação natural interna. Foram utilizados a Dinâmica de Fluidos Computacional (CFD) e algoritmos paramétricos no Grasshopper, nos quais foi aplicada uma metodologia baseada em design evolutivo. O objetivo é otimizar o projeto de residências unifamiliares com pátio central e ventilação cruzada, avaliando como a morfologia das residências influencia seu desempenho em termos de ventilação natural. Por meio de processos de morfogênese e design evolutivo, foram geradas mais de 200 variações morfológicas (amostras), cujos resultados permitiram a seleção dos modelos de melhor desempenho. Os genes mais bem-sucedidos foram combinados em novas gerações para repetir as avaliações e, por fim, chegou-se a um modelo de habitação que otimiza a ventilação até 2,5 vezes mais do que o modelo tradicional de casa com pátio central.

Palavras-chave:
design evolutivo, ventilação natural, arquitetura sustentável, CFD em habitação com pátio central

INTRODUCTION

In the field of architectural analysis, according to computational simulations, the use of digital tools based on computational fluid dynamics (CFD) has enabled significant progress in design, particularly in improving natural ventilation. This analysis, which focuses on contributing to biophilic architecture (Zhong et al., 2021), is based on the design strategy of: 'the built environment morphology where it directly influences the airflow dynamics, affecting the natural ventilation distribution and the speed of currents within the space' (ASCE. 2023a, p. 107); improving the comfort conditions (El Ahmar et al., 2019), while reducing energy demand. This analysis focuses on optimizing the central courtyard housing typology with parametric methods, according to Bensalem (1996):

> The few studies on courtyards indicate that, with large sizes, a part of the air current could penetrate the empty space, raising the pressure on the courtyard's rear wall. This could increase the cross ventilation in the leeward walls. This effect was less evident in smaller courtyards (pg. 74).

Wind pressure is the ventilation mechanism that primarily affects central courtyard housing. When the wind hits a building, it creates a distribution of static pressures on the outside surface that depend on the wind direction, speed, density, orientation of the surface, surrounding conditions, and the shape of the building (ASHRAE, 2009).

The main problem is that design methods do not always optimally consider how morphological variations affect the airflow behavior inside. Consequently, approaches that integrate evolutionary methods and parametric simulations are needed to develop architectural typologies, such as housing, that maximize wind use. The objective is to start from the central courtyard house and create geometric layouts that improve natural ventilation and reduce energy demand.

STATE-OF-THE-ART

In the research of Albel Tablada de la Torre et al. (2005), where CFD is used to study 3-floor central courtyard homes, they realized that performance is optimized when ventilation is not unilateral but crossed. Similarly, the importance of having more central courtyards was also studied. It was also determined that the rooms on the upper floor of the narrow courtyard (Figure 1) have higher air velocities than the upper floors of the wider courtyard; 'since they capture most of the airflow entering the courtyard cavity, causing the rooms on the lower floors to have much lower air velocities' (Tablada de la Torre et al., 2005, p. 3)

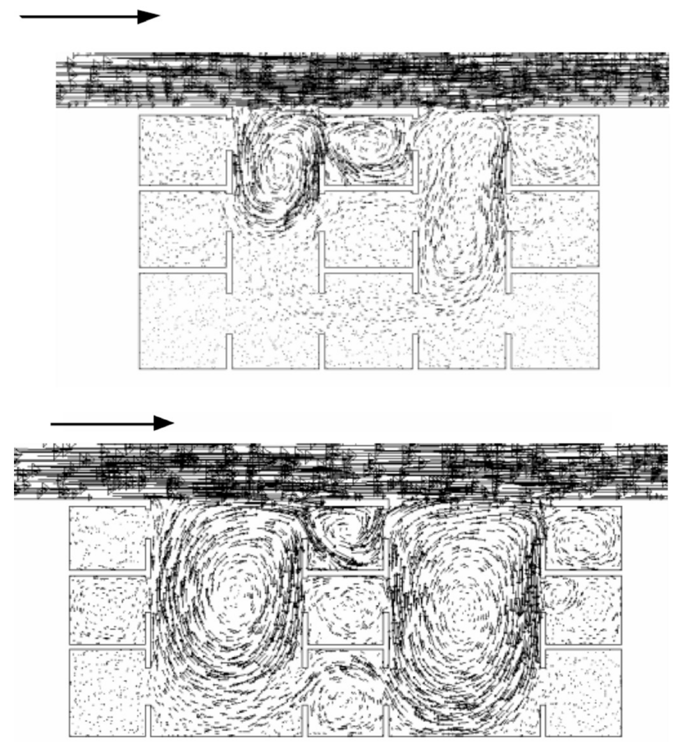

Figure 1. Airflow inside two interior courtyards and rooms with open windows. Source: Image taken from Tablada de la Torre et al. (2005)

In the investigation of Malawi. et al. (2005), a model based on genetic algorithms for the evolution of the design, using dynamic CFD to evaluate the model's performance, which generates the possibility of creating models that improve natural ventilation and previewing the results (Zheng et al., 2020), is presented. They analyze and evaluate the cross-ventilation capacity of a low-rise building with blinds to create shade, also known as louvers. Based on the coupled airflow model (similar to wind flow), the model couples indoor and outdoor airflow to perform a cross-ventilation evaluation. The greatest reduction in the ventilation rate used by louvers was up to 66.6%.

On the other hand, Rodrigues Marques Sakiyama et al. (2021) presented a CFD analysis of indoor ventilation using the wind tunnel process. They concluded that the building's orientation determines the quality of natural indoor ventilation.

Wind tower studies are also considered in this state-of-the-art as they are traditional architectural solutions that share the goal of improving natural ventilation; in addition to the hygrothermal quality, evaporative wind towers not only increase the amount of fresh air but also increase the relative

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humidity of the air, which generates greater thermal comfort. This happens due to the Stack Pressure ventilation mechanism, caused by the mass of an air column inside or outside a building. It can also occur inside a flow element, such as a duct or a chimney. (ASHRAE, 2009)

METHODOLOGY

A methodology based on parametric and CFD simulation was followed, integrating the following steps:

a. Base model (common ancestor): This is based on an initial central courtyard housing model, which acts as a common ancestor.
b. Morphological transformations: An algorithmic methodology is used in Grasshopper (Echeverri Montes, 2021), applying a series of transformations inspired by the Theory of Transformations to the base model's morphology.
c. CFD simulations: Each generated typology is evaluated using CFD simulations, which aim to analyze the natural ventilation behavior in each transformation.
d. Selection and crossing of genes: The 'winning' samples or best-performing ones are identified, and the areas of the house with the highest ventilation flows are recognized. These are combined with other winning samples.
e. Final selection: This second generation of samples is evaluated, and we obtain the one with the best performance (fitness[1]).
f. Analysis of window height: The best-fit wind behavior is analyzed using the results achieved regarding window heights (outlet), sill height, and lintel.
g. Comparison with the common ancestor: The air intake inclination angle in the central courtyard is compared between the two results.

THEORY OF TRANSFORMATIONS

This is a morphogenesis proposal conceived by D'Arcy Thompson (1917, as cited in Werritty 2010), which examines, especially from a geometric perspective, the different types of formal transformations that could have a biological and physicochemical significance related to evolution (Figure 2) (Iurato & Igamberdiev, 2020). The

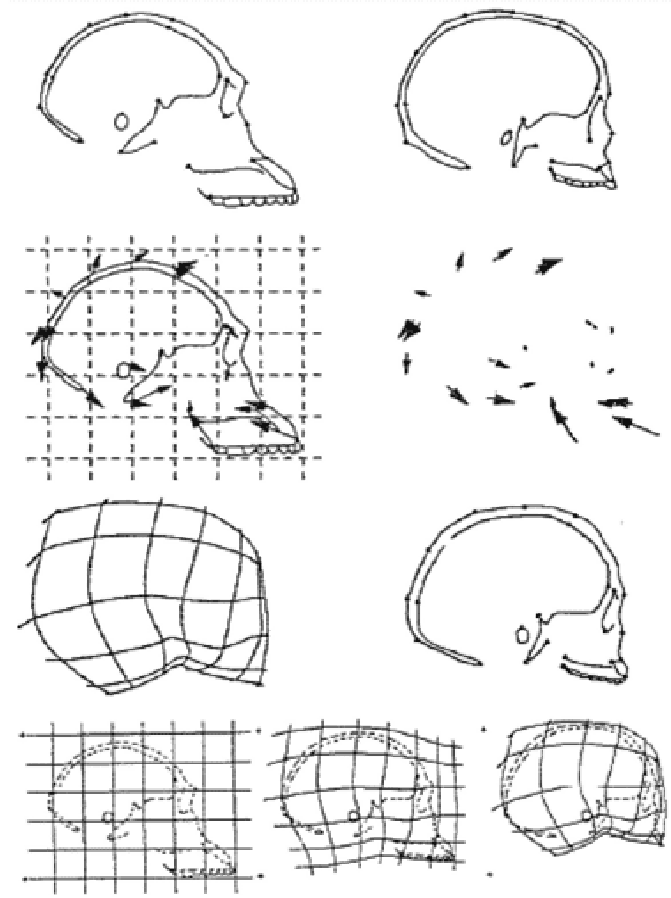

Figure 2. Theory of Transformations. Source: Image taken from Werritty (2010).

homologous points and the outlines indicated are shown in the first row. The movements needed to bring the homologous points from the first image to the second are represented in the second row. Finally, the two ends of the transformation are presented in the bottom row (Werritty, 2010).

EVOLUTIONARY DESIGN

Darwin's preferred term for evolution is "descent with modification." Genetic information is transmitted by DNA between generations in most organisms (Whitlock, 2014). Usually, the population starts randomly, i.e., with randomly selected elements considered potentially useful in the given environment. Then, the fitness of each solution is evaluated, which involves a measurement or calculation to determine the relative effectiveness of each one. The results of this evaluation are used

1 Fitness involves the ability of organisms to survive and reproduce in the environment they are in. The consequence of this survival and reproduction is that organisms contribute genes to the next generation (Allen, 2009).

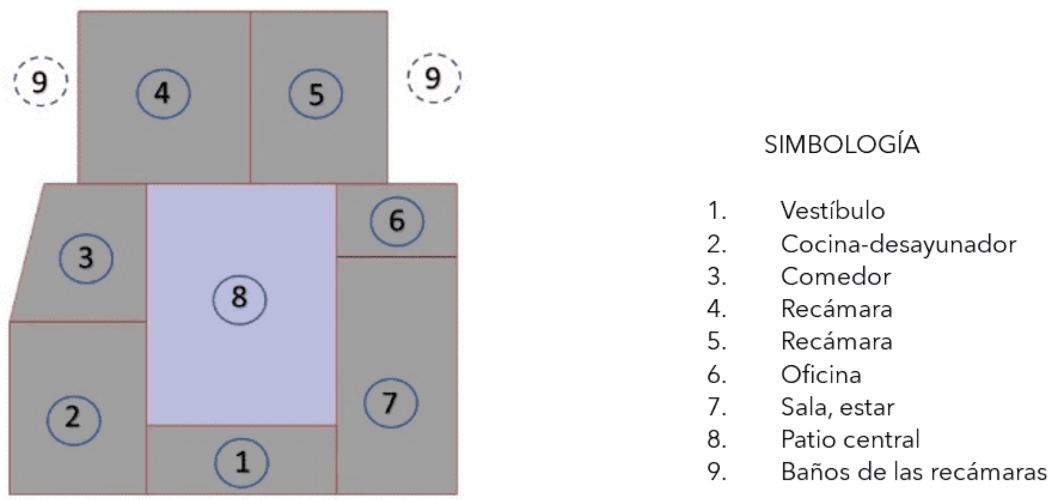

Figure 3. Design of the common ancestor. Areas 9 (bathrooms) are excluded from the analysis. Source: Preparation by the authors.

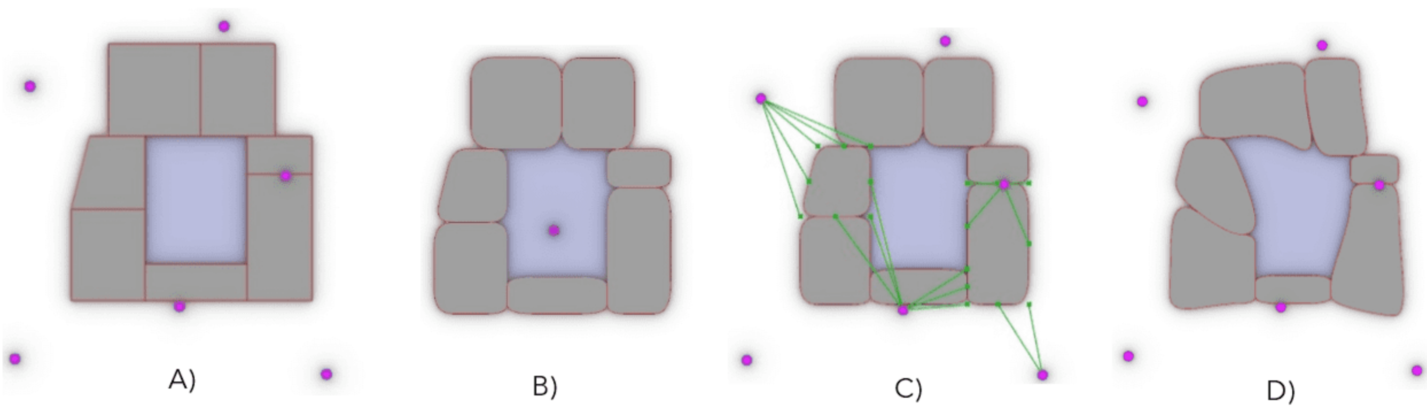

Figure 4. Transition. Source: Preparation by the authors.

at the selection stage to decide which individual solutions will continue in the competition for resources. (Banzhaf, 2013). Variations can occur due to mutation, duplication, or crossing of genes, among other reasons. According to Banzhaf, the main components of evolutionary design to create generation-by-generation sampling are as follows:

- Evaluation: As a process, adaptation describes the part of evolutionary change in a trait driven by natural selection. As a state, this refers to "adaptation features" (Futuyma, 2017).
- Reproduction: The multiplicity of species implies that evolution branches into different population lineages over time.
- Variation: In reproduction, there must be variability among descendants so that natural selection can operate effectively.
- Selection: This determines which species have the best qualities for reproduction.

RESULTS

Next, a series of steps are presented for modeling this analysis's algorithmic, evolutionary, and CFD simulation processes.

STEP 1: BASE MODEL

The common ancestor (Figure 3) on which the future morphological transformations are going to be carried out was designed based on historical architectural typologies of central courtyard housing, such as the traditional Mozabite housing (Algeria) (Zamani et al., 2012) and the Kahkeshan house, in the city of Isfahan (Iran), along with the premise that the central courtyard is directly alongside all areas of the house, the social areas are accessed through a hall, while the private areas are

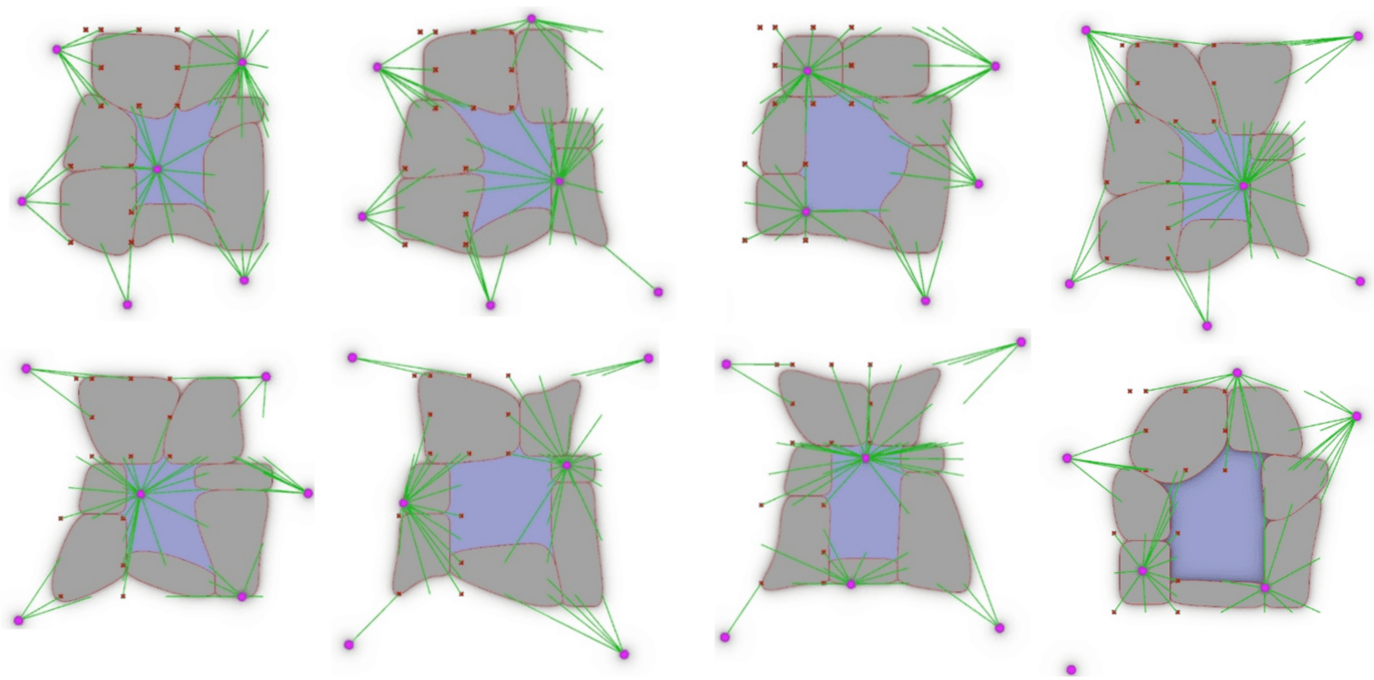

Figure 5. Some samples obtained. Source: Preparation by the authors.

at the end of the hallway. An algorithm is developed in Grasshopper that creates variations of this common ancestor; each variation is considered a sample. The algorithm must have particular parametric conditions so that each transformation's results always give a single closed surface area without lines, surfaces, or vertices crossing. In addition, all these samples have a very similar total area.

STEP 2: MORPHOLOGICAL TRANSFORMATIONS

Inspired by the theory of transformations, the vertices of each house area (kitchen, bedroom, etc.) are stretched towards the points represented with violet spheres (Figure 4). These are placed in ranges of randomness in space. The random points stretch the vertices that are closer to them. This direction's force (magnitude) is related to the distance from these points.

This begins by first converting the square areas by rounding the corners (Figure 4 B). For explanatory purposes, Figure 4(C) only measures the random points of the dining room, living room, and hall areas. The models are made from all the areas. The samples obtained are shown in Figure 5.

Similarly, to comply with an orderly and logical structuring of each house model, the partial selection of the curves alongside the central courtyard is contemplated. This is in order to select one part as a window and another as a column-type structuring element (these rules will be implemented by the algorithm based on the contour derivative of each geometry, which contemplates the alternation between contiguous figures, where the smaller curves obtained from the derivation are considered as columns) (Figure 6). In this way, the edge surfaces or boundaries are also determined, which is essential data for the calculation by CFD (Figure 8).

Figure 6. Structural alternation. Vertex control points in violet. Air outlet openings in light blue. Entrance openings in white. Source: Preparation by the authors.

STEP 3: CFD SIMULATIONS

The study's primary tool is Grasshopper, where the evolutionary algorithm and selection process are

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https://doi.org/10.22320/07190700.2024.14.02.04

made. The natural ventilation simulation is done similarly using Butterfly. The latter is a Python plugin and library for creating and running advanced CFD simulations using OpenFOAM[2] (Ladybug Tools [LLC], 2022). CFD involves solving coupled partial differential equations, which must be solved successively. It can be used to solve fluid flow, heat transfer, chemical reactions, and even thermal stress problems. The main equations remain constant for all indoor airflow and heat transfer applications. However, the boundary conditions change depending on the specific problem: for example, the room layout or the supply air velocity may vary (ASHRAE, 2009).

The type of simulation used in this experiment is called "Inlet-Outlet," which simulates the flow of air driven by the wind indoors to evaluate the effectiveness of ventilation. It is the most suitable method, unlike the wind tunnel (urban-type study) and HVAC[3], among others. These calculations take grasshopper geometric surfaces as edge boundaries to distinguish the three indispensable values for this simulation: 1. Inlet: natural air inlet. 2. Outlet: natural air outlet. 3. Walls: boundary, contour, or, in this case, the house's morphology limits. The inlet is the surface representing the central courtyard at the house's highest point (Figure 8).

Since all geographical areas have different values for air velocity, temperature, and inclination due to topography, the density of buildings, vegetation, etc. (ASCE, 2023d), this process must be carried out according to the meteorological information of the geographical area where it is they are located (Figure 9). Due to these factors, the results can vary up to 200 m/s.

The inlet air velocity values are considered in randomness ranges from 0.2 to 0.8 at m/s—perception values of "calm" ventilation (Soler & Palau, 2022). In addition, there are small negative values vertically or on the z-axis of 10 degrees: this is a common practice in analyzing wind dynamics in urban environments. Although a wind tunnel was not used, the logic of applying variations at small angles is consistent with standards such as those mentioned in (ASCE, 2023c, p. 25), which recommends testing wind directions in increments of 10 degrees of azimuth, an approach designed to capture significant airflow responses.

The inlet temperature is set randomly between 22 and 35° C because it is the temperature at which it is considered that this house-room model can have the most benefit and scope to mitigate the sensation of heat without using mechanical means. The 'Wall' component defines the edge or contour limits of the entire house. The temperature for this is between 15 and 30° C, although simulations were repeated at 40° C that report few differences because it is a central courtyard housing model. The remaining parameters of this component come by default from the software; these include a non-slip condition and zero pressure gradient in the direction perpendicular to the wall, among others (OpenFOAM, 2019). The air velocity and direction generate the pressure in this type of analysis, so the pressure value is set at 0, which indicates that the pressure values start from this value.

Different sources of information, such as Wolf Dynamics (2018), were used to adapt the SnappyHexMesh4 (SPM) component to an architecture with curved shapes. Contrary to how the 'snap' input is preset, it must be disabled. The 'additional parameter' input must be set at the lowest possible integer: 1; the lower this number, the better the component adheres to curved surfaces.

The results obtained in the simulations are the indoor ventilation flow diagram (horizontal analysis x, z) and a pressure diagram. The first consists of a field of vectors (total V) containing (N) number of cells with one vector each: each vector has direction and magnitude (or force), which represents the wind speed and direction in m/s. Each variation obtained in the evolutionary process is subjected to these tests. The magnitudes are added and divided by N to obtain an average wind

$$Vinterior = \frac{1}{N}\sum_{i=1}^{N} \| Vi \|.$$

speed inside the house (V interior) (Equation 1):
(Equation 1)

Vectors with SPM cells equal to or less than $0.5m^2$ are discarded since they are empty and do not contain magnitude. In many cases, N reduces its value considerably, resulting in effective N.

ANALYSIS OF THE COMMON ANCESTOR - CFD SIMULATIONS

The first evaluation: the common ancestor (Figure 7), obtains an interior speed of 0.8367 m/s. Total V = 410 m/s. N = 490. The morphological transformations explained in Step 1 occur in the second generation of

2 OpenFOAM is an open-source software used for computational fluid dynamics (CFD) simulations.
3 HVAC, or Heating, Ventilation, and Air Conditioning is a system that mechanically provides heating and cooling in residential and commercial buildings.
4 Specifically designed to generate high-quality dominant Hexa meshes for complex geometries (Wolf Dynamics, 2018).

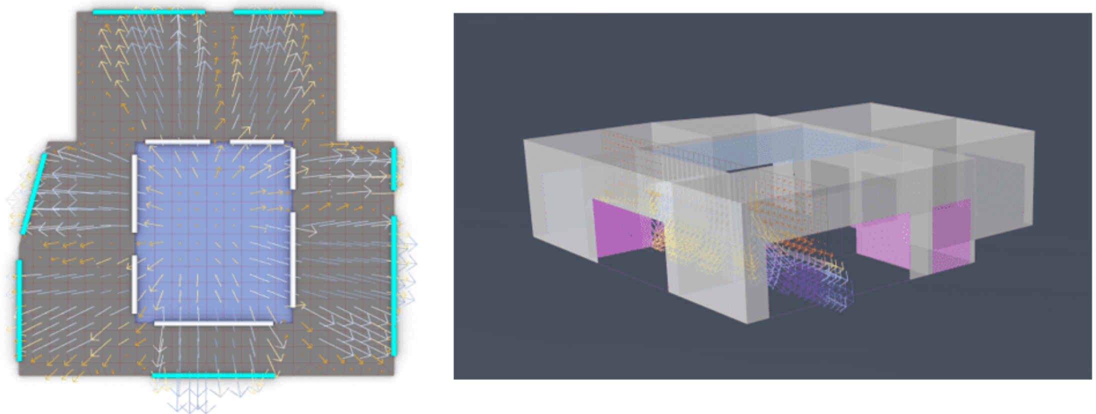

Figure 7. Simulation of the common ancestor Source: Preparation by the Authors.

Figure 8. Input data for the simulation. Source: Preparation by the authors.

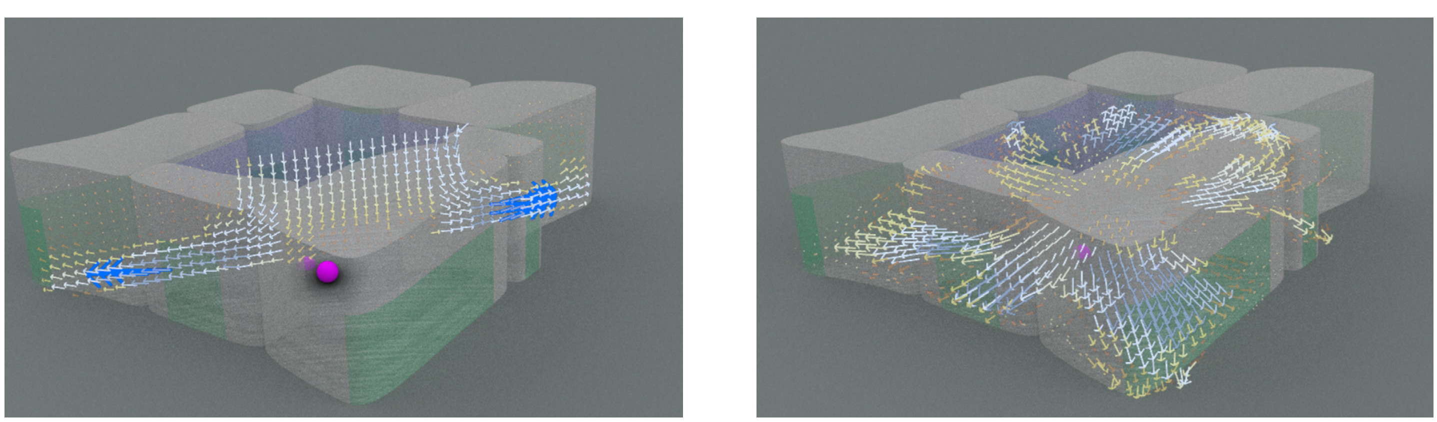

Figure 9. Analysis of the models. A) Vertical analysis: with x-coordinates. B) Horizontal analysis: x, z. Source: Preparation by the authors.

models, resulting in 75 different models being evaluated. In Figure 8, the inlet surface is blue, the outlet surface is turquoise, the normal surface is green, and the walls are white. Figure 7 (B): Snappy Hex Mesh (SHM) grid.

STEP 4: SELECTION AND CROSSING OF GENES

The higher magnitude vectors are extracted from the analysis. The random points that determine these vectors must be found to do this (Figure 9). These are the ones that are combined with those of another champion species to define the reproduction, variation, and general morphology of the third-generation models. Figure 10 shows how only 3 random points are selected from the original 6 to 8. In this way, only the most powerful genes will be detected, and new points will be added randomly

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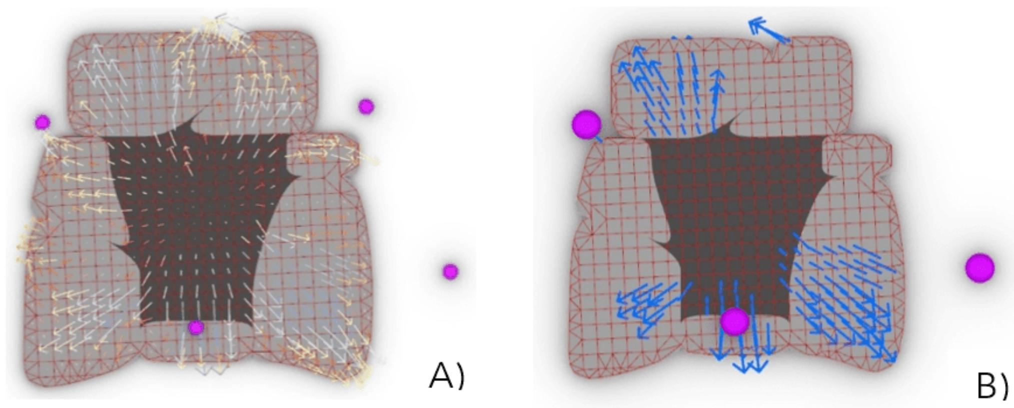

Figure 10. The process of combining winning genes. The blue color vectors (B) have a higher magnitude. Source: Preparation by the author.

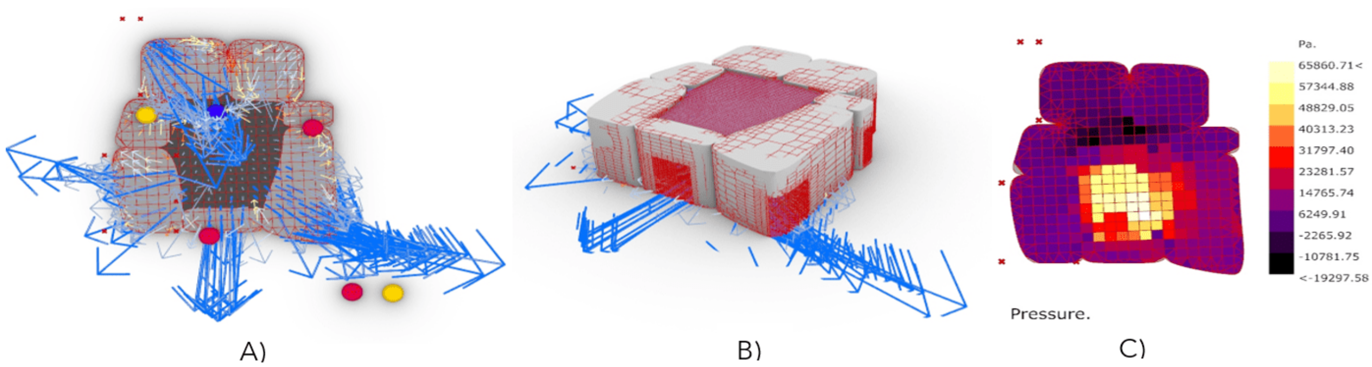

Figure 11. Winning model 09 of the third generation. Increased visualization of the vectors. Source: Preparation by the authors.

Table 1. Window height analysis of second-generation model 09. Source: Preparation by the authors.

Sim.	Type of simulation	Horizontal analysis H (m)	Sum. Total (m/s)	Interior V (m/s)	Window H (m)	Lintel H (m)	Sill H (m)
A	Vertical		925.3	1.7	0.5	2.3	1.2
B	Vertical		1398.7	2.6	0.8	2.0	1.2
C	Vertical		1471.2	2.7	1.4	0.6	2.0
D	Vertical		1474.5	2.7	2.3	0.6	1.1
E	Vertical		1439	2.7	2.3	1.6	0.1
F	Horizontal	3.2	1557.4		0.8	0.8	2.4
G	Horizontal	0.1	1620.2		0.8	0.8	2.4
H	Horizontal	0.1	1760.6		2.3	0.1	1.6

to enrich the obtained models' variation.

STEP 5: FINAL SELECTION

The model with the best fitness is model 09 of the third generation, having a Vtotal= 1,760.62 m/s. N=855v, observed in Figure 11; blue spheres are random points of the champion model of a previous generation, pink points of another champion model, and blue points that represent new possibilities for this latest generation.

STEP 6: WINDOW HEIGHT ANALYSIS (OUTLET)

Vertical (x, z) and horizontal (x, y) analyses are carried out on the two models with the best fitness regarding natural ventilation performance in terms of window height (outlet) and height variations in sill and lintel (Figure 11). The best performance is obtained when the window is located at floor level with heights of 1.4 to 2.3 meters and the lowest from below 0.80 m.

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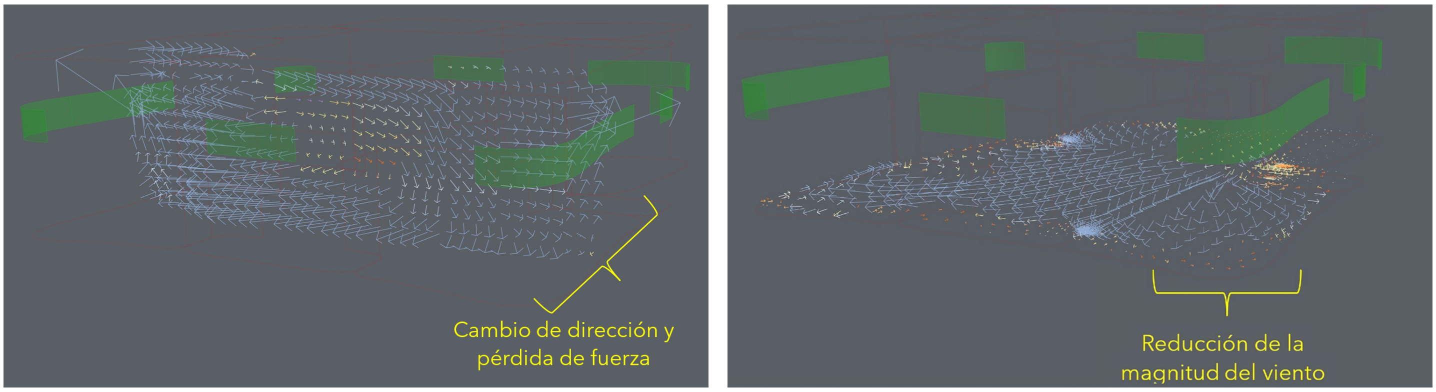

Figure 12. Outlet Analysis, simulations A, E, G, H. specified in Table 2. Source: Preparation by the authors.

Table 2. Comparison with the common ancestor. Source: Preparation by the authors.

Type of simulation	Cross-section H h (m)	(N) vector	Sum. Total (m/s)	Inlet V: Z (m/s)	V entrada: Z (m/s)	V interior (m/s)	Window H (m)
A.C.	0.1	412	160	0.8	- 0.5	0.38	
M.G.		911	825.3			0.90	
A.C.		482	322		- 1.0	0.62	2.3
M.G.		922	1253			1.32	
A.C.		482	402	0.2	-2.0	0.83	
M.G.		965	1662			1.72	

Considerable Total Vs are obtained (Table 1, F and G sim) with heights of 0.8 m. and large sills, but as can be seen: the wind direction near the sills and lintels is deviated perpendicularly to the walls or contours, which are interpreted as stagnation and turbulence zones (ASCE, 2023b), which can cause a decrease in the ventilation flow rate (Figure 12).

STEP 7: WINDOW HEIGHT ANALYSIS (OUTLET)

The results of both simulations are compared to the air intake inclination angle in the central courtyard. CA = Common ancestor, WM= Winning Model.

RESULTS AND DISCUSSION

The best fitness model obtained 1355 N, where more than 500 are empty cells; therefore, effective N is 855. Vtotal= 1,760.62 m/s. In this model 85% of the vectors are larger than 1.6 m/s. This means that in 85% of the house, not counting the central courtyard, there is a velocity greater than 1.6 m/s. This is interpreted that, with this procedure, the temperature inside the house is reduced by up to 4.2° C (Table 4) in 85% of the house (Soler & Palau, 2022). According to the Beaufort Scale, the sensation goes from having a feeling of 'calm" ventilation to "light air" (Table 3).

Table 3. Beaufort scale. Source: Information extracted from Soler & Palau (2022)

Beaufort Scale	Wind name	Speed (m/s)
0	Calm	0.5
1	Light air	1.5
2	Light breeze	3
3	Gentle breeze	6

The winning model's natural air velocity inside the house is 2.50 times higher than the common ancestor's, as shown in Figure 13 through pre-visualization.

CONCLUSIONS

These results show that it is possible to analyze and obtain a better performance of natural indoor ventilation in a house through the evolutionary design

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https://doi.org/10.22320/07190700.2024.14.02.04

Table 4. Effect on the human body. Source: Information extracted from Soler & Palau (2022)

Air velocity on people (m/s)	Feeling that the ambient temperature has been lowered by (°C)
0.1	0
0.3	1
0.7	2
1.0	3
1.6	4
2.2	5

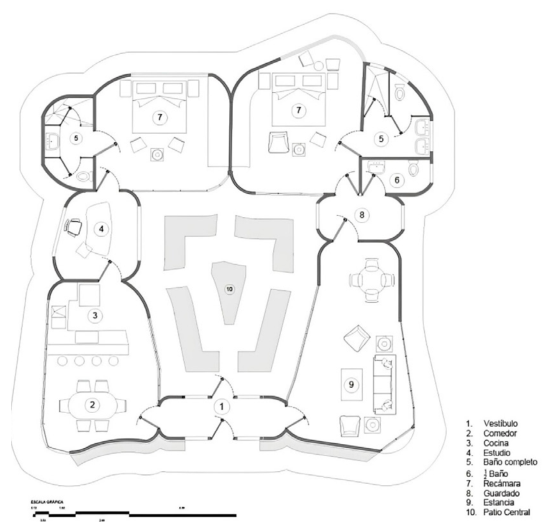

Figure 13. Application and visualization of the results of second-generation Model 03. Source: Preparation by the authors.

process presented in this article. This is appropriate in the context of biophilic architecture for its sustainability and incorporation of natural patterns in its morphology.

This process should be considered in an architectural design context since the methodology allows for analyzing natural ventilation performance in central courtyard housing through evolutionary design and CFD. This shows how evolutionary design can be an effective tool for exploring morphological variations. Moreover, this method is proposed to add value to work with existing sustainable architecture methods and techniques such as the garden slab and earthship, among others. This method is also proposed to contemplate using contemporary construction techniques, such as 3D printing.

The results could be developed further if more species are evaluated. This would include the growth of the housing area, new areas, uses, and layouts, among others, as well as the improvement of the algorithm, such as increasing the gene or DNA values and starting from a common ancestor of a different nature, up to the exploration of the ventilation behavior in different types of housing with different air inlets and outlets. The search and experimentation in other phenomena cause a relevant research hypothesis, such as the 'funnel' effect, 'the spiral,' and 'biomimetics,' among others. It also analyzes the hygrothermal properties of natural ventilation, such as air humidity.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, D.R. de-I. and L. a-S. C.; Data Curation, D.R. de-I.; Formal analysis, D.R. de-I.; Acquisition of financing, D.R. de-I. and L. a-S. C.; Research, D.R. de-I.; Methodology, D.R. de-I. and L. a-S. C.; Project Management, D.R. de-I.; Resources, D.R. de-I. and L. a-S. C.; Software, D.R. de-I.; Supervision, D.R. de-I. and L. a-S. C..; Validation, D.R. de-I.; Visualization, D. R. de-I.; Writing - original draft, D. R. de-I. and L. a-S. C.; Writing - proofreading and

Editing, D.R. de-I.

ACKNOWLEDGMENTS

We are grateful for the support provided through the CONAHCYT grant for the development of this research, "Evolutionary design for the optimization of comfort in natural ventilation".

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs.60 - 75
https://doi.org/10.22320/07190700.2024.14.02.05

Recibido 09/07/2024
Aceptado 02/12/2024

NATURE IN SPACES FOR OLDER PEOPLE: A BIOPHILIC APPROACH, IN THE WORLD

LA NATURALEZA EN LOS ESPACIOS PARA EL ADULTO MAYOR: UN ENFOQUE BIOFÍLICO, EN EL MUNDO

A NATUREZA EM ESPAÇOS PARA IDOSOS: UMA ABORDAGEM BIOFÍLICA, NO MUNDO

Hanlly del Pilar Velarde-Espinoza
Estudiante de Arquitectura y Diseño de Interiores,
Facultad de Arquitectura y Diseño
Universidad Privada del Norte, Trujillo, Perú
https://orcid.org/0009-0006-5848-6565
hanllyve17@hotmail.com (Autor de Correspondencia)

Alberto Carlos Llanos-Chuquipoma
Arquitecto
Docente tiempo completo, Carrera de Arquitectura y Diseño de Interiores,
Facultad de Arquitectura y Diseño, Carrera de Arquitectura y Urbanismo -
Universidad Privada del Norte, Trujillo, Perú
https://orcid.org/0000-0001-7525-7669
betico10@hotmail.com

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs.60 - 75
https://doi.org/10.22320/07190700.2024.14.02.05

RESUMEN

El propósito del estudio es conocer cómo la biofilia puede condicionar el diseño de espacios arquitectónicos del adulto mayor. La investigación es descriptiva, cualitativa y no experimental, se utilizó la revisión documental de antecedentes teóricos y arquitectónicos para precisar el tema de estudio, el comportamiento de la variable e identificar criterios arquitectónicos. Se analizaron cinco casos de la realidad empírica para validar los criterios y obtener lineamientos de diseño. Asimismo, uno de los resultados obtenidos en los cinco casos fue el lineamiento de generar terrazas y espacios exteriores naturales transitables que crean integración con el área libre y éstos conecten con el entorno natural, un lineamiento aplicado en un 100 por ciento de los casos estudiados. Se concluye que, la biofilia condiciona el diseño de espacios del adulto mayor al generar una relación fluida entre interior/exterior mediante espacios abiertos y semiabiertos, que incluyan la naturaleza y promuevan la interacción social de los ancianos.

Palabras clave
biofilia, naturaleza, adultos mayores, teoría biofílica

ABSTRACT

The study aims to find out how biophilia can condition the design of architectural spaces for older people. The research is descriptive, qualitative, and non-experimental, using a documentary review of the theoretical and architectural background to specify the subject of study, the behavior of the variable, and to identify architectural criteria. Five cases of empirical reality were analyzed to validate the criteria and obtain design guidelines. Similarly, one of the results obtained in the five cases became the guideline to generate terraces and natural, walkable outdoor spaces that create integration with open areas and connect with the natural environment, a guideline applied in 100% of the cases studied. It is concluded that biophilia conditions the design of spaces for older people by generating a fluid indoor/outdoor relationship through open and semi-open spaces, which includes nature and promotes social interaction among older people.

Keywords
biophilia, nature, older people, biophilic theory

RESUMO

O objetivo do estudo é descobrir como a biofilia pode condicionar o projeto de espaços arquitetônicos para idosos. A pesquisa é descritiva, qualitativa e não-experimental. Uma revisão documental de antecedentes teóricos e arquitetônicos foi utilizada para definir o objeto de estudo, o comportamento da variável e identificar critérios arquitetônicos. Cinco casos de realidade empírica foram analisados para validar os critérios e obter diretrizes de projeto. Da mesma forma, um dos resultados obtidos nos cinco casos foi a diretriz de criar terraços e espaços externos naturais e transitáveis que permitam a integração com a área aberta e a conexão com o ambiente natural, diretriz aplicada em 100% dos casos estudados. Conclui-se que a biofilia condiciona o projeto de espaços para idosos ao gerar uma relação fluida entre o interior e o exterior por meio de espaços abertos e semiabertos que incluem a natureza e promovem a interação social dos idosos.

Palavras-chave:
biofilia, natureza, idosos, teoria biofílica

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs.60 - 75
https://doi.org/10.22320/07190700.2024.14.02.05

INTRODUCTION

Biophilia connects the natural environment with human beings, seeking a direct and indirect connection between them, allowing the well-being of all individuals to coexist and create a more balanced environment (Trevisam & Silva, 2024). Similarly, biophilia responds to different natural stimuli through contact with urban nature, demonstrating the social, physiological, and even emotional benefits and that this urban nature manifests itself through direct or indirect contact (Villalpando & Bustos, 2023). It is known that biophilic design constitutes an essential contribution to architecture. It links the characteristics of built environments and natural elements through biophilic patterns grouped into three dimensions: Nature in Space, Natural Analogies, and the Nature of Space. The biophilic theory of nature in space refers to the direct, physical, and ephemeral presence of natural elements in a place (Gareca, 2022), which is the most relevant dimension in this study.

On the other hand, the rapid pace of aging in countries has been rising, with the need for facilities and spaces for older adults to improve their functionality, well-being, and social insertion effectively (Araya et al., 2018). Globally, the increase in the older population highlights the importance of having facilities that offer adequate solutions to improve this group's quality of life and provide spaces in the following areas: physical, emotional, economic, educational, and social (Barahona, 2020). Recreational spaces for older people are not always suitable or safe in these facilities, so it is necessary to create areas where activities can be carried out that can generate physical, emotional, and social well-being in this older adult population (Quispe, 2023).

Similarly, there is a need to incorporate biophilia in the spaces of older adults for their benefit since, at present, the spaces where they perform their daily activities are not looking for an appropriate solution and are deficient in their infrastructure and the correct use of spaces (Lorenzo, 2020). The case studies selected from the research, Biophilic cities, green spaces, and quality of life in the metropolitan area of San Luis Potosí, Mexico, have shown that contact with nature has a positive impact on health and well-being and that older adults have an innate inclination towards natural spaces, to take advantage of the great benefits they offer (Moreno & Sánchez, 2018). In addition, applying biophilic principles in architectural spaces for older adults improves their quality of life, safety, and emotional comfort by allowing them to interact socially through diverse activities in built environments with a biophilic architecture design (Failoc & Ojeda, 2022).

Older people have great difficulties staying active due to physical conditions or limitations. It has been shown that incorporating nature into spaces

Figure 1. Principles of biophilic theory of nature in space. Source: Prepared by the authors adapted from Medina et at. (2023)

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is very important for older people's physical and psychological well-being. Integrating natural elements into architectural design improves the conditions of habitability, mobility, and balance (Torrontegui, 2020). As people age, their health tends to decline, and they are more prone to diseases, reduced mobility, and even disorders. Biophilic patterns bring benefits to people, particularly older adults. Integrating the biophilic design shows improvements and benefits in the quality of life of this older population, who are usually the most physically and mentally vulnerable (Mari Tamil et al., 2023).

This research seeks to determine how architectural design can incorporate nature into spaces to

1 BIOPHILIC DESIGN STRATEGIES IN LONG-TERM RESIDENTIAL CARE ENVIRONMENTS FOR PERSONS WITH DEMENTIA

JOURNAL OF AGING AND ENVIRONMENT

Peters, T., & Verderber, S. (2022). Biophilic design strategies in long-term residential care environments for persons with dementia. Journal of Aging and Environment, 36(3), 227-255. https://doi.org/10.1080/26892618.2021.1918815

El diseño biofílico y la aplicación a residencias, generan la interacción de los residentes con la naturaleza y el paisaje y su proximidad a ello, y las transacciones inspirados en la biofílica.

2 CIUDADES BIOFÍLICAS, ESPACIOS VERDES Y CALIDAD DE VIDA EN ZONA METROPOLITANA DE SAN LUIS POTOSÍ

REVISTA LEGADO DE ARQUITECTURA Y DISEÑO

Moreno-Mata, F. A., & Sánchez-Moreno, D. M. (2018). Ciudades biofílicas, espacios verdes y calidad de vida en la zona metropolitana de San Luis Potosí, México. Revista Legado de Arquitectura y Diseño, 24, 48-59. https://www.redalyc.org/journal/4779/477957975007/html/

Los vínculos que hay entre los habitantes y el entorno natural, aplicando la biofílica. Se identifica el uso y actividades, y la apropiación de las personas con el espacio verde.

3 BIFILIA: PRODUCÁO DE VIDA ATIVA EM CUIDADOS PALIATIVOS

REVISTA SAÚDE DEBATE

Zanatta, A. A., José Santos-Junior, R., Perini, C. C., & Fischer, M. L. (2019). Biofilia: Produção de vida ativa em cuidados paliativos. Saúde em Debate, 43(122), 949-965. https://doi.org/10.1590/0103-1104201912223

La biofílica se aplicó en los aspectos emocionales y la zoo terapia, con la finalidad de encontrar que la biofílica puede ser insertada en los cuidados paliativos.

4 BIOPHILIC EXPERIENCE IN HIGH-RISE RESIDENTIAL AREAS IN CHINA: FACTOR STRUCTURE AND VALIDITY OF A SCALE

SUSTAINABILITY

Yue, M., Zhang, X., & Zhang, J. (2024). Biophilic experience in high-rise residential areas in china: Factor structure and validity of a scale. Sustainability, 16(7), 2866. https://doi.org/10.3390/su16072866

La creación de entornos de espacio vital biofílico, es primordial para la salud a la personas, por su beneficios de la naturaleza.

5 BIOPHILIC DESIGN FOR ELDERLY HOMES IN MALAYSIA FOR IMPROVED QUALITY OF LIFE

JOURNAL OF ENGINEERING SCIENCE AND TECHNOLOGY

Mari, T., Hua, H., Gunasagaran, S., Veronica, N., Srirangam, S., & Kuppusamy, S. (2023). Biophilic design for elderly homes in malaysia for improved quality of life. Journal of Engineering Science and Technology, 18, 96-112.

Los beneficios para la salud de la biofília con los principios biofílicos en las personas mayores de Malasia, Los patrones biofílicos se deben incorporar en las residencias para mejorar su calidad de vida.

6 CONTRIBUIÇÕES DA BIOFILIA PARA A O DESENVOLVIMENTO SUSTENTÁVEL

VEREDAS DO DIREITO - DIREITO AMBIENTAL E DESENVOLVIMENTO SULTENTÁVEL

Contribuições da biofilia para a o desenvolvimento sustentável. (2024). Veredas do Direito Direito Ambiental e Desenvolvimento Sustentável, e212408.

El desarrollo sostenible, da la conexión intrínseca entre el ser humano y la naturaleza. La biofílica como principio del desarrollo sostenible, aplicada en área urbanas, conecta las relaciones humanas con la naturaleza.

7 REVITALISING URBAN SPACES TO THE NEEDS OF THE AGING POPULATION - BIOPHILIC HEALING INDEX SUPPORTING ACTIVE AGING IN INCLUSIVE CITIES

IAFOR

Tracada, E. (2022). Revitalising urban spaces to the needs of the aging population – biophilic healing index supporting active aging in inclusive cities. https://doi.org/10.22492/issn.2435-4937.2022.5

Se identifica que el comportamiento de las personas mayores vulnerables con los espacios publicos abiertos pueden afectar en el estado de animo y comportamiento de las personas con entorno construido.

8 BIOFILIA: LA NATURALEZA COMO FACTOR DE TENDENCIA EN EL DISEÑO DE UNA VIVIENDA

REVISTA CIENCIA, TECNOLOGÍA E INNOVACIÓN

Gareca Apaza, M. L. (2022). Biofilia: La naturaleza como factor de tendencia en el diseño de una vivienda. Revista Ciencia, Tecnología e Innovación, 20(26), 137-160. http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S2225-87872022000200137

El diseño biofílico para mejorar las condiciones ambientales y espaciales de las viviendas. El diseño arquitectónico que no contenga espacios abiertos ajardinados y otros, afectará la calidad del hábitat.

9 BIOPHILIC EXPERIENCE- BASED RESIDENTIAL HYBRID FRAMEWORK

INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH

Lee, E.-J., & Park, S.-J. (2022). Biophilic experience-based residential hybrid framework. International Journal of Environmental Research and Public Health, 19(14), 8512. https://doi.org/10.3390/ijerph19148512

La biofílica da soluciones a los problemas ambientales y cambio climático. La biofílica en entornos residenciales, da mejoras como el bienestar y la salud de los residentes, destacando la sostenibilidad.

10 LA NATURALEZA URBANA EN LAS CIUDADES CONTEMPORÁNEAS LA IMPORTANCIA DEL DISEÑO BIOFÍLICO EN LA SALUD PÚBLICA

REVISTA UNAM

Villalpando Flores, A. E., & Bustos Aguayo, J. M. (2023). La naturaleza urbana en las ciudades contemporáneas. La importancia del diseño biofílico en la salud pública. Academia XXII, 14(28), 8-29. https://doi.org/10.22201/fa.2007252Xp.2023.14.28.87234

El diseño biofílico busca integrar los elementos naturales en los diseños urbanos-paisajísticos, y promover así el estilo de vida de forma positiva y reconceptualizar lo social sobre la naturaleza.

Figure 2. Theoretical and architectural background. Source: Preparation by the authors.

encourage socialization and offer emotional support to older adults, promoting their participation in the community, with nature, and among themselves. It has been studied that biophilia improves spaces through the connection between the built and the natural, which generates positive influences and benefits in environments, which in turn provides greater well-being and comfort, especially for older adults (Medina et al., 2023). Biophilic design contributes directly and indirectly to improving the quality of life in residential environments, such as comfort, accessibility, and relationships, generating an active interest in and development of biophilic design (Lee & Park, 2022).

11 PROGRAMA CENTROS DIURNOS DEL ADULTO MAYOR: RECOMENDACIONES PARA MEJORAR SU FUNCIONAMIENTO

GEROKOMOS

Araya, A.-X., Iriarte, E., Rioja, R., González, G., Araya, A.-X., Iriarte, E., Rioja, R., & González, G. (2018). Programa Centros Diurnos del Adulto Mayor: Recomendaciones para mejorar su funcionamiento. Gerokomos, 29(1), 9-12.

El estudio contribuye a entender a las personas mayores con un servicio que reporte beneficios en su funcionalidad, aumento de bienestar y mayor inserción social. También las mejoras del lugar con criterios inclusivos y flexibles.

12 ENVELHECIMENTO, SENTIDO DE LUGAR E PLANEJAMENTO URBANO: FACILITADORES E BARREIRA

PSICOLOGIA EM ESTUDO

Albuquerque, D., Goulart, F., Klavdianos, N., Günther, I., & Portella, A. (2023). Envelhecimento, sentido de lugar e planejamento urbano: Facilitadores e barreiras. Psicologia em Estudo, 28. https://doi.org/10.4025/psicolestud.v28i0.54416

Mejorar la calidad de vida, y a su vez el envejecimiento con nuevas formas que comprenden la conexión de las personas adultas mayores con el medio ambiente dando una relación anciano-entorno.

13 CRIANCAS DA NATURALEZA: VIVÉNCIAS, SABERES E PERTENCIMENTO

INFANCIAS E EDUCACCÁO DAS RELACOES ETNICOS-RACIAIS

Tiriba, L., & Profice, C. C. (2019). Crianças da Natureza: Vivências, saberes e pertencimento. Educação & Realidade, 44(2), e88370. https://doi.org/10.1590/2175-623688370

La experiencia de niños en la naturaleza y las posibles consecuencias en su desarrollo, todo apartir de la naturaleza. El estudio demuestra las condiciones biofílicas y discute los dibujos y habla de niños.

14 ARQUITECTURA BIOFILICA: INFLUENCIA DE SU APLICACION EN EL DISEÑO DE UN CENTRO RESIDENCIAL PARA EL ADULTO MAYOR

REVISTA DE INVESTIGACIÓN APORTE SANTIAGUINO

Medina Changa, M., Migliori Ochoa, L., & Soria Caballero, G. (2023). Arquitectura biofílica: Influencia de su aplicación en el diseño de un centro residencial para el adulto mayor. Aporte Santiaguino. https://doi.org/10.32911/as.2023.v16.n2.1058

La biofílica da espacios con conexión entre el entorno construido y la naturaleza. Usar criterios de la arquitectura biofílica en una residencia, da una influencia positiva, generando beneficios en los ambientes y adultos.

15 A FRAMEWORK OF SMART-HOME SERVICE FOR ELDERLY'S BIOPHILIC EXPERIENCE

SUSTAINABILITY

Lee, E. J., & Park, S. J. (2020). A framework of smart-home service for elderly's biophilic experience. Sustainability, 12(20), 8572. https://doi.org/10.3390/su12208572

Los servicios y hogares inteligentes, refuerzan la experiencia de la naturaleza con las personas, dando una vida sostenible entre las personas mayores. La naturaleza en entornos residenciales sostenibles.

16 EL CONTEXTO Y EL CENTRO RESIDENCIAL PARA LAS PERSONAS ADULTOS MAYORES EN COLOMBIA Y ESPAÑA

REVISTA DE ESTUDIOS COOPERATIVOS

Osorio Bayter, L., & Salinas Ramos, F. (2016). El contexto y el centro residencial para las personas adultas mayores en Colombia y España. La empresa social Una alternativa para el bienestar. REVESCO. Revista de Estudios Cooperativos, (121), 205-227.

Los espacios donde un adulto pueda vivir y compartir sus años. Mejora el bienestar hacía el adulto mayor en los hogares o residencias.

17 ADULTO MAYOR: ENVEJECIMIENTO, DISCAPACIDAD, CUIDADO Y CENTROS DÍA

SALUD UNINORTE

Pinilla Cárdenas, M. A., Ortiz Álvarez, M. A., & Suárez-Escudero, J. C. (2022). Adulto mayor: Envejecimiento, discapacidad, cuidado y centros día. Revisión de tema. Salud Uninorte, 37(02), 488-505. https://doi.org/10.14482/sun.37.2.618.971

El proceso y los modelos del envejecimiento, la discapacidad, el cuidado y los centros día para atención de toda la población adulta mayor, brinda el cuidado integral de dichas personas en los lugares.

18 HÁBITAT Y ADULTO MAYOR: EL CASO DE VALPARAÍSO

REVISTA INVI

Fadda, G., & Cortés, A. (2009). Hábitat y adulto mayor: El caso de valparaíso. Revista INVI, 24(66). https://doi.org/10.4067/S0718-83582009000200003

El indice de envejecimiento es mayor, y busca la calidad de vida de este grupo etario según su localización y situación socioeconómica,. El hábitat urbano brinda condiciones propicias para este grupo de población.

19 PROMOTING STRESS AND ANXIETY RECOVERY IN OLDER ADULTS: ASSESING THE THERAPEUTIC INFLUENCE OF BIOPHILIC GREEN WALLS AND OYDOOR VIEW

FRONTIERS IN PUBLIC HEALTH

Xiaoxue, S., & Huang, X. (2024). Promoting stress and anxiety recovery in older adults: Assessing the therapeutic influence of biophilic green walls and outdoor view. Frontiers in Public Health, 12, 1352611. https://doi.org/10.3389/fpubh.2024.1352611

Incorporar los principios de conexión con la naturaleza en los entornos interiores sobre todo en los centros de atención para adultos mayores, contribuye con la reducción del estrés y el alivio de ansiedad.

20 ENVEJECIMIENTO Y ESTRATEGIAS DE ADAPTACIÓN A LOS ENTORNOS URBANOS DESDE LA GERONTOLOGÍA AMBIENTAL

ESTUDIOS DEMOGRÁFICOS Y URBANOS

García-Valdez, M. T., Sánchez-González, D., & Román-Pérez, R. (2018). Envejecimiento y estrategias de adaptación a los entornos urbanos desde la gerontología ambiental. Estudios Demográficos y Urbanos, 34(1), 101-128. https://doi.org/10.24201/edu.v34i1.1810

La adaptación a entornos urbanos en el envejecimiento con estrategias de adaptación ambiental en el lugar, debido a los activos personales y los atributos y funciones del ambiente urbano.

Figure 3. Theoretical and architectural background. Source: Preparation by the authors.

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https://doi.org/10.22320/07190700.2024.14.02.05

DISCOVERING THE BIOPHILIC THEORY OF NATURE IN SPACE

Biophilic theory is based on the idea that humans feel an innate connection with nature. One of its dimensions is nature in space, which aims to link the built with the natural environment. This dimension seeks to reinforce the integration of the outdoor environment with the built interior spaces, which considers incorporating natural elements in the spaces to promote well-being, foster skills, and increase productivity. Biophilic theory is composed of three key principles: volumetric composition and nature, open spaces and the relationship with the natural environment, and finally, natural elements and architecture (Figure 1).

METHODOLOGY

The study is descriptive in terms of its depth, defining the behavior of the variable biophilia. It is also classified as qualitative due to the condition of the data, which was focused on obtaining non-quantifiable information based on observation. In addition, it is considered non-experimental since the variable is not manipulated but is mainly based on the observation of the behavior of biophilia in empirical case analyses.

Therefore, the study is structured in three research phases. The first begins with a documentary review of the theoretical and architectural background material to specify the topic of study and the biophilia variable. Research and scientific articles were used to search for the theoretical background, which generally addresses the research topic. This theoretical background review was needed to understand everything related to biophilia and how it is linked to older adults (Figure 2).

On the other hand, the architectural background information addresses the research topic in a specific way, including research and scientific articles. Similarly, this documentary review of the architectural background contributes to the research on how biophilia can be integrated into an architectural design for older adults (see Figure 3).

During the process, a list of databases and official search engines of Universidad Privada del Norte, such as EBSCO and Google Academic, and documents in indexed journals (Web of Science, Scopus, and Scielo) (Figure 2 and Figure 3) was prepared. The study of these documents yields architectural criteria grouped into three study categories: Volumetric Composition, Spatial Typology, and Architectural Details.

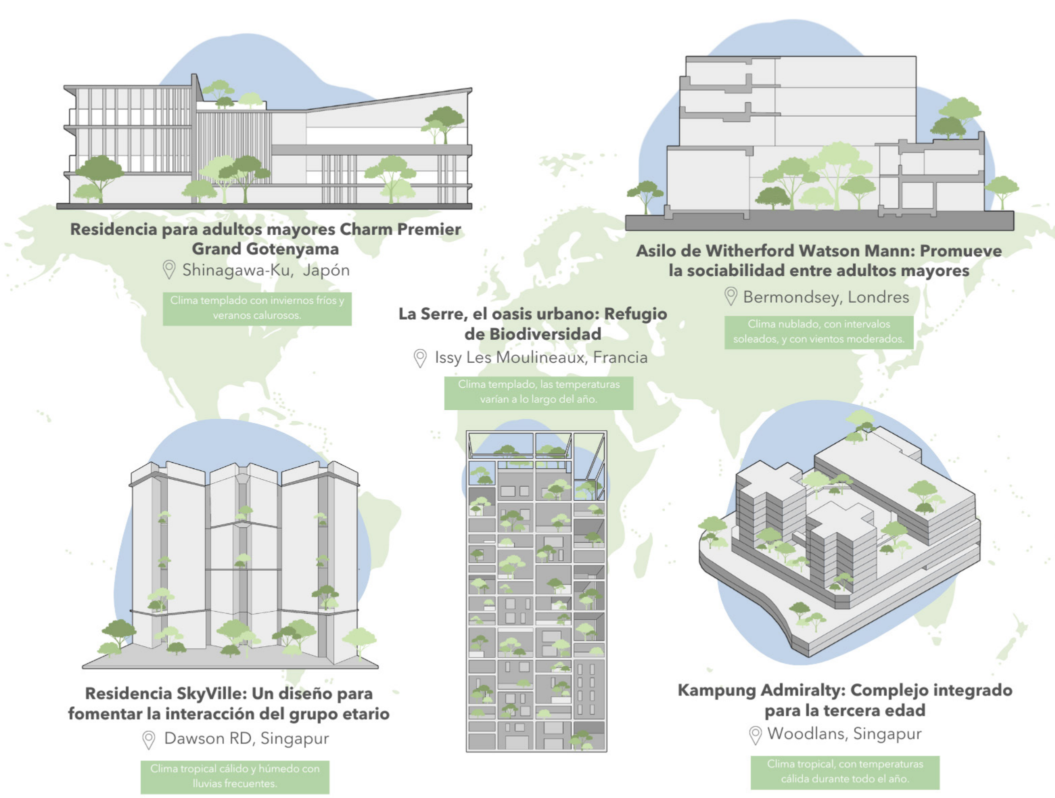

Figure 4. Architectural cases in the international field. Source: Preparation by the authors.

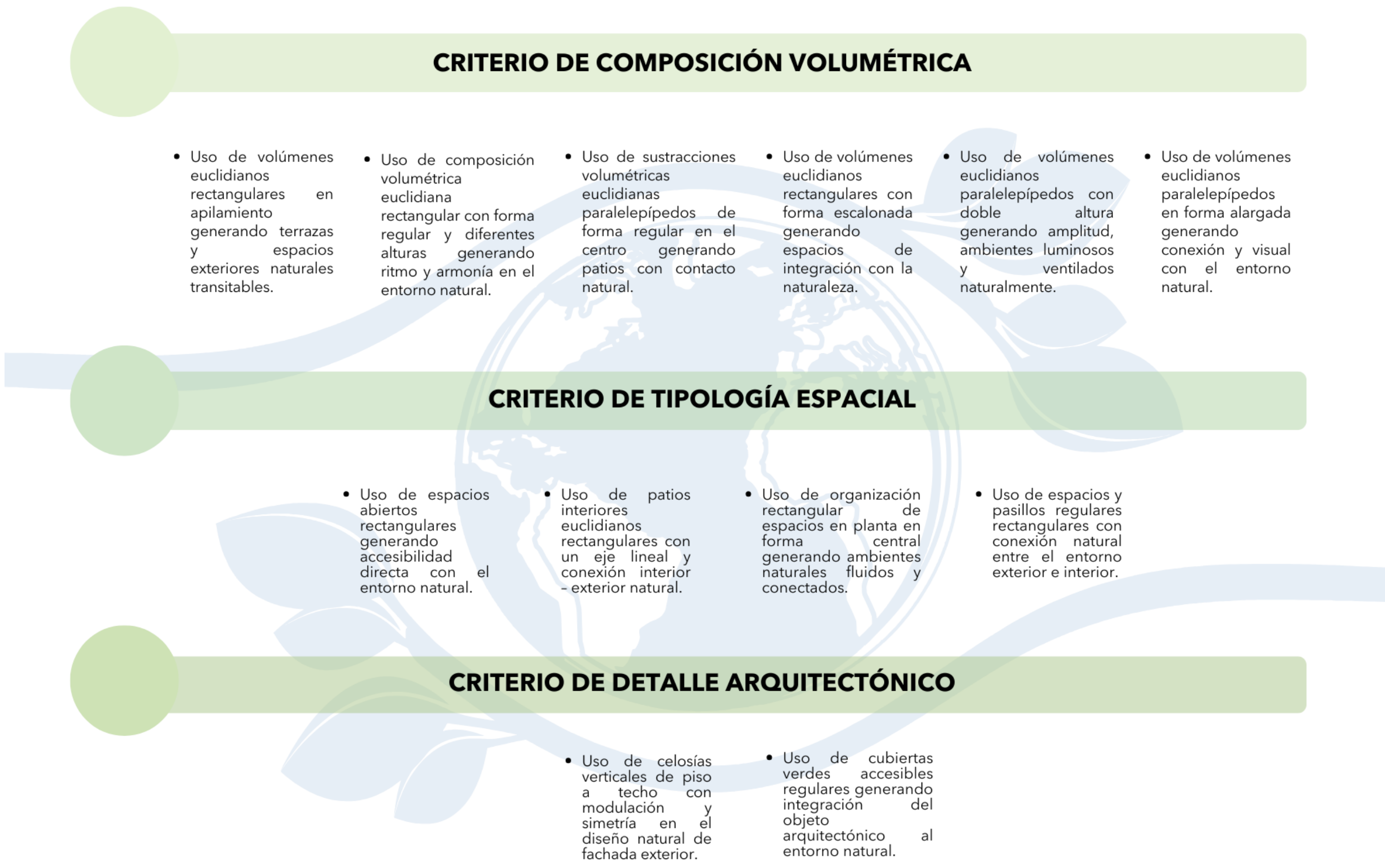

Figure 5. Architectural criteria. Source: Preparation by the authors based on the bibliography.

Subsequently, a finite sample was selected, which comprised five empirical cases. These contained the architectural criteria previously identified in the studied background information, as seen in Figure 5. The cases were chosen to identify and validate the architectural criteria analyzed in the three study categories. These cases were selected because they are homogeneous, relevant, representative, and are also part of an international scope (Figure 4). Each architectural case was modeled with the SketchUp Pro software.

Finally, in the third phase, the results obtained in the analysis of architectural cases are described qualitatively and graphically. This confirms the application of architectural criteria in the empirical reality that impacts the space and thus becomes architectural design guidelines distributed among the three study categories (Table 1).

RESULTS AND DISCUSSION

Five previously presented international architectural cases were studied and analyzed to demonstrate the relationship between architectural spaces intended for older people and nature. Data collection and analysis were carried out in each case, which will be presented using initial descriptive language and explanatory graphics.

1. CASE N°1: CHARM PREMIER GRAND GOTENYAMA SENIOR RESIDENCE

Designed by the Nikken Housing System Ltd architects in 2022 on an area of 4,397m^2 (Abdel, 2023), it is a senior residence intertwined in the city, located on a green street in the center of Tokyo, Japan. It has a sizeable double-height lobby that floods the space with light and has the strategic interaction of the outdoor and indoor levels with a feeling of openness and continuity, creating a fluid route. The spaces are lit and ventilated naturally, which creates the perfect connection with the outside world and reduces environmental impact.

Indeed, the Nursing Home integrates biophilic principles into its design, connecting residents with the urban environment and the natural landscape of Tokyo, which favors their social skills. Garcia et al. (2018) state that environmental adaptation strategies promote active and social aging.

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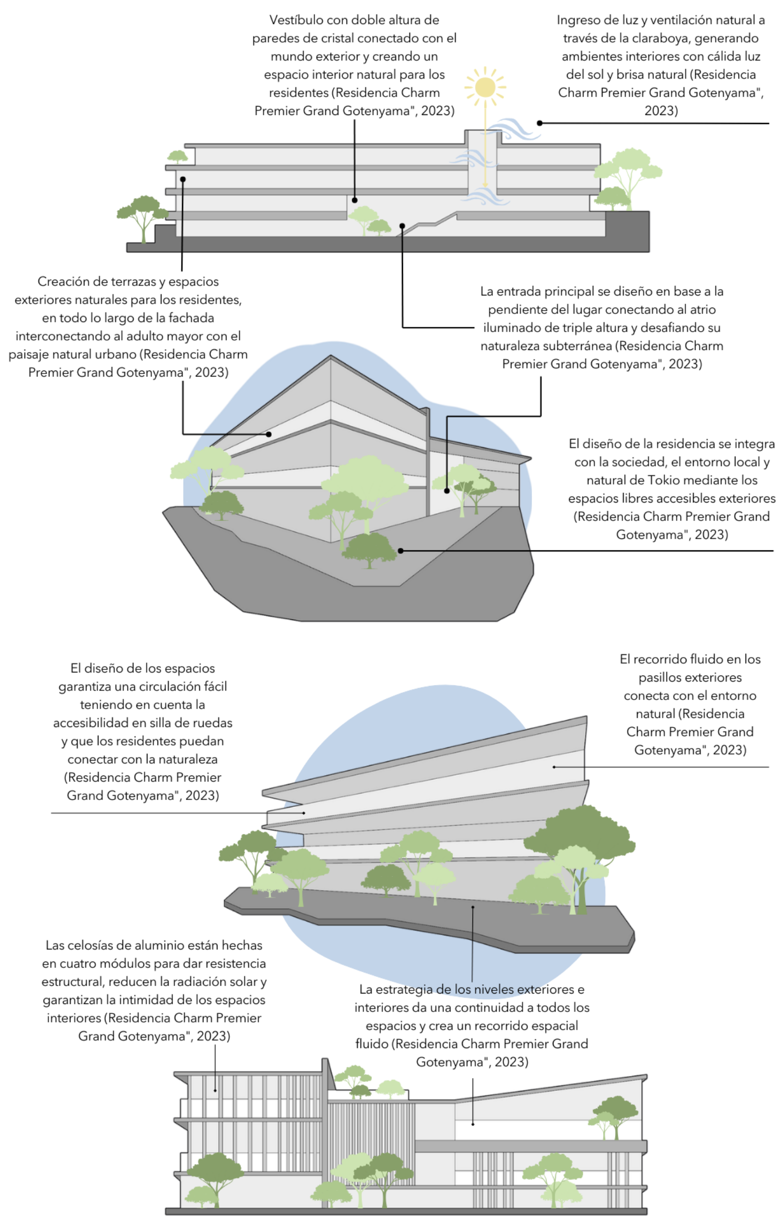

Figure 6. Graph of Case N° 01. Source: Preparation by the authors.

According to this, it is understood that, although environmental factors influence the abilities of older adults, biophilic design links indoor spaces with the outdoor natural environment, allowing older adults to actively participate and avoid isolation, which favors their social skills (Figure 6).

2. CASE N°02: KAMPUNG ADMIRALTY: INTEGRATED COMPLEX FOR OLDER ADULTS

Designed by WOHA architects, with a total area of 32,331.60m^2 (Castro, 2018), it has a height limit of 45m in the Woodlands neighborhood in the northern region of Singapore. It is considered a vertical village, which connects nature with people.

The apartments have design principles with natural ventilation and optimal daylight; the central green area is presented in a staggered way with accessible and walkable ceilings; in addition, the daylight comes from the perimeter windows and the central courtyard it has.

The complex in Woodlands, Singapore, meets the needs of older adults through a community park that integrates biophilia, promoting social and active interaction. Fadda and Cortés (2019) indicate that the urban habitat and social spaces provide favorable conditions for this age group. According to this, it is inferred that it is necessary to create socialization spaces and integrate a biophilic

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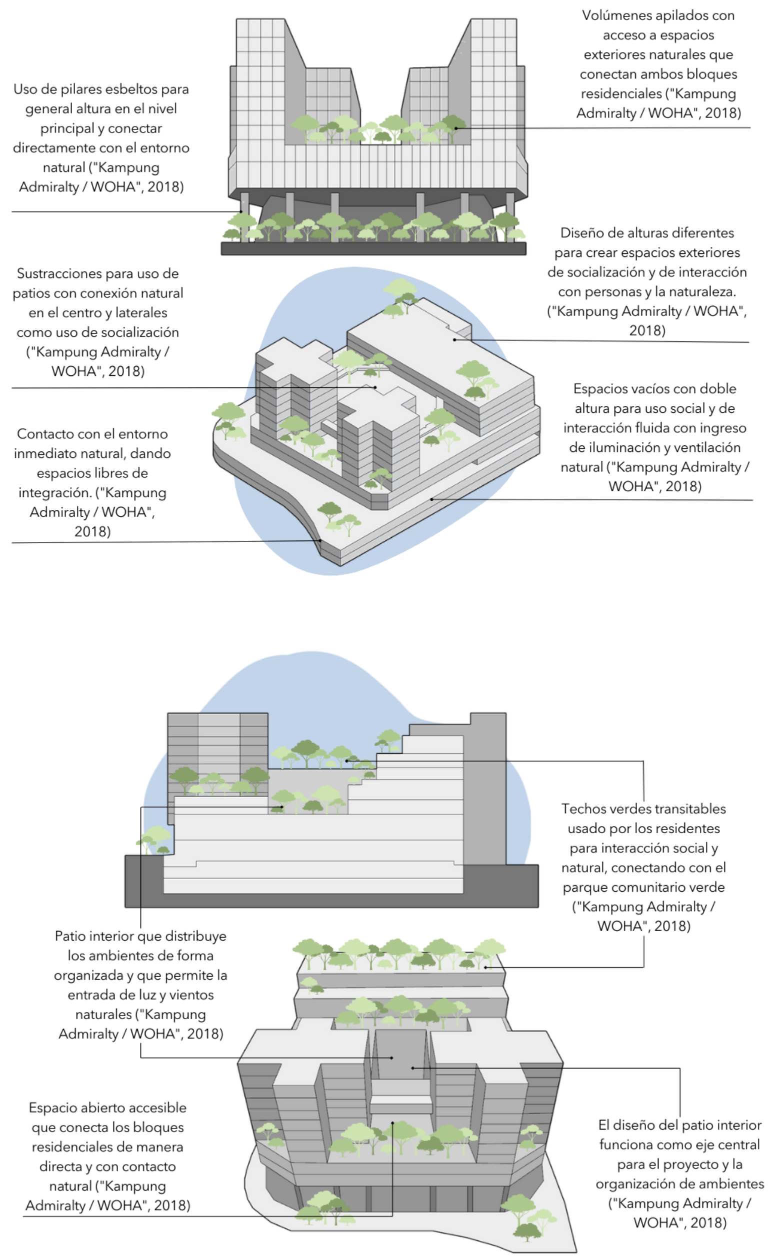

Figure 7. Graph - Case N° 02. Source: Preparation by the authors.

design, allowing residents to connect with nature and themselves, improving their social skills (Figure 7).

3. CASE N°03: SKYVILLE RESIDENCE: A DESIGN TO ENCOURAGE THE AGE GROUP'S INTERACTION

Designed by WOHA architects, with an area of 29,392m^2 (ArchDaily, 2016), located on Dawson Rd, Singapore, the project is open; all common areas are open to the public and situated in a mixed-height housing area. It presents a square located along a linear park. Also, the design offers three floorplan variations for each unit size; the designs are flexible and based on open spaces of columns and beams. All rooms are naturally lit and ventilated due to the open design.

The project is designed to encourage social interaction through a biophilic design, which gives residents free access to the different common spaces and areas open to the public. Osorio and Salinas (2016) point out that generating spaces allows participation and social involvement for older people. According to this, it follows that creating spaces is not enough to promote social skills but that intertwining these spaces with natural elements connects people in a way that encourages social participation (Figure 8).

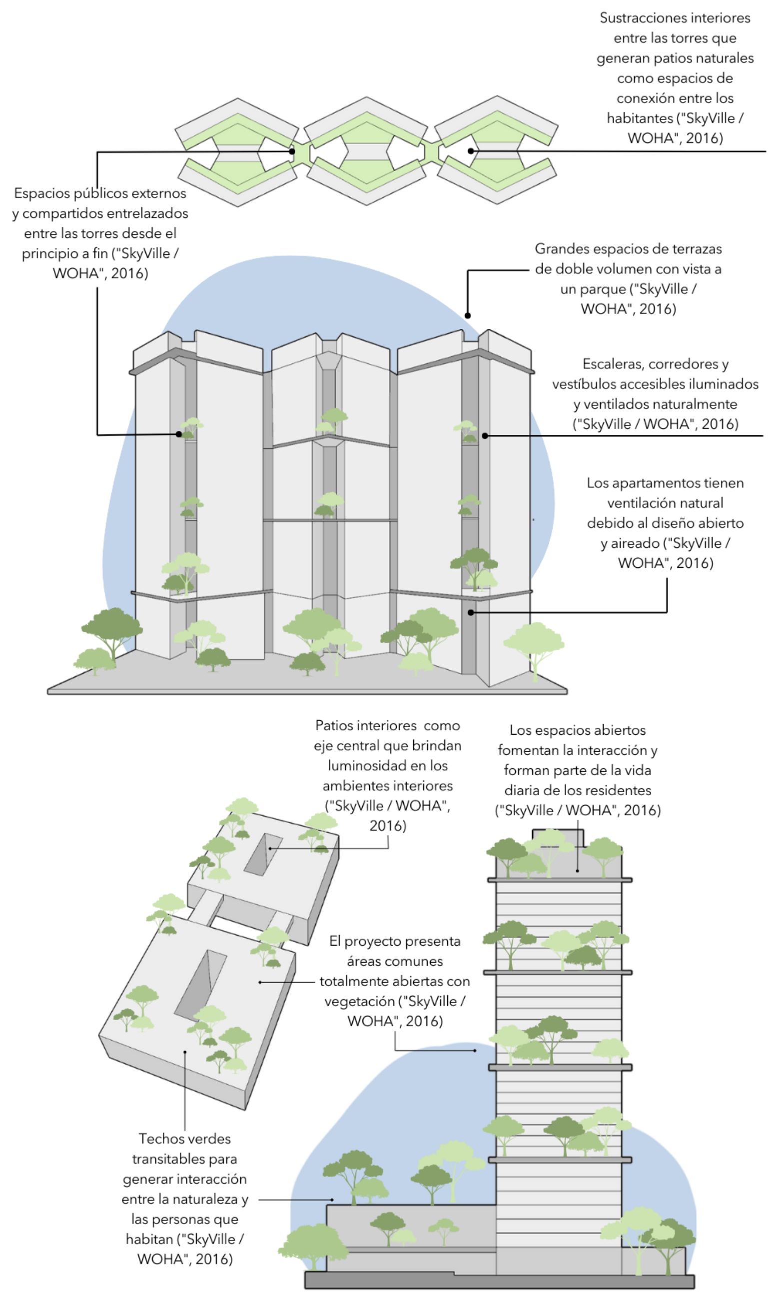

Figure 8. Graph - Case N° 03. Source: Preparation by the authors.

4. CASE N°04: LA SERRE, THE URBAN OASIS: REFUGE OF BIODIVERSITY

Designed by MVRDV in collaboration with the architect Alice Tricom in 2023, it is located in Issy Les Moulineaux, France. It has 3,000 m^2 of open area (Fakharany, 2023). The residential project has 190 units distributed over 22 floors, 30% of which are for social housing. The project integrates nature into the urban environment, establishing a biodiversity refuge where nature stands out as a central feature. It also provides a wide shared path encouraging people to use the green space and socialize.

The project incorporates abundant vegetation and integrates biophilia with the building's architecture to encourage the residents' social activities. Albuquerque et al. (2023) point out that urban planning creates an elder-environment connection, favoring their social and community ties. According to this, it is inferred that planning the city helps not only with social skills but also that the implementation of biophilia promotes the participation of older adults (Figure 9).

5. CASE N°05: WITHERFORD WATSON MANN NURSING HOME: PROMOTES SOCIABILITY AMONG OLDER ADULTS

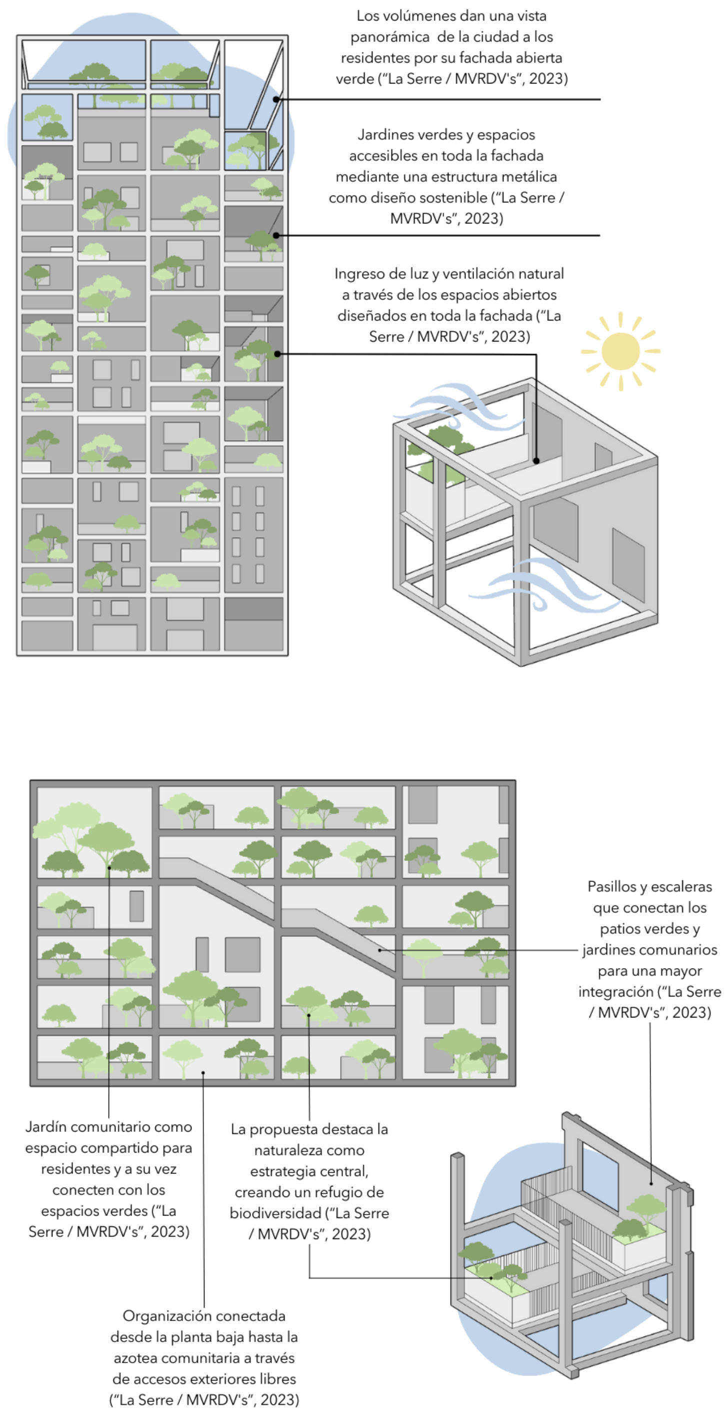

Figure 9. Graph - Case N° 04. Source: Preparation by the authors.

Designed by architects from Witherford Watson Mann Architects, located in Bermondsey, London, with an area of 6,152m² (Santos, 2016), it is an accommodation for about 90 residents. The project has five floors and a prominent elevation of two glazed levels. A central courtyard connects the residence; the project delivers an abundance of green, spacious neighboring landscape views, and nature integrates with the traditional natural environment through its exterior design and materials.

The project is an urban building that is active, open, and in direct contact with the natural exterior. It is where older adults interact and socialize in spaces designed with biophilic elements that were applied to create environments with green encounters. Pinilla Cárdenas et al. (2021) indicate that infrastructures oriented to the care and well-

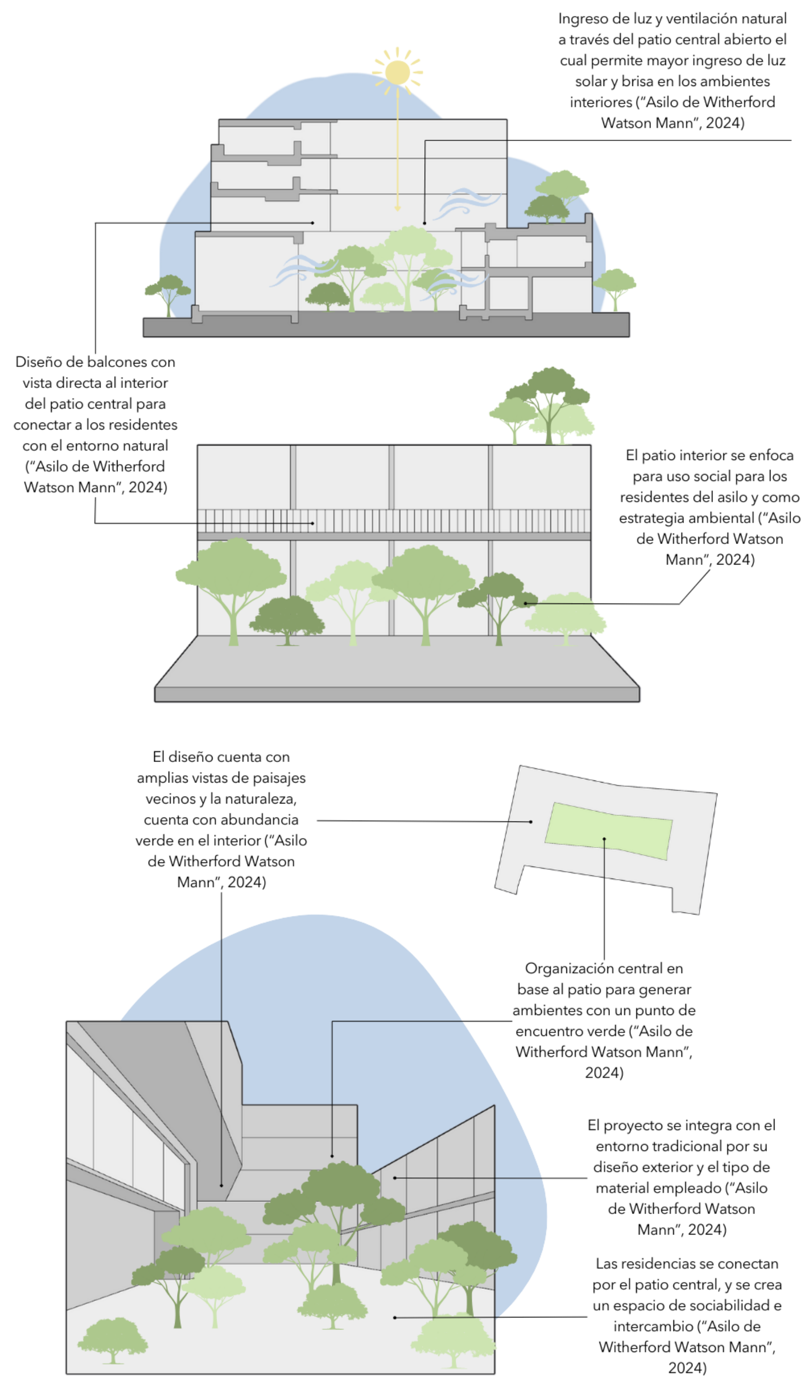

Figure 10. Graph - Case N° 05. Source: Preparation by the authors.

being of older people improve their social skills. According to this, creating lounges does not thoroughly encourage the participation of this age group, but rather, integrating natural elements into these infrastructures promotes their social activities (Figure 10).

In fact, the design with biophilic principles reinforces social integration, as the connection with nature encourages the participation of older adults inside and outside the built spaces, as found in the five case studies analyzed. However, Araya et al. (2018) point out that the unique contact between older people significantly impacts social insertion within these spaces, where their participation is generated. According to this, it can be inferred that although social contact between older people is important, it is not enough to encourage their social skills. Applying the biophilic principles in architectural design is necessary, as it creates an environment that

Table 1. Final guidelines. Source: Preparation by the authors.

Guidelines	Results	Percentage
Guidelines of volumetric composition		
Parallelepiped Euclidean volumes with double height generate spacious, luminous, and naturally ventilated environments to create comfortable interior spaces. These spaces present vertical amplitude inside, taking advantage of daylight and air circulation, which provides fresh and better-lit spaces due to the higher height used.	Cases N° 1, 2, 3, 4, 5	100%
The use of rectangular Euclidean volumetric composition with regular shapes and different heights generates rhythm and harmony in the natural environment and provides a volumetric pattern that integrates the natural environment. The composite heights in the volumetric design create a variation of lights and shadows, giving the design flexibility and functionality.	Cases N° 2	20%
The use of rectangular Euclidean volumes in stacking generates terraces and walkable natural outdoor spaces that integrate with the open area. The spaces also connect with the natural environment, providing users with accessible outdoor social environments as rest and recreation areas.	Cases N° 1, 2, 3, 4, 5	100%
The use of parallelepiped Euclidean volumes in an elongated shape creates a visual connection with the natural environment, integrating it into the natural landscape and creating interior spaces that take advantage of the entrance of light and natural breeze through the elongated facade. This improves the environment and gives them a panoramic view of the outside.	Cases N° 1, 3, 4	60%
The use of rectangular Euclidean volumes with a stepped shape creates functional spaces that integrate with nature. The shape used in the design links the natural environment through accessible spaces that allow social interaction with other people and the surrounding nature.	Cases N° 2	20%
Use of Euclidean parallelepiped volumetric subtractions of a regular shape in the center that creates courtyards with natural contact to integrate the spaces with nature, and that these are functional around the courtyards that act as a central meeting point that connects with the other spaces.	Cases N° 2, 3, 5	60%
Guidelines of Spatial Typology		
The use of rectangular open spaces that allow direct access to the natural environment provides social integration. Open spaces and their fluid access to nature directly connect people and the surrounding green environment.	Cases N° 2, 3, 5	60%
The use of regular rectangular spaces and corridors with a natural connection between the outdoor and indoor environment creates functional environments and provides a relationship with nature. Paths with natural, direct visuals also allow fluidity between indoor and outdoor spaces.	Cases N° 1, 3, 4, 5	80%
The use of rectangular Euclidean interior courtyards with a linear axis and natural indoor-outdoor connection creates functional and accessible spaces through the orderly distribution of the environments, resulting in better use of said spaces and incorporating nature.	Cases N° 2, 3, 5	60%
A rectangular organization of spaces on the floor centrally generates fluid and connected natural environments. These are interconnected with each other, so users have better accessibility to all spaces, and functional environments are given a greater connection with the natural environment.	Cases N° 1, 4, 5	60%
Architectural detail guidelines		
Regular accessible green roofs integrate the architectural object with the natural environment, allowing them to be used as social recreation spaces that provide environmental well-being and relate to nature, resulting in higher-transited spaces.	Cases N° 2, 3, 4	60%
The use of vertical floor-to-ceiling lattices with modulation and symmetry in the natural design of the exterior facade gives a natural approach and functions as a solar control. This provides privacy to the indoor environments, shading, and wind circulation. In addition to serving as a structure, the facade also organizes it.	Cases N° 1	20%

Table 2. Spatial/biophilic qualities. Source: Preparation by the authors.

Spatial/biophilic qualities	Case N° 1 Charm Premier Grand Gotenyama Senior Residence	Case N° 2 Kampung Admiralty: Integrated complex for older people	Case N° 3 Skyville Residence: A design to promote the integration of the age group	Case N° 4 La Serre, the Urban Oasis: Biodiversity Refuge	Case N°5 Witherford Watson Mann Nursing Home: Promotes sociability among older adults
Integration of vegetation	X	X	X	X	X
Access to daylight	X	X	X	X	X
Natural social spaces	X	X	X	X	X
Use of sustainable materials	X	X			X
Connection with the natural environment	X	X	X	X	X

facilitates interaction and stimulates participation. Applying the integration of natural elements and the connection with the external environment are essential principles to promote the social skills of older people.
Finally, the results obtained from twelve theoretical architectural design guidelines are presented in Table 1 of the final guidelines, organized by categories: guidelines of volumetric composition, spatial typology, and architectural detail. They also indicate in which architectural cases these guidelines are found; in addition to displaying a percentage that indicates how many of all the analyzed cases use the guideline, a comparison analysis of the five studied cases of spatial/biophilic qualities was also performed, where the cases that have or do not have such a quality are seen (Table 2).

CONCLUSIONS

Finally, the study shows that the relationship between biophilia and architectural spaces for older adults is fundamental to promoting their social skills. Biophilia conditions architecture by incorporating natural elements in the architectural design that facilitate the connection between older people and the environment surrounding them. Biophilic spaces allow the adult population to interact with nature, which can contribute to their psychological and physical well-being. This interaction helps motivate social purpose since providing natural areas, terraces, and outdoor spaces provides opportunities for socialization and integration due to direct contact with the natural environment.

Similarly, biophilic elements can improve the life experience of older adults, which contributes to a socially active life; in addition, biophilic design in spaces can promote skill development and create areas where people enjoy activities within the architectural space, integrating and connecting with the nature present. This older population interacts in natural spaces, which motivates them to participate in activities due to the design of architectural spaces with biophilic patterns.

On the other hand, results demonstrated the connection between architectural spaces and nature, as seen in Table 2, which summarizes the guidelines identified in the analyzed cases. For example, one of the guidelines consists of generating terraces and walkable natural outdoor spaces that integrate the open area and connect with the natural environment; this guideline is present in the five cases studied. Another guideline refers to the spaces and corridors with a natural connection between the exterior and interior environment that provide functional environments related to nature. This guideline is observed in only four of the cases studied.

Biophilia contributes significantly to the quality of life of older adults since it allows them to interact simply with spaces with plants and green areas, thus promoting their social well-being. In addition, biophilia facilitates the connection between architectural spaces and nature since it creates social areas where older adults can actively socialize. The results also show that biophilia promotes the social relationships of older adults, which evidences their connection with the natural environment.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, H.V.E., A.L.L.C.H.; Data Curation, H.V.E., A.L.L.C.H.; Formal analysis, H.V.E., A.L.L.C.H.; Acquisition of financing, H.V.E., A.L.L.C.H.; Research, H.V.E., A.L.L.C.H.; Methodology, H.V.E., A.L.L.C.H. ; Project Management, H.V.E., A.L.L.C.H.; Resources, H.V.E., A.L.L.C.H.; Software, H.V.E., A.L.L.C.H.; Supervision, H.V.E., A.L.L.C.H.; Validation, H.V.E., A.L.L.C.H.; Visualization, H.V.E., A.L.L.C.H.; Writing – draft original, H.V.E., A.L.L.C.H.; Writing – revision and editing, H.V.E., A.L.L.C.H.

ACKNOWLEDGEMENTS

We are grateful for Universidad Privada del Norte's support in implementing a pilot project to prepare scientific articles for the Thesis Project course in Architecture and Design.

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 76 -85
https://doi.org/10.22320/07190700.2024.14.02.06

POTENTIAL OF A LOW-COST SYSTEM FOR MEASURING INDOOR ENVIRONMENTAL QUALITY IN LATIN AMERICAN EXTREME CLIMATES TOWARDS ENERGY EQUITY

Recibido 07/08/2024
Aceptado 02/12/2024

POTENCIAL DE UN SISTEMA DE BAJO COSTO PARA MEDIR LA CALIDAD AMBIENTAL INTERIOR EN CLIMAS EXTREMOS LATINOAMERICANOS HACIA LA EQUIDAD ENERGÉTICA

POTENCIAL DE UM SISTEMA DE BAIXO CUSTO PARA MEDIR A QUALIDADE AMBIENTAL INTERIOR EM CLIMAS EXTREMOS DA AMÉRICA LATINA VISANDO A EQUIDADE ENERGÉTICA

Claudia Eréndira Vázquez-Torres
Doctora en Arquitectura
Posdoctorante de la Facultad de Ingeniería, Laboratorio de Modelado y Optimización de Procesos Energéticos y Ambientales
Universidad Autónoma de Yucatán, Mérida, México
https://orcid.org/0000-0002-5388-0780
claudia.vazquez@correo.uady.mx (Autor de Correspondencia)

Renán Gabriel Quijano-Cetina
Doctor en Ingeniería
Profesor Investigador, Facultad de Ingeniería
Universidad Autónoma de Yucatán, Mérida, México
https://orcid.org/0000-0001-9515-9249
renan.quijano@correo.uady.mx

Israel Sánchez-Domínguez
Doctor en Ingeniería
Técnico Académico Titular B TC, Unidad Académica del IIMAS en Yucatán
Universidad Nacional Autónoma de México, Mérida, México
https://orcid.org/0000-0002-7040-9552
israel.sanchez@iimas.unam.mx

Bassam Ali
Doctor en Ingeniería
Profesor Investigador, Facultad de Ingeniería, Laboratorio de Modelado y Optimización de Procesos Energéticos y Ambientales
Universidad Autónoma de Yucatán, Mérida, México
https://orcid.org/0000-0001-7526-6952
baali@correo.uady.mx

ABSTRACT

Public health has multidisciplinary challenges involving a combination of physical, mental, and social welfare. Two limitations to quantifying indoor pollutants (gases, chemical compounds, and suspended particles) are the high cost and the complexity of available measurement systems. Under this scenario, an experimental approach was used to develop a low-cost system to measure variables that affect human and environmental health. Calibration, validation, and technical adjustment processes were conducted in an extreme-climate location in southern Mexico, following domestic and international standards. The key results showed the feasibility of using low-cost tools to measure pollutants in developing countries. 57% of the data for H2S had a result above 150 ppm, which is considered harmful to human health. On the other hand, developing the measurement system in the studied locality showed the importance of having data to measure environmental pollution levels according to each region's habits and customs. Sensors and open access systems were used as these can directly benefit resource-constrained researchers and the public and private sectors interested in measuring environmental and comfort variables to promote universal access to knowledge.

Keywords
environmental measurement system, low-cost sensors, indoor environmental quality, pollutant measurement.

RESUMEN

La salud pública presenta retos multidisciplinares que implican una combinación entre el bienestar físico, mental y social. Dos limitaciones para cuantificar los contaminantes en interiores (gases, compuestos químicos y partículas en suspensión) son el elevado coste comercial y la complejidad de los sistemas de medición disponibles. En este escenario, se utilizó un enfoque experimental para desarrollar un sistema con sensores de bajo coste para medir variables que influyen en la salud humana y ambiental. Los procesos de calibración, validación y ajuste técnico se realizaron en una localidad de clima extremo en el sur de México, bajo estándares nacionales e internacionales. Los resultados principales mostraron la viabilidad del uso de herramientas de bajo coste para medir contaminantes en países en vías de desarrollo. El 57 % de los datos de H2S mostraron un rendimiento superior a 150 ppm, lo que se considera perjudicial para la salud humana. Por otro lado, el proceso de desarrollo del sistema de medición en la localidad de estudio demostró la importancia de disponer de datos para medir los niveles de contaminación ambiental según los hábitos y costumbres de cada región. Los sensores y sistemas de acceso abierto se utilizaron para beneficiar directamente a investigadores con recursos limitados y a los sectores público y privado interesados en medir variables medioambientales y de confort para promover el acceso universal al conocimiento.

Palabras clave
sistema de medición ambiental, sensores de bajo costo, calidad ambiental interior, medición de contaminantes.

RESUMO

A saúde pública apresenta desafios multidisciplinares que envolvem uma combinação de bem-estar físico, mental e social. Duas limitações para a quantificação de poluentes internos (gases, compostos químicos e partículas em suspensão) são o alto custo e a complexidade dos sistemas de medição disponíveis. Neste cenário, uma abordagem experimental foi utilizada para desenvolver um sistema de baixo custo para medir variáveis que afetam a saúde humana e ambiental. Os processos de calibração, validação e ajuste técnico foram realizados em um local de clima extremo no sul do México, seguindo padrões nacionais e internacionais. Os principais resultados mostraram a viabilidade do uso de ferramentas de baixo custo para medir poluentes em países em desenvolvimento. 57% dos dados relativos ao H2S tiveram um resultado acima de 150 ppm, o que é considerado prejudicial à saúde humana. Por outro lado, o desenvolvimento do sistema de medição na localidade estudada mostrou a importância de contar com dados para medir os níveis de poluição ambiental de acordo com os hábitos e costumes de cada região. Foram utilizados sensores e sistemas de acesso aberto, pois podem beneficiar diretamente pesquisadores com recursos limitados e os setores público e privado interessados em medir variáveis ambientais e de conforto para promover o acesso universal ao conhecimento.

Palavras-chave:
sistema de medição ambiental, sensores de baixo custo, qualidade ambiental interna, medição de poluentes

INTRODUCTION

In Latin America, people spend considerable amounts of time indoors, making indoor environmental quality (IEQ) vital for health and productivity (Nilandita et al., 2019). Many of them experience poor indoor air quality, which is associated with various health issues, such as sick-building syndrome and reduced cognitive performance in educational environments (Khalil & Kamoona, 2022), and it has been seen that environmental factors contribute to between 25% and 33% of these health issues worldwide (National Institute of Public Health, 2022). Apart from this, it has been seen that exposure to sulphur dioxide (SO_2) can harm the airways of asthmatics (Nurhisanah & Hasyim, 2022). In this vein, Mentese et al. (2020) identified a correlation between indoor pollutants and comfort variables with respiratory symptoms, where the persistence of these indoor pollutants is influenced by climatic conditions and building characteristics (Enyoh et al., 2020). Consequently, mitigation strategies depend on the specific pollutants, construction methods, and energy policies in place. Research has highlighted the need for effective monitoring systems, indicating that indoor air can often be more polluted than outdoor air, emphasising the need for robust solutions to address these risks (Kim & Sohanchyk, 2022).

The potential for low-cost systems (LCS) to measure indoor IEQ in extreme climates in Latin America is a pressing issue. As urbanization continues to rise in Latin America, indoor air quality has become a significant concern, with implications for public health and energy efficiency. The interplay between indoor air quality (IAQ) and energy efficiency is complex, and achieving optimal IAQ often conflicts with energy-saving measures (Dabanlis et al., 2023). This is particularly relevant in extreme climates where ventilation strategies must be carefully balanced to avoid exacerbating indoor pollution levels (Tran et al., 2020). The main pollutants in the environment are divided into gases (CO, CO_2), chemical compounds (CH_2O, NO_2), and suspended particles (PM). When reacting with nitrogen oxides (NO_x), volatile organic compounds can also affect the health of the building and its users in the short and long term (Jung et al., 2021). Meanwhile, SO_2 and NO_x are responsible for acid rain and air pollution in urban areas. On the other hand, SO_2 in combination with PM_{10} increases morbidity in chronic heart and upper respiratory patients (Secretaría de Salud, 2019). Finally, there is carbon dioxide (CO_2), a colourless, odourless, and tasteless gas from the complete combustion of carbon and biological respiration (Occupational Safety and Health Administration [OSHA], 2015). In summary, the potential for an LCS to measure IEQ in extreme climates in Latin America is not only a matter of public health but also a critical step towards achieving energy equity.

Jung et al. (2021) found that cost is a limitation for measuring indoor pollutants, especially in developing countries with low research resources. Although systems have been developed to measure PM and gas concentrations using development boards (Arduino, Raspberry Pi, etc.) (Kalia & Ansari, 2020), it has been shown that exposure to pollution is higher when factors such as poverty and segregation are present (Burbank et al., 2023). Health conditions have additional limitations, given the lack of information on the presence of pollutants in the indoor and outdoor environment, climate change, and other problems. García et al. (2013) studied pollution levels in Guadalajara, Mexico, and found higher concentrations of SO_2 after the rainy season. Mexico's diverse climates, ranging from arid to tropical, significantly affect IEQ and public health. Hence, implementing measurement systems can empower communities, especially in low-income areas, to proactively enhance their living conditions, thereby promoting energy equity and public health (Koengkan et al., 2020).

The economic situation in Mexico reinforces the need for low-cost solutions, as many households face financial constraints. Thus, developing affordable systems would promote widespread adoption, enabling communities to monitor and enhance their IEQ without significant costs (Nugroho et al., 2016). This perspective is crucial for energy equity, as low-income households often endure higher energy expenses and poorer living conditions, exacerbating health issues linked to inadequate IEQ (Balza et al., 2024). LCS could also improve understanding of the connection between indoor environmental factors and health outcomes, helping to identify pollution sources and inform public health interventions, ultimately benefiting vulnerable populations (Ginebreda & Barceló, 2022). However, in Latin American countries, the authors could not find an LCS that integrates the measurement of gases, chemical compounds, particulate matter, and thermal comfort variables in the same system. For this reason, it is important to generate new alternatives that meet domestic requirements.

The main objective was to evaluate an integral low-cost monitoring system, using current technology, and validate its technical performance in a social housing project under extreme climatic conditions in Mexico, as is the case in Merida, Yucatan, Mexico. This study will serve as a guide for environmental control in these spaces with energy poverty

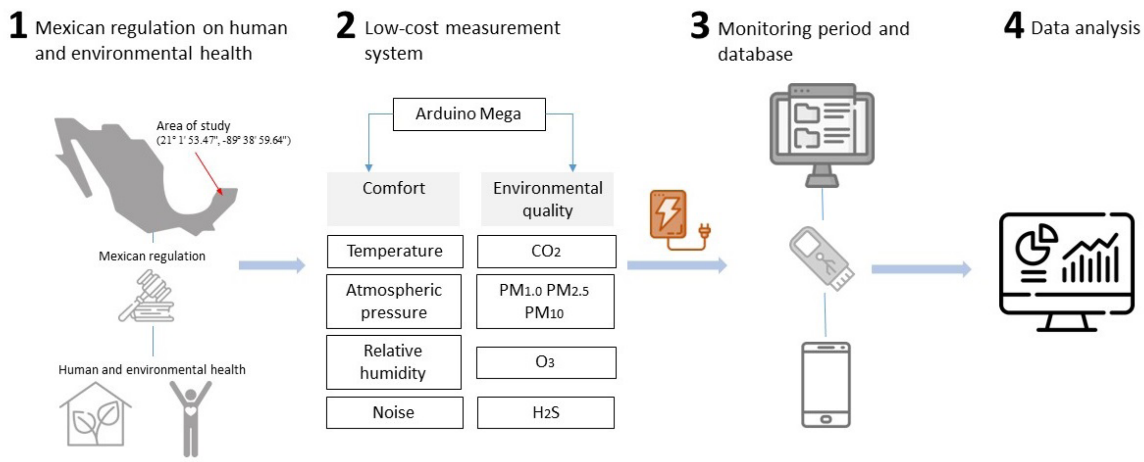

Figure 1. Methodological development for the measurement system. Source: Preparation by the authors.

Table 1. Regulatory recommendations for the main environmental pollutants. Source: Preparation by the authors.

Pollutant	Mexican Standard	WHO (World Health Organization, 2021)	NAAQS/EPA (Environmental Protection Agency, 2022)
CO	26 ppm (1 h) (Secretaría de Salud, 2021b)	4 mg/m³ 4 h)	35 ppm/h*
NO_2	0.106 ppm (1 h) (Secretaría de Salud, 2022a)	25 µg/m³ (24 h)	0.05 ppm (1 year)
SO_2	0.11 ppm (24 h) (Secretaría de Salud, 2019)	40 µg/m³ (24 h)	0.14 ppm (24 h)
PM	PM2.5 45 µg/m³ (24 h)	PM2.5 15 µg/m³ (24 h)	PM2.5 35 µg/m³ (24 h)
	PM10 75 µg/m³ (24 h) (Secretaría de Salud, 2022b)	PM10 45 µg/m³ (24 h)	PM10 150 µg/m³ (24 h)
O_3	0.09 ppm (1 h) (Secretaría de Salud, 2021a)	60 µg/m³ peak season	0.07 ppm (8 h)
Pb	0.5 µg/m³ (1 year) (Secretaría de Salud, 2021c)	-	0.15 µg/m³ **

* Not to exceed this concentration once a year ** 3-month average

and vulnerability. The obtained measurements were evaluated under the criteria of Mexican standards. In summary, developing LCS for measuring IEQ in Mexico is crucial not only from an economic standpoint but also for public health, energy equity, and sustainability.

METHODOLOGY

An experimental method was employed with the following phases (Figure 1):

1. Review current environmental health regulations for buildings (domestic and international).
2. Place low-cost sensors for IEQ variables into a container with 2-inch holes on all sides to allow airflow.
3. Monitoring period and creation of a database. The location is a representative urban development in southern Mexico (Figure 1). The measuring system was placed in the entrance hall, a key point for the exchange of internal and external climatic conditions. The monitoring period considered the time it takes for all sensors to have a valid reading. The sampling rate was 20 minutes, and measurements were recorded from 09-22-2023 to 10-22-2023.
4. Analyse the results.

ENVIRONMENTAL HEALTH REGULATIONS FOR BUILDINGS

Table 1 presents domestic and international standards establishing limits and recommendations for indoor pollutants. The Official Mexican Standard NOM-022-SSA1-2019 (Secretaría de Salud, 2019) on environmental health establishes a maximum of 0.075 ppm per hour in a 3-year arithmetic average for SO_2, or 0.04 ppm daily as the maximum for three consecutive

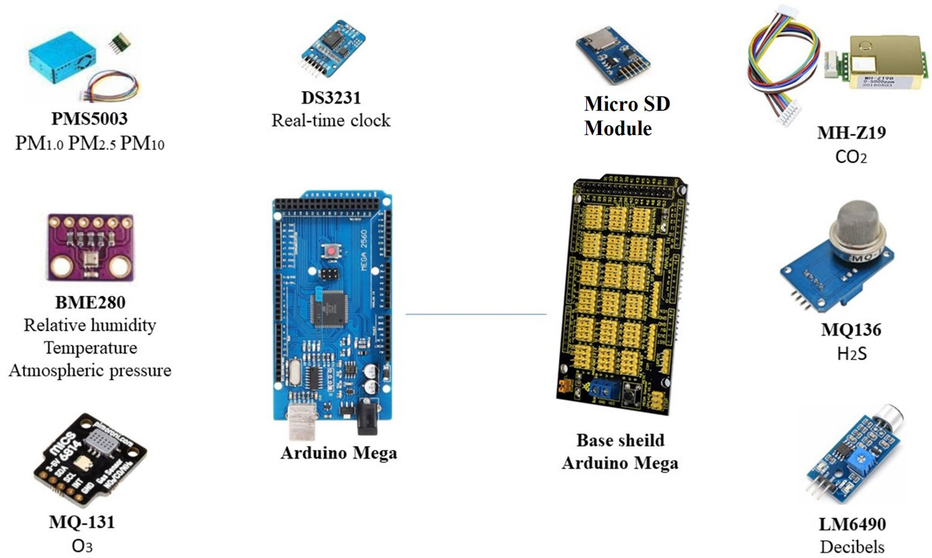

Figure 2. Diagram of sensors used in the LCS. Source: Preparation by the authors.

years. The Mexican Official Standard (Secretaría de Salud, 2022b) establishes permissible values for PM10 and PM2.5. O_3 can cause a considerable reduction in agricultural crop yields (Secretaría de Salud, 2021a). The Air Quality Guidelines (World Health Organization, 2021) are based on a global and regional assessment of diseases caused by air pollution. These levels are not mandatory, but are considered a reference for IEQ. Table 1 summarises the pollutant concentration recommendations of the Mexican and international standards.

CO_2 levels indicate air quality because an excess of this chemical compound can become an asphyxiant gas. ASHRAE (2024) suggests that indoor CO_2 levels should not exceed 1000 ppm (ASHRAE, 2024; Gangwar et al., 2024). Meanwhile, the Occupational Safety and Health Administration sets a limit of 5000 ppm in 8 h and 2 ppm every 15 minutes for formaldehyde (OSHA, 2015). In Mexico, maximum concentration limits have been established for the following pollutants in ambient air: ozone, carbon monoxide, sulphur dioxide, nitrogen dioxide, lead, total suspended particles, and suspended particles smaller than 10 and 2.5 micrometres (Secretaría de Salud, 2021a).

LOW-COST SYSTEM DEVELOPMENT

The development of the prototype considered the stages described below.

- System selection. The selection and procurement are based on regional custom analysis and market availability to measure IEQ variables such as gases, chemical constituents, PM, and noise levels.
- Calibration.
- Adjustments and validation.
- Analysis of results.

Figure 2 shows the measurement system's sensors and components. LCS reduced the cost of commercial measurement equipment for recording the same environmental variables by approximately 85 %, resulting in a total cost of USD 350.

CALIBRATION

The calibration consisted of setting the measurement system for a house in southern Mexico, coordinates (21° 1′ 53.47″, -89° 38′ 59.64″). The location experiences an average annual temperature of 33.6 °C (Sistema Meteorológico Nacional, 2020). It has a typical yearly relative humidity of 73% and an annual solar irradiance averaging 233.5 W/m² (Red Universitaria de Observatorios Atmosféricos, 2023). The extreme thermal characteristics of the locality determined the interest in this site. Commercial monitoring equipment with calibration certificates was used to validate the LCS sensors' measurements. This section presents the calibration of the relative humidity variable as an example. The procedure described was very similar and, in many cases, the same as that used for all variables measured by the LCS. First, the low-cost BME280 sensor, capable of providing temperature, relative humidity, and atmospheric pressure measurements, was connected to the open-source Arduino Mega development board and configured to take relative humidity readings every 10 seconds. The average of these readings was stored every 5 minutes. The sampling rate was selected to match the configuration of the HOBO U12-012 data

Table 2. LCS (BME280) and reference instrument (HOBO U12-012). Source: Preparation by the authors.

Sensor	Brand	Measuring range	Accuracy	Resolution
BME280	BOSCH	0 – 100 %	±3%	0.008 %
HOBO U12-012	Onset	5 – 95 %	±2.5%	0.05 %

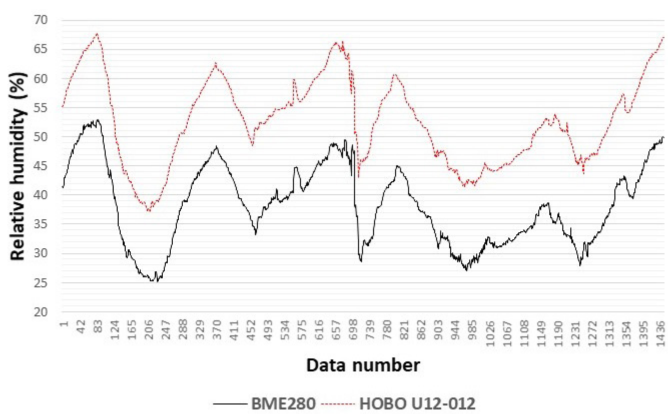

Figure 3. Relative humidity measurements under LCS and the reference instrument. Source: Preparation by the authors.

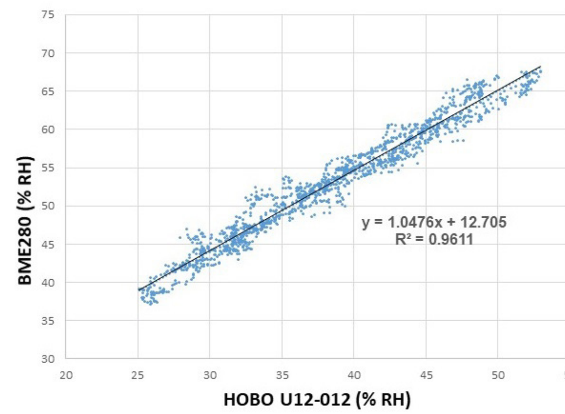

Figure 4. Least squares linear regression plot of the LCS and the reference. Source: Preparation by the authors.

acquisition system used as the reference instrument for calibration. The main characteristics of the LCS and the reference instrument are shown in Table 2.

The calibration process was performed using the "Calibrated Reference" method (Nicholas J. V. & White D. R., 2001). This method consists of comparing measurements of the device being tested (DTU) against the measurements of a calibrated instrument, which must be certified, and its calibration must be traceable to domestic and international standards. Thus, both instruments are placed in a room under equal conditions and left to measure simultaneously. Once the measurement period was over, which in this case was a little more than five days, the data stored in the memory of each device were collected and analysed in a statistical sheet. 1445 sampled data pairs were plotted against time to see if they were acquired correctly (Figure 3).

Figure 3 shows that the DTU measurements are consistently below those of the reference instruments, representing an approximate -12.7 (% RH) offset. The data was fitted into a scatter plot for linear least squares regression. A fitting equation was obtained using this linear regression that minimised the sensitivity (slope) and offset errors (Figure 4).

ADJUSTMENTS AND VALIDATION

The correction equation was obtained from the calibration described in section 2.3 :

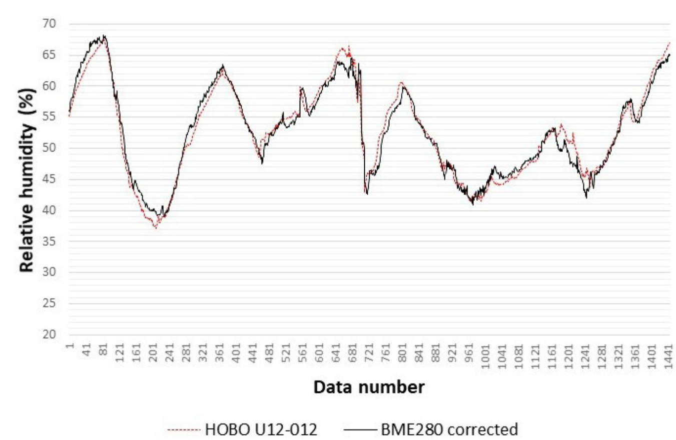

Figure 5. Comparison of BME280 against HOBO U12-012. Source: Preparation by the authors.

$$y = 1.0476x + 12.705$$

Where is the Relative Humidity (calibrated) in percentage and is the Relative Humidity measurement reported by the BME280 sensor. The last term of equation (1) is the offset compensation of the low-cost sensor measurements. Equation (1) was applied to the data from the LCS BME280 to reduce the error concerning the commercial sensor HOBO U12-012 measurements. The corrected data, together with the reference sensor data, can be seen in the graph of Figure 5. From this graph, the calibrated measurements match the behaviour and magnitude of the reference instrument.

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At the end of the functional testing, calibration, and validation, the code of the sensors was shared to promote universal access to knowledge and to provide continuous feedback to improve the system through the following link: https://shorturl.at/Nzn1g

RESULTS AND DISCUSSION

2232 results were obtained for each variable measured from September 22nd to October 22nd, 2023. Figure 6 and Figure 7 present the hourly averages during the monitoring period. The dotted red lines represent the upper limit of the comfort model (CM) for relative humidity, air temperature, and the regulatory limits for pollutants (O_3, Particulate Matter, CO_2, H_2S, and decibels). Figure 6a presents the temperature behaviour with the adaptive CM of the ASHRAE Standard 55, which satisfies 80% of the users (Quah, 2021). During the measurement period, there were no heating needs, so it was not necessary to represent the lower limit of the CM. This was similar for relative humidity, whose behaviour is presented in Figure 6b with the upper limit of the CM (between 30% and 50 %). 85% of the monitoring time presented cooling needs under an adaptive CM to satisfy 80% of the users, and 74% of the data were observed above the CM for relative humidity. Figure 6c presents the results for the noise level. NOM-081-SEMARNAT-1994 (Secretaría de Medio Ambiente y Recursos Naturales, 2024) establishes noise limits of 55 dB.

Figure 7a does not show the regulatory limit of NOM-020-SSA1-2021 (Secretaría de Salud, 2021a) because it is 0.09 ppm per hour, and no values above this were present during the monitoring period. The red line in Figure 7b represents the WHO limit for $PM_{2.5}$. There were no values above the limits recommended by Mexican regulations (45 and 75 microns for $PM_{2.5}$ and PM_{10}, respectively). 3.6 % of $PM_{2.5}$ was observed above the WHO regulatory limit. It is important to note that $PM_{1.0}$ has no regulatory exposure limit. The regulatory limit of 500 ppm for CO_2 in Figure 7c was set for outdoor spaces, which is representative of this study because there are no regulations to qualify indoor spaces (ASHRAE, 2024).

The Occupational Safety and Health Administration [OSHA] (2024) states that 100 ppm H_2S for more than 1 hour could generate irritation; between 100 ppm and 150 ppm would produce the risk of fatigue or olfactory paralysis and increase the risk by increasing the hours of exposure to this gas. In the monitoring period, values above 150 ppm could risk human health (Figure 7d). The case

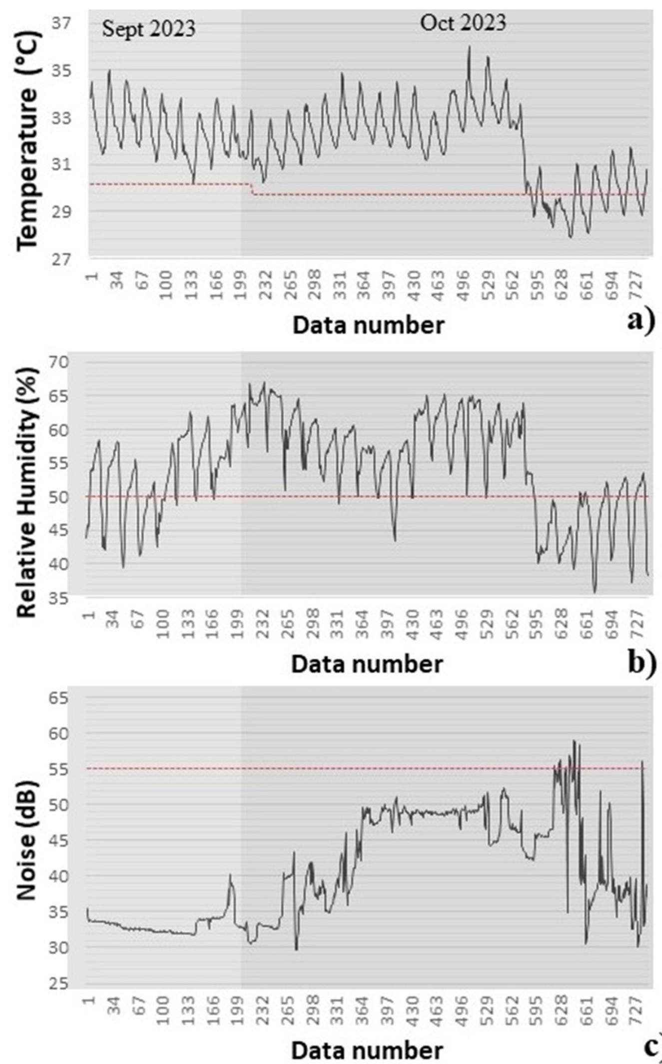

Figure 6. Results of the monitoring period for comfort variables.
Source: Preparation by the authors.

study allowed the design of a monitoring system that reduced the cost of commercial sensors for measuring environmental quality and comfort variables by 85 %. Afroz et al. (2023) emphasised the importance of calibrating and validating low-cost sensors. The authors documented the possible influence of relative humidity on sensors measuring PM2.5 when RH is above 75 % due to excess ambient water. On the other hand, Cowell et al. (2022) monitored particulate matter, temperature, and relative humidity in a residential environment using sensors for less than USD 126. These authors agreed on the influence that excess humidity could have on the accuracy of the sensors. Meanwhile, Frederickson et al. (2023) measured NO_2, O_3, and $PM_{2.5}$ and used a linear regression model to calibrate low-cost sensors. In this study, RH was below the limits detected as harmful for LCS. Tang

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 76 -85
https://doi.org/10.22320/07190700.2024.14.02.06

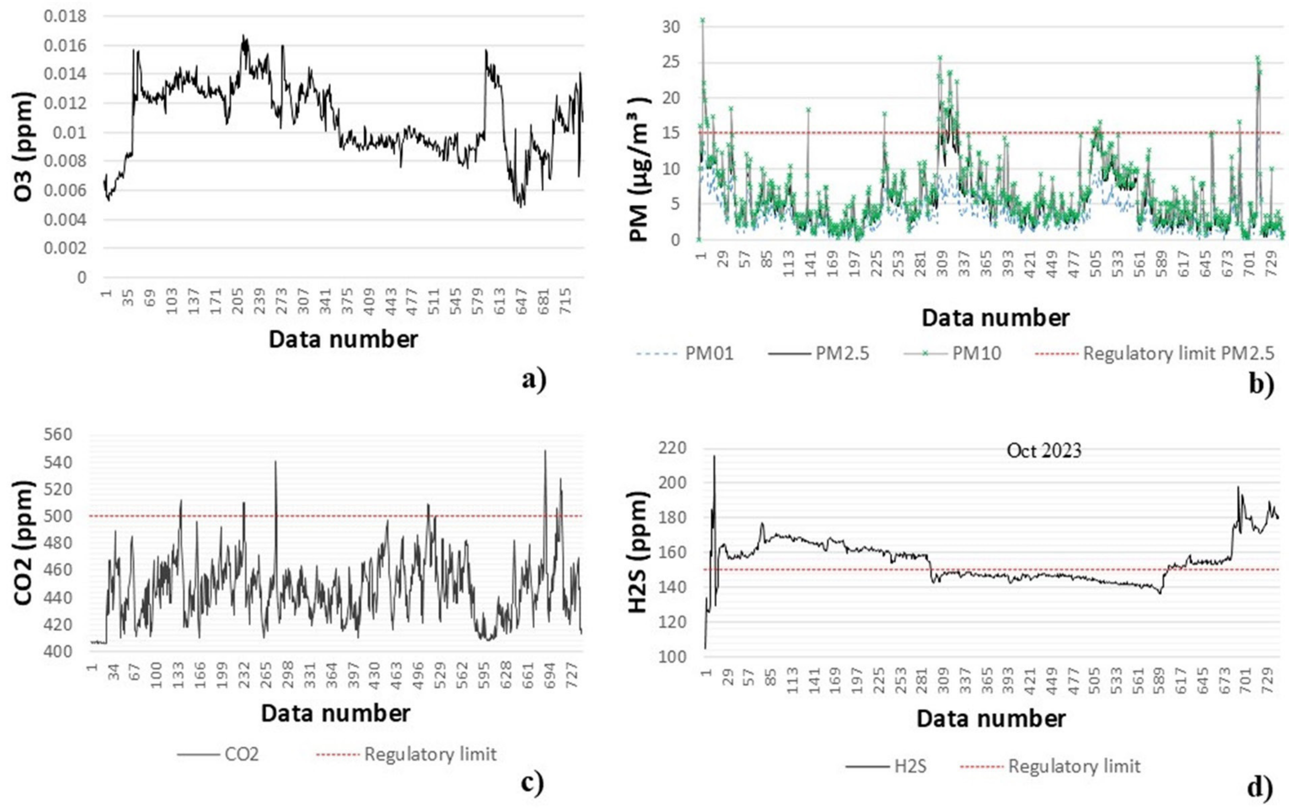

Figure 7. Results of the monitoring period for IEQ variables (pollutants). Source: Preparation by the authors.

and Pfrang (2023) used a linear regression method as a calibration method for low-cost sensors to measure suspended particles, with an overall accuracy of 70.7 %. These authors, in this case, recommended periodic calibrations and comparing LCS with high-accuracy instruments where possible, criteria that matched the characteristics of this study.

Ortiz et al. (2022) designed an experimental system to measure Mexico's temperature, relative humidity, and air speed. They compared their data against numerical data and found a maximum difference of almost half a degree Celsius. These findings show the interest in generating adequate instrumentation to address climate change in Latin America. Although Mexico's National Air Quality Information System generates real-time information through continuous monitoring stations (Ministry of Environment and Natural Resources, 2024), there are localities in the south with only one station and gaps in the information from recent years. The results represent a long-term challenge to corroborate the optimal functioning of the sensors in their performance and as an integral system. To this end, a calibration process should be periodically carried out to detect possible errors promptly.

As an area of opportunity, extending the monitoring period to one year and comparing the results with monitoring station databases as a reference is necessary to ensure the optimal functioning of the LCS. In the next stage, it is proposed that the LCS be located in other sectors and geographical locations to extend the range of influence and the available database. Additionally, the LCS performance is limited by the accuracy of the reference instrument used during calibration. Finally, historical data measured with reliable instrumentation represent a greater certainty about the presence of pollutants in the residential sector in Mexico. The results put into perspective two possible routes for localities in Latin America. The first is aimed at stakeholders, who could generate effective strategies to improve users' quality of life in the face of sudden climate change. The second refers to the environmental education needed in Latin American countries, with dissemination and outreach events backed by accurate data to inform the population and generate awareness towards informed adaptation to climate change.

CONCLUSIONS

This study developed an LCS for measuring environmental quality variables in buildings, validating and calibrating the sensors at a site in southern Mexico. The results demonstrated an 85% saving compared to off-the-shelf measuring systems, thereby enabling universal access to the instrumentation and, consequently, to knowledge regarding the reduction of indoor pollution in homes.

The implementation of the proposed LCS may be particularly beneficial for developing countries such as Mexico. The measurements taken over a month revealed that the thermal characteristics of the study locality align with those of an extreme climate, highlighting the need for cooling, even in a month that is not the warmest. This highlights the importance of periodically monitoring residential spaces to ensure compliance with Mexican regulations, which still require updates to address pollutants that lack specific regulatory limits and pose a risk to public health.

The results from the measurement month, between September and October 2023, indicated that the regulatory limits for several pollutants were exceeded, reinforcing the need for continuous monitoring. The LCS developed in this study presents itself as a potential tool for addressing the challenges of climate change with a focus on social equity by providing data that can guide strategies to reduce emissions from pollutant sources within homes. This approach not only contributes to improving IEQ but also promotes energy equity in Mexico, ensuring that all communities have access to the necessary resources for a healthier living environment. However, the accuracy of the developed LCS can be improved if a calibrated reference instrument with a higher accuracy level becomes available.

AUTHOR CONTRIBUTIONS CRediT

Conceptualization, R.G.Q.C., C.E.V.T.; Data Curation, R.G.Q.C., C.E.V.T.; Formal Analysis, R.G.Q.C., C.E.V.T.; Funding Acquisition; Research, C.E.V.T.; Methodology, C.E.V.T., R.G.Q.C.; Project Management, I.S.D., A.B.; Resources, R.G.Q.C., C.E.V.T., I.S.D., A.B.; Software, R.G.Q.C.; Supervision, I.S.D., A.B.; Validation, R.G.Q.C.; Visualization, R.G.Q.C., C.E.V.T.; Writing - original draft, C.E.V.T.; Writing - revision and editing, R.G.Q.C.

ACKNOWLEDGEMENTS

The first author gratefully thanks CONAHCYT for a postdoctoral fellowship to CVU 181807.

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 86 - 97
https://doi.org/10.22320/07190700.2024.14.02.07

EVALUATION OF RAIN BARRELS AND GREEN ROOFS FOR FLOOD MITIGATION IN A WARM SUB-HUMID CLIMATE - STATE OF COLIMA, MEXICO

Recibido 06/08/2024
Aceptado 02/12/2024

EVALUACIÓN DE BARRILES DE LLUVIA Y TECHOS VERDES PARA MITIGAR INUNDACIONES EN CLIMA CÁLIDO SUBHÚMEDO, ESTADO DE COLIMA, MÉXICO

AVALIAÇÃO DE BARRIS DE CHUVA E TELHADOS VERDES PARA MITIGAÇÃO DE ENCHENTES EM CLIMA QUENTE SUBÚMIDO, ESTADO DE COLIMA, MÉXICO

Samir Josué Figueroa-Avalos
Ingeniero Civil
Estudiante de Maestría en Arquitectura Sostenible y Gestión Urbana (MASGU)
Tecnológico Nacional de México, Villa de Álvarez, México
https://orcid.org/0000-0001-9023-0050
g2246004@colima.tecnm.mx (Autor de Correspondencia)

Dora Angélica Correa-Fuentes
Doctora en Arquitectura
Profesora investigadora del cuerpo académico consolidado Ciudad Sostenible de la Maestría en Arquitectura Sostenible y Gestión Urbana
Tecnológico Nacional de México, Villa de Álvarez, México
https://orcid.org/0000-0002-1804-5480
dora.correa@colima.tecnm.mx

Jesús López-de-la-Cruz
Doctor en Ingeniería del Agua y Medio Ambiente
Profesor Investigador y Director de la Facultad de Ingeniería Civil
Universidad de Colima, Coquimatlán, México
https://orcid.org/0000-0001-8230-6414
jlopez71@ucol.mx

Jorge Armando Gutiérrez-Valencia
Doctor en Educación
Coordinador de la Maestría en Arquitectura Sostenible y Gestión Urbana
Tecnológico Nacional de México, Villa de Álvarez, México
https://orcid.org/0009-0005-5394-064X
jorge.gutierrez@colima.tecnm.mx

Ignacio Barajas-Ávalos
Magíster en Arquitectura Profesor,
Departamento de Ciencias de la Tierra
Tecnológico Nacional de México, Villa de Álvarez, México
https://orcid.org/0000-0003-4834-370X
ignaciobarajas@colima.tecnm.mx

RESUMEN

Las inundaciones en las áreas urbanas se presentan con mayor frecuencia producto del intensivo cambio de uso de suelo y los efectos del cambio climático. Los Sistemas Urbanos de Drenaje Sostenible (SUDS) buscan replicar el ciclo hidrológico local y con ello, reducir las inundaciones. Se evaluaron dos tipologías: los Barriles de Lluvia (BLL) y los Techos Verdes (TV). El objetivo fue determinar qué técnica alcanza mayor eficiencia en la reducción de volúmenes de escorrentía en la ciudad de Villa de Álvarez, Colima, México. La simulación se realizó, a través del software Storm Water Managment Model (SMWW), y los resultados indicaron que los BLL y TV lograron reducir el volumen de la escorrentía un 14.36% y 26.40% respectivamente, bajo la condición más crítica.

Palabras clave
inundaciones, sustentabilidad, cambio climático, hidrología

ABSTRACT

Flooding in urban areas is becoming ever more frequent due to intensive land-use change and the effects of climate change. Sustainable Urban Drainage Systems (SUDS) aim to replicate the local hydrological cycle and, thereby, reduce flooding. Two typologies were evaluated: Rain Barrels (RB) and Green Roofs (GR). The objective is to determine which technique is more efficient in reducing runoff volumes in the city of Villa de Álvarez, Colima, Mexico. The simulation was carried out using the Storm Water Management Model (SWMM) software, and the results indicate that RB and GR reduced runoff volume by 14.36% and 26.40% respectively, under the most critical conditions.

Keywords
floods, sustainability, climate change, hydrology.

RESUMO

As enchentes em áreas urbanas estão ocorrendo com mais frequência como resultado da intensa mudança no uso da terra e dos efeitos das mudanças climáticas. Os Sistemas Urbanos de Drenagem Sustentável (SUDS) têm como objetivo replicar o ciclo hidrológico local e, assim, reduzir as inundações. Duas tipologias foram avaliadas: barris de chuva (BLL) e telhados verdes (TV). O objetivo foi determinar qual técnica alcança maior eficiência na redução dos volumes de escoamento na cidade de Villa de Álvarez, Colima, México. A simulação foi realizada usando o software Storm Water Management Model (SMWW), e os resultados indicaram que o BLL e o TV foram capazes de reduzir o volume de escoamento em 14,36% e 26,40%, respectivamente, sob a condição mais crítica.

Palavras-chave:
enchentes, sustentabilidade, mudanças climáticas, hidrologia.

INTRODUCTION

Changes in land use due to urbanization represent a relevant anthropogenic process in floods. Urban components such as buildings, roofs, streets, and parking lots reduce soil permeability (Zúñiga-Estrada et al., 2022), and impermeable surfaces in urban areas significantly alter the local hydrological cycle; therefore, rainwater infiltration is reduced, and the volume and speed of runoff is increased (Lizárraga-Mendiola et al., 2017)—these factors overload drainage systems, which increases the risk of floods. In addition, as part of the effects of climate change, more frequent and intense rain events are expected (Zuniga-Teran et al., 2020).

Green infrastructure has been promoted recently. This consists of implementing nature-based solutions to obtain ecosystem benefits, especially for water regulation. These practices are known as sustainable urban drainage systems (SUDS) in the United Kingdom, low-impact developments (LID) or best management practices (BMPs) in North America, and alternative techniques (ATs) in France (Fletcher et al., 2015).

These practices seek to mitigate the maximum runoff peaks generated by urbanization's waterproofing of the soil, mimicking preexisting natural hydrology. They include green roofs, infiltration wells, permeable pavements, wetlands, green ditches, and rain barrels (Liu et al., 2015). These solutions promote evapotranspiration, infiltration, and the recharge of aquifers and improve runoff quality by eliminating pollutants (Lizárraga-Mendiola et al., 2017).

Numerous studies have been conducted on the behavior of urban runoff when implementing different techniques. Guo et al. (2019) developed an LID model in Tsingtao, one of the pilot sponge cities in China, where rain barrels, green roofs, rain gardens, and permeable pavements were implemented, managing to reduce runoff by 20.7% to 63.2%. Andrés-Doménech et al. (2018) analyzed the hydrological behavior of green roofs in Valencia, Spain, and demonstrated its effectiveness even in Mediterranean climates, where the runoff coefficient was reduced below 75%. On the other hand, Chapman and Hall (2021) analyzed the behavior of runoff in different scenarios in which they applied bioretention cells, green roofs, and permeable pavements, highlighting that the available area for effective SUDS decreases with increasing housing density, which forces the adaptation of green infrastructure, prioritizing green roofs in homes.

Evaluating these solutions requires simulating their effects in a hydrological model, a somewhat complex process due to the multiple variables involved. The Storm Water Management Model (SWMM) program, developed by the United States Environmental Protection Agency (EPA), allows modeling the hydrodynamic behavior of rainwater (Mendoza González et al., 2017). The SWMM has a LID editor that models sustainable technologies and estimates the basin's response regarding runoff volume, water quality, infiltration, evaporation, and pollutant load (Zúñiga-Estrada et al., 2022).

This study highlights the city of Villa de Álvarez, located in western Mexico, as an example of an urban area that has suffered recurrent floods during the rainy season between June and October. This research evaluates two types of SUDS commonly applied in homes: rain barrels (RB) and green roofs (GR). SWMM is used to simulate and compare the hydrological behavior of both models and determine the technique that provides the best results. This evaluation is based on runoff volume, peak runoff, and runoff coefficient for different precipitation intensities.

METHODOLOGY

LOCATION AND CLIMATE

Villa de Álvarez is located in the state of Colima, Mexico. It has a population of 149,723 inhabitants and is the third most populous city in the state (Figure 1). The city has experienced remarkable population growth, above the national average, leading to dispersed urban development and inadequate infrastructure (Ramírez-Rivera et al., 2021).

According to the National Institute of Statistics and Geography (INEGI), the city has a warm sub-humid climate, an average annual temperature of 25°C and an average annual rainfall estimated at 900 mm, with rain predominating in summer, between June and October (INEGI, 2016). Villa de Álvarez has experienced an increase in the frequency of floods in the last two decades, mainly due to tropical storms associated with hurricanes and mesoscale convective systems (MCS). Examples include Hurricanes Jova (2011), Manuel (2013), and Patricia (2015), which recorded accumulated rainfall of 200 mm in 24 hours. Floods also occur due to intense, short-lasting rains (Pérez-González et al., 2017), a product of the MCS, which are complicated to monitor.

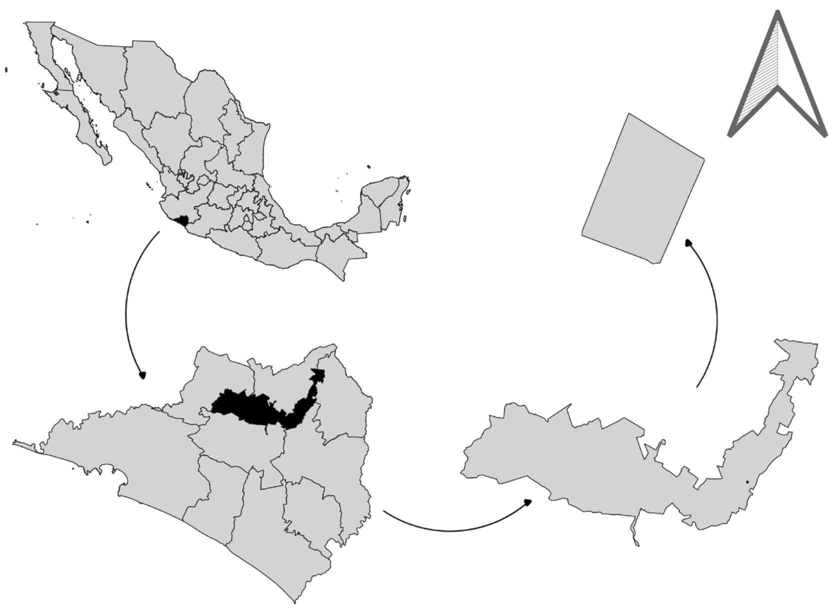

Figure 1. Study area location. Source: Preparation by the authors.

Figure 2. Marking out of sub-basins. Preparation by the authors.

GENERAL DESCRIPTION OF THE STUDY AREA'S CHARACTERISTICS

Urban growth in Villa de Álvarez has spread to the north, increasing impervious surfaces and resulting in recurrent flooding in low-lying areas. However, conventional solutions based on expanding storm drainage have not mitigated the problem. Hence, a new perspective on stormwater management that adopts green infrastructure harmonizing urban development with the natural hydrological cycle is needed.

The study area was chosen based on the need to implement upstream SUDS techniques to efficiently manage water in low-lying areas, considering the average rooftop area and future vulnerability to flooding.

The research used QGIS with vector data from the National Geostatistical Framework of Mexico (INEGI,

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 86 - 97
https://doi.org/10.22320/07190700.2024.14.02.07

Table 1. Minimum requirements to build the model. Source: Ponce de León García (2022).

Parameters	Definition	Units
Basin area	Total area of each sub-basin	Hectares
Basin length	Total distance of the basin	Meters
Basin width	Ratio between area and length	Meters
Basin slope	Percentage ratio between elevations and distance	Percentage
%-Imperm	Percentage of impermeable area	Percentage
N-Imperm	Manning's value for the impermeable fraction	Dimensionless
N-Perm	Manning's value for the permeable fraction	Dimensionless
Curve number	Soil Conservation Service (SCS) Infiltration Model	Dimensionless

Table 2. General characteristics of the study area. Source: Preparation by the authors.

Sub-basin	Area	Length	Width	Slope	%-Imperm	N-Imperm	N-Perm
1	0.13	140.61	9.25	2.29	68.01	0.014	0
2	0.85	161.72	52.56	2.14	53.99	0.014	0.06
3	0.82	158.73	51.66	2.69	63.11	0.014	0
4	0.78	157.50	49.52	2.16	63.58	0.014	0
5	0.77	156.09	49.33	2.53	63.53	0.014	0
6	0.44	152.89	28.78	1.83	64.46	0.014	0

2023). The study area of 3.80 hectares is characterized by a predominantly residential land use, which covers 74.15%, reflecting a high housing density. Cobblestone streets represent 20.93%, and green areas constitute the remaining 4.92%. Continental relief rasters with a resolution of 5 m and a scale of 1:10,000 (INEGI, 2019) were used to mark out the sub-basins.

Based on the topography, it was possible to mark out six sub-basins in the study area (Figure 2). In addition, it was observed that surface runoff runs north to south along the streets. This is due to the lack of a storm drainage system to facilitate adequate water channeling.

To build the model in SWMM, it was necessary to identify the minimum characteristics required by the system (Table 1).

The parameters were determined using QGIS. However, the impermeable area percentage was determined considering the land use of each sub-basin, and its respective runoff coefficient was used, taken from Table 2.4 of the Manual for Drinking Water, Sewerage, and Sanitation: Storm Drainage (CONAGUA, 2019, p. 57). Manning values for the impermeable and permeable fractions were obtained from Table 5-6 of the Hydraulic Book on Open Channels (Chow, 1994, p. 108). The curve number was estimated using vector data on surface hydrology and soil science (INEGI, 1981; INEGI, 2007) and soil and vegetation of the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2021). Using the vector data, the soil type was classified according to its physical properties and permeability. For this, the values of Table No.11 (Díaz Herrera, 1987, p. 64) were used, and it is highlighted that it belongs to a type B soil classification. Finally, the curve number was calculated considering the soil classification and its use. The values in Table 2-2a of the book Urban Hydrology for Small Basins, TR-55 (Cronshey et al., 1986, pp. 2-5) for a type B soil and land use with human settlements were used; hence, the value designated to the curve number was 92.

The main characteristics of the sub-basins are shown in Table 2.

SELECTION OF DESIGN RAINS

The design precipitation was estimated using historical records of the National Water Commission (CONAGUA, 2020). The climatological station 6052-E.T.A 254 Comala was selected for its influence on the study area. Monthly maximum rainfall data were collected from this station from 1975 to 2017.

The collected data were subjected to statistical tests to validate their use in the research, which includes the detection of outliers, the Helmert test, Student's t, Cramer's test, and Anderson's independence test (Escalante Sandoval & Reyes Chávez, 2002). The satisfactory results of these tests confirm that the maximum rainfall series in 24 hours is independent and free of trends.

Once the hypotheses for frequency analysis have been validated, the technique is implemented to build the intensity-duration-return period (I-D-Tr) curves, which allow rainfall lasting less than 24 hours to be estimated. Frederick Bell's method was chosen because its application best fits return period conditions between 2 and 100 years and durations between 5 and 120 minutes. Bell's formula is expressed in Equation 1 below (Campos Aranda, 1998, pp. 4–56).

$$P_t^T = (0.35\, Ln\, T + 0.76)(0.54t^{0.25} - 0.50)P_{60}^2$$

(Equation 1)

Where:
T is the return period.
t is the duration of the storm.
P_{60}^2 storm precipitation for a 2-year return period lasting one hour.

The storm duration, also known as concentration time, is determined using Kirpich Equation 2 (CONAGUA, 2019, p. 41). The concentration time in the study area is one hour.

$$t_{cs} = 0.0003245\left(\frac{lt}{\sqrt{S_{lc}}}\right)$$

(Equation 2)

Where:
lt is the length of the main channel (m).
S_{lc} average slope of the channel (dimensionless).

The construction of the I-D-Tr curves allows obtaining precipitation design hyetographs for return periods of 2, 5, and 10 years, which assume a storm duration of one hour. The design rainfalls for these periods were 47.90 mm, 63.23 mm, and 74.82 mm, respectively. Figure 3 presents the hyetographs used in SWMM to build the model.

ESTIMATION OF EVAPOTRANSPIRATION

Soil moisture is important for processes such as infiltration and evaporation. The hydrological model requires evapotranspiration data to accurately represent soil moisture during the simulation period, especially at the beginning of the rainfall event (Andrés-Doménech et al., 2018).

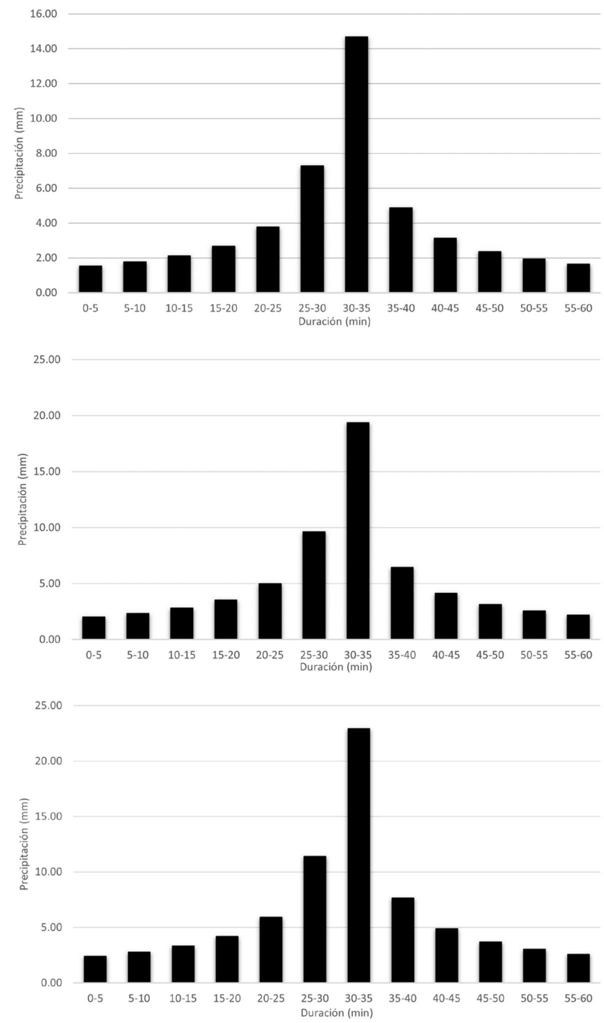

Figure 3. Hyetographs for different return periods: a) 2 years, b) 5 years, and c) 10 years. Source: Preparation by the authors.

Because the weather stations do not record the necessary data, the potential monthly evapotranspiration is calculated using Thornwaite's formula (Equation 3). This formula is based mainly on the average temperature and is adjusted according to the hours of sunlight at a specific site. Evapotranspiration is calculated for the same period of years as precipitation.

$$PE_m = 16N_m\left(\frac{10\overline{Tm}}{I}\right)^a$$

(Equation 3)

Where:
PE_m potential evapotranspiration (mm/month).
N_m monthly adjustment factor related to the hours of sunlight (without units).
T_m Average monthly temperature (°C).
a Constant (Equation 4).
I Annual thermal index (Equation 5).

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} I + 0.49$$

(Equation 4)

$$I = \sum_{m}^{i} = \sum \left(\frac{Tm}{5}\right)^{1.5}$$

(Equation 5)

The potential evapotranspiration was estimated in millimeters per month. To obtain the daily value, it was necessary to divide it by the number of days of the month because the rain simulation is based on a single precipitation event. The value for September, the month with the highest precipitation in the region, was chosen (Table 3).

Table 3. Potential evapotranspiration per day. Source: Preparation by the authors.

Month	PEm (mm/day)	Correction factor	Corrected PEm (mm/day)
January	2.55	0.95	2.43
February	2.74	0.90	2.47
March	3.00	1.03	3.09
April	3.52	1.05	3.70
May	4.14	1.13	4.67
June	4.40	1.11	4.87
July	4.15	1.14	4.72
August	4.07	1.11	4.50
September	3.84	1.02	3.92
October	3.79	1.00	3.79
November	3.37	0.93	3.14
December	2.88	0.94	2.72

Construction of the model

The model's simulation consists of three scenarios: A, the area's current state without interventions; B, RB implementation; and C, GR implementation. The RB capacity is 2500 liters for each house. This is determined based on commercial products. On the other hand, the roofs, the main receivers of rainwater in the research, have an average surface of 80m². In addition, it is considered that the GRs will cover the entire rooftop. Table 4 presents the GR design used in SWMM based on the parameters of Chapman and Hall (2021).

Table 4. Parameters used in the SWMM simulation. Source: Chapman and Hall (2021).

Tabla 4. Parámetros usados en la simulación SWMM. Fuente: Chapman y Hall (2021).

Type of SUDS	Parameter	Values used in the model
GR	Height of the ditch (mm)	20
	Vegetation volume fraction	0.05
	Surface area roughness (Manning n)	0.24
	Slope %	0
	Soil layer	
	Thickness (mm)	80
	Porosity (Volume fraction)	0.464
	Field capacity (Volume fraction)	0.20
	Withering point (Volume fraction)	0.10
	Conductivity (permeability - mm/hr)	119.40
	Conductivity slope	45.05
	Suction load (mm)	49.80
	Drainage material	
	Thickness (mm)	25
	Fraction of voids	0.50
	Roughness (Manning n)	0.30
RB	Barrel height (mm)	1320

Figure 4. Construction of the model in SWMM. Source: Preparation by the authors.

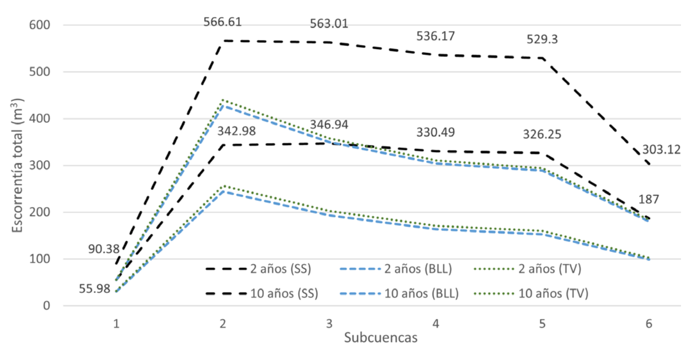

Figure 5. Runoff according to maximum and minimum values. Source: Preparation by the authors.

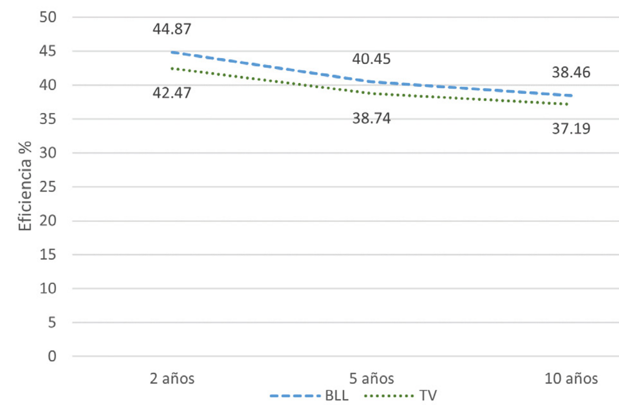

Figure 6. General efficiency ratio in the reduction of runoff volumes for different return periods. Source: Preparation by the authors.

The study area lacked a storm drainage system; the streets (7m wide and 15cm high) were modeled as rectangular open surface channels in SWMM to simulate water evacuation. The outlets of each sub-basin were established in nodes located at their ends, which simulate that the runoff generated descends to their lowest point and connects with the street that joins the sub-basins (Figure 4).

RESULTS AND DISCUSSION

Scenario A, without SUDS (SS), was simulated under three rainfall conditions (2, 5, and 10 years) lasting one hour, which allowed evaluating the hydrological behavior. Sub-basin 2 had the highest values according to the runoff volumes: with precipitation of 47.90 mm, it generated 342.98 m^3 of runoff and a maximum flow of 308.23 lps. With 63.23 mm of precipitation, these values increased to 469.46 m^3 and 436.61 lps, respectively. Finally, with 74.82 mm of rain, 566.61 m^3 of runoff and 536.09 lps of maximum flow were reached. According to the results, a direct relationship between the increase in precipitation intensity and runoff was evidenced.

Figure 5 shows the simulation results when considering the application of SUDS for precipitation events with return periods of 2 and 10 years. They represented the minimum and maximum intensities, respectively. Generally, the RBs and GRs show satisfactory results in water retention for the three precipitation conditions. Sub-basin 2 has the highest runoff volumes for a 10-year rainfall and experiences a significant reduction of 139.15 m^3 with the RB and 126.94 m^3 with the GR. However, sub-basin 5 achieves the highest absolute reduction, reaching 240.75 m^3 with RB and 235.35 m^3 with GR.

The RBs and GRs follow a similar behavior for a 2-year rainfall event. Although the RBs manage the storm runoff slightly better than the GRs, the difference between the two is not significant according to the descriptive analysis. The percentages of efficiency in the volume for sub-basin 2 with a 2-year rainfall event are 28.86% for RB and 25.30% for GR. Despite their high efficiency in 2-year storms, the RBs have overflows even in events of this magnitude. However, even with overflows, their performance is superior to GR in higher-intensity rainfall. In the same sub-basin, with a 10-year rainfall event, the efficiency of the RBs reach 24.56%, while the GRs reach 22.40%.

Figure 6 shows the efficiency of both technologies in general and demonstrates that their effectiveness depends on the magnitude of the precipitation. The RBs perform better in any precipitation condition. However, their efficiency decreases with increasing rainfall intensity due to their limited storage capacity (2500 l). The overflows that occur when exceeding this capacity increase the surface runoff. Conversely, the GRs have a lower performance than the RBs in all the evaluated precipitation conditions. Both techniques are functional for the analyzed return periods in the study area—however, both decrease efficiency with higher-intensity rainfall.

The peak runoff refers to the maximum flow that flows through a basin during a rainfall event. The techniques managed to reduce the peak runoff (Figure 7). A noticeable difference in peak runoff reduction is observed between the GRs and the RBs. In contrast to the reduction of runoff volumes, where the RBs showed better performance, in the reduction of peak runoff, the GRs outperformed the RBs in terms of efficiency. Sub-basin 2 has a lower reduction of peak runoff due to the smaller number of techniques implemented, in contrast, Sub-basin 5 achieves a higher reduction thanks to its higher density of

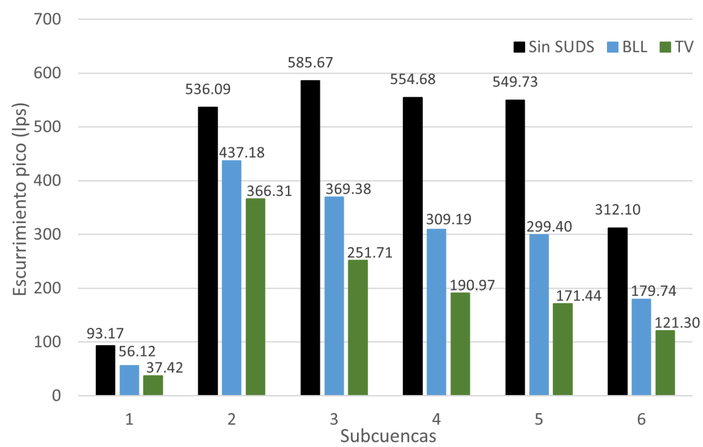

Figure 7. Peak runoff for a 10-year return period. Source: Preparation by the authors.

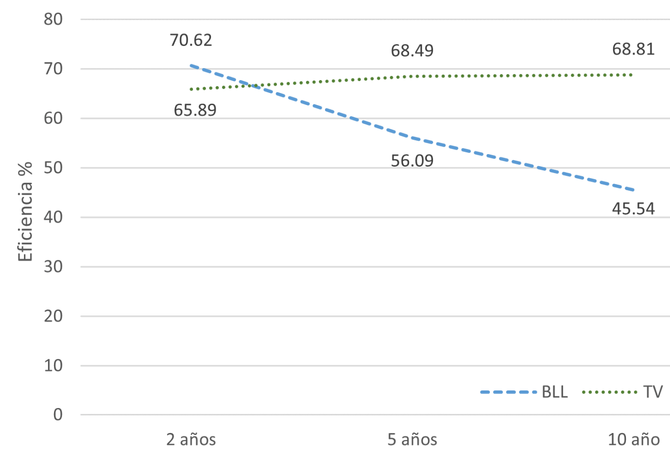

Figure 8. Comparison of the effectiveness of RB and GR in reducing peak runoff for different return periods. Source: Preparation by the authors.

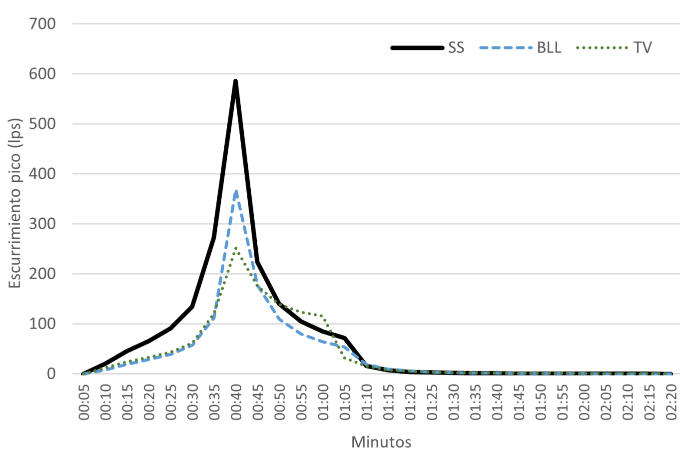

Figure 9. Hydrograph of sub-basin 3 for a 10-year return period. Source: Preparation by the authors.

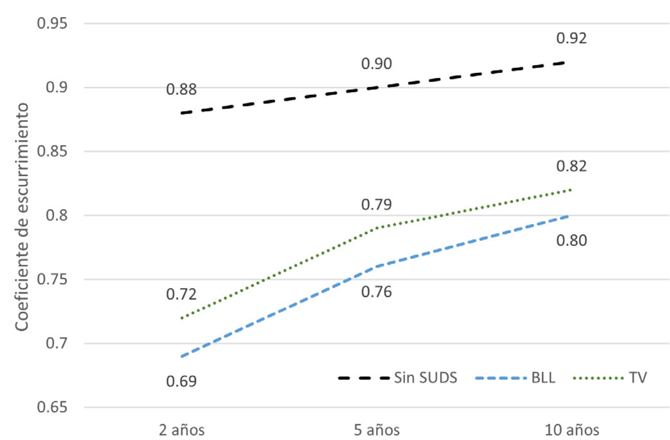

Figure 10. Comparison of the mean runoff coefficient in the sub-basins applying RB and GR. Source: Preparation by the authors.

dwellings, which allows a greater application of the catchment techniques.

The general performance of both techniques was evaluated under different precipitation conditions. Figure 8 shows that the RBs stand out in their efficiency for 2-year rainfall events, but their performance decreases in higher-intensity rains. On the other hand, the GRs perform better in more intense rainfall conditions. Generally, the GRs surpass the RBs in the peak flow reduction, primarily in events with greater intensity. The RBs reach their maximum efficiency (70.62%) in rains with a return period of 2 years, while the GRs demonstrate a significantly higher efficiency (60.81%) in rains with a return period of 10 years.

In Sub-basin 3, the peak runoff is reached 40 minutes after the onset of precipitation. The implementation of RB reduces this peak by 36.93%, while the GRs achieve an even greater reduction of 57.02% (Figure 9). The techniques show satisfactory performances in terms of reducing the peak flow rate. However, there is a significant difference between the two techniques. The RBs significantly reduce the peak flow rate with satisfactory behavior. On the other hand, the GRs far exceed this efficiency by attenuating the peak flow rate by more than 50% compared to the scenario without intervention.

It is observed that the concentration time in the scenario without intervention has a steep ascent and descent. However, the RBs reduce the peak flow; they

Table 5. Statistical significance of the differences between scenarios. Source: Preparation by the authors.

Year	AvsB Volume	AvsC Volume	CvsB Volume	AvsB flow rate	AvsC flow rate	CvsB Flow rate	AvsB coefficient	AvsC coefficient	CvsB coefficient
2 years	0.0049	0.004	0.008	0.0051	0.0059	0.0090	0.0002	0.0006	0.00003
5 years	0.0046	0.004	0.010	0.0057	0.0056	0.0059	0.0002	0.0006	0.00010
10 years	0.0044	0.037	0.014	0.023	0.0053	0.0047	0.0004	0.0007	0.00030

exhibit similar behavior, although on a smaller scale. In contrast, the GRs decrease the peak flow and flatten the hydrograph curve, defining them as the most effective technique.
The runoff coefficient was evaluated, showing a notable reduction in all cases. Figure 10 shows how the runoff coefficient in scenario A increases steadily with the increase in precipitation. However, both techniques reduce it considerably, with the RBs being the most effective. Despite the more significant reduction observed with the RBs, the GRs are more stable when facing more intense rains.

It was analyzed whether the reduction observed in the three variables was statistically significant. Although the descriptive analysis shows a decrease in absolute terms, it is essential to determine whether this reduction is statistically significant to confirm the effectiveness of the interventions for each scenario. t-tests were performed for paired samples, where a P-value <0.05 indicates significant differences between the scenarios. The results show statistically significant reductions in the analyzed variables (Table 5).

CONCLUSIONS

The simulation with SWMM allows us to observe the sub-basins' response to different rainfall conditions and their behavior when implementing sustainable techniques. The RBs achieve significant runoff volume reductions by performing better in higher-intensity precipitation events, unlike the GRs, which show their best behavior in less intense storms.

Both techniques reduce the volume, the peak flow, and the runoff coefficient. However, the GRs demonstrate superior performance (68.81%), exceeding the RBs (45.54%) in managing average peak runoff for 10-year rains; even the hydrograph shows that the GRs achieve more significant flattening of the curve than the RBs.

The results allow us to demonstrate the effectiveness of these sustainable solutions in managing runoff in the study area. By mimicking natural hydrological conditions, it is possible to recover the local hydrological cycle and mitigate the impacts of urban runoff for storms of different intensities. Implementing nature-based solutions to manage runoff, especially to reduce the peak flow and minimize the risk of floods, is essential.

This research evaluated the application of the techniques for 90% of the homes, a possibly unrealistic percentage. The study's main limitation is the model's lack of calibration due to the complexity of determining all the necessary parameters. It is suggested that future research focus on calibration and evaluation for different application percentages in homes.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, S.J.F.A.; Data curation, S.J.F.A.; Formal analysis, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Acquisition of financing D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Research, S.J.F.A.; Methodology, S.J.F.A.; Project management, D.A.C.F.; Resources; Software. S.J.F.A.; Supervision, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Validation, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Visualization, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Writing - original draft, S.J.F.A.; Writing - revision and editing, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.

ACKNOWLEDGMENTS

Thanks must be given to the National Council of Humanities, Sciences, Technologies, and Innovation (CONAHCYT) for this research that stems from the project "Design and Evaluation of Sustainable Urban Drainage Systems (SUDS) to Mitigate Floods in the City of Villa de Álvarez, Colima." Thanks are also given to the Tecnológico Nacional de México (TECNM) Colima Campus and the Master's Degree in Sustainable Architecture and Urban Management (MASGU).

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https://doi.org/10.22320/07190700.2024.14.02.08

Recibido 10/09/2024
Aceptado 09/12/2024

HABITATION PRACTICES FOR ADAPTATION AND RESILIENCE IN AN AMPHIBIOUS ENVIRONMENT IN COLOMBIA

PRÁCTICAS DEL HABITAR HACIA LA ADAPTACIÓN Y RESILIENCIA EN UN ENTORNO ANFIBIO EN COLOMBIA

PRÁTICAS DE HABITAÇÃO PARA ADAPTAÇÃO E RESILIÊNCIA EM UM AMBIENTE ANFÍBIO NA COLÔMBIA

Angélica Chica-Segovia
Doctora en Arte y Arquitectura
Profesora asociada, Escuela de Arquitectura y Urbanismo, Facultad de Artes
Universidad Nacional de Colombia, Bogotá, Colombia
https://orcid.org/0000-0002-3172-1543
achicas@unal.edu.co

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https://doi.org/10.22320/07190700.2024.14.02.08

RESUMEN

La Gran Depresión del Caribe colombiano ubicada en la macrocuenca Magdalena-Cauca, enfrenta una degradación ecosistémica significativa, debido a actividades antropogénicas que han impactado negativamente el hábitat y la calidad de vida de sus habitantes. Este artículo presenta el avance del proyecto Yuma: diversidad cultural infinita, centrado en la identificación de indicadores de adaptación y resiliencia de las comunidades frente a los retos contemporáneos relacionados con el agua de sus humedales, que enfatiza el valor de los saberes y prácticas locales. A través de una metodología cualitativa etnográfica, se exploran las tres subregiones: La Mojana, la Depresión Momposina y la Zapatosa, en que se busca delinear estrategias multiescalares para intervenciones que respeten el habitar tradicional y fomenten la autogestión y la gobernanza. Los resultados preliminares destacan la necesidad de políticas públicas que reconozcan las prácticas locales y fortalezcan la capacidad adaptativa de las comunidades, que aseguren su resiliencia ante los desafíos ambientales actuales.

Palabras clave
aguas superficiales, arquitectura vernácula, cultura del Caribe, adaptación al cambio climático.

ABSTRACT

The Colombian Caribbean Great Depression, located in the Magdalena-Cauca macro-basin, faces significant ecosystem degradation due to anthropogenic activities that have adversely affected its inhabitants' habitat and quality of life. This article presents the progress of the Yuma project - infinite cultural diversity, which focuses on identifying adaptation and resilience indicators for the communities to face contemporary challenges related to the water of their wetlands, emphasizing the value of local knowledge and practices. Three sub-regions are explored through a qualitative ethnographic methodology: La Mojana, the Momposina Depression, and La Zapatosa, which seeks to outline multi-scale strategies for interventions that respect traditional habitation and foster self-management and governance. Preliminary results highlight the need for public policies that acknowledge local practices and strengthen the adaptive capacity of communities to ensure their resilience when facing current environmental challenges.

Keywords
surface water, vernacular architecture, Caribbean culture, climate change adaptation.

RESUMO

A Grande Depressão do Caribe colombiano, localizada na macrobacia de Magdalena-Cauca, enfrenta uma degradação significativa do ecossistema devido a atividades antropogênicas que afetaram negativamente o hábitat e a qualidade de vida de seus habitantes. Este artigo apresenta o progresso do projeto Yuma: diversidade cultural infinita, focado na identificação de indicadores de adaptação e resiliência das comunidades diante dos desafios contemporâneos relacionados à água de suas zonas úmidas, o que enfatiza o valor do conhecimento e das práticas locais. Por meio de uma metodologia etnográfica qualitativa, as três sub-regiões foram exploradas: La Mojana, La Depresión Momposina e La Zapatosa. O objetivo era delinear estratégias multiescalares para intervenções que respeitassem a habitação tradicional e promovessem a autogestão e a governança. Os resultados preliminares destacam a necessidade de políticas públicas que reconheçam as práticas locais e fortaleçam a capacidade de adaptação das comunidades para garantir sua resiliência diante dos atuais desafios ambientais.

Palavras-chave:
águas de superfície, arquitetura vernacular, cultura caribenha, adaptação às mudanças climáticas.

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INTRODUCTION

The GDC (Great Depression of the Caribbean), located in the north of Colombia in the Magdalena-Cauca macro-basin, comprises La Mojana, the Momposina Depression, and the Zapatosa Marsh, from the departments of Córdoba, Sucre, Bolívar, Magdalena, and Cesar. These wetlands regulate the Magdalena, Cauca, San Jorge, and Cesar rivers, with an average temperature ranging from 24 to 37°C, rainfall from 17 to 137 mm, and humidity from 82 to 100%. Their rising dynamics and low-lying water bodies have four hydrological conditions: low, rising, high, and falling waters, depending on how the ecosystem is organized.

The riparian wetlands and their water pulses are fundamental ecosystems that act as flood buffers by decanting and accumulating sediment from tributary rivers (National University of Colombia - Observatory of Environmental Conflicts [OCA, in Spanish] and Institute of Environmental Studies [IDEA], 2017). This benefits agricultural and fish farming use, generating habitats for a large number of living beings, with a high number of environmental services (RAMSAR, 2018). However, this has led to over-exploitation and degradation, making them vulnerable and putting communities at risk (Torremorell et al., 2021).

These have been the support structure for amphibian and surrounding communities that inhabit them interdependently, providing them with much of what they need and requiring their protection. Historically, there has been an adaptation to this ecosystem, as is the case of the hydraulic works of the Zenú indigenous group (Olmos-Severiche et al., 2022) (Figure 1), in interaction with the dynamics of water. However, since the Spanish colonization in the sixteenth century, some activities throughout the macro-basin and climate change have modified productive practices and ways of living, putting the socio-ecosystem at risk (Calderón-Contreras, 2021).

Although wetlands are resilient and can self-repair, human interaction affects this possibility (Folke, 2003, cited in Medina et al., 2014). This sometimes irreversibly affects the habitat, making reciprocal actions that allow restoring the socio-ecosystem balance a matter of urgency (Torres-Carral, 2021).

Conflicts and obstacles that affect their conservation have been evidenced, such as hydrological transformations, weaknesses in socio-ecological management, scarce knowledge and valorization by society, insufficient efforts in conservation and sustainable use, low intervention with a focus on resilience and adaptation, and limited technical capacities of management and territorial planning (National Council of Economic and Social Policy Republic of Colombia. National Planning Department [CONPES], 2022; Vargas et al., 2023). This compels integrated regional management solutions to be implemented based on knowledge, conservation, and the sustainable use of natural and cultural capital to avoid reaching the point of no return.

This issue has become relevant due to the hydrological and climatic emergencies that affect the population's

Figure 1. Zenú channels in Las Flores, Sucre. Source: Preparation by the authors.

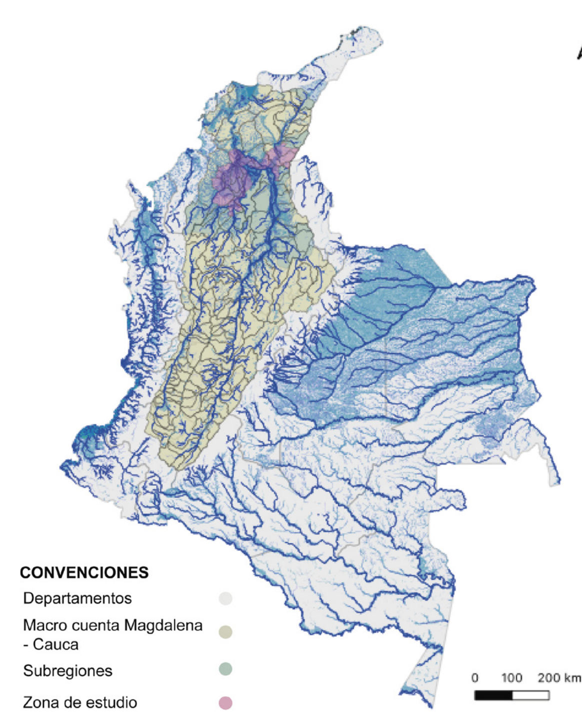

Figure 2. Magdalena-Cauca Macro-basin. Source: Preparation by María Camila Ramos Zapata.

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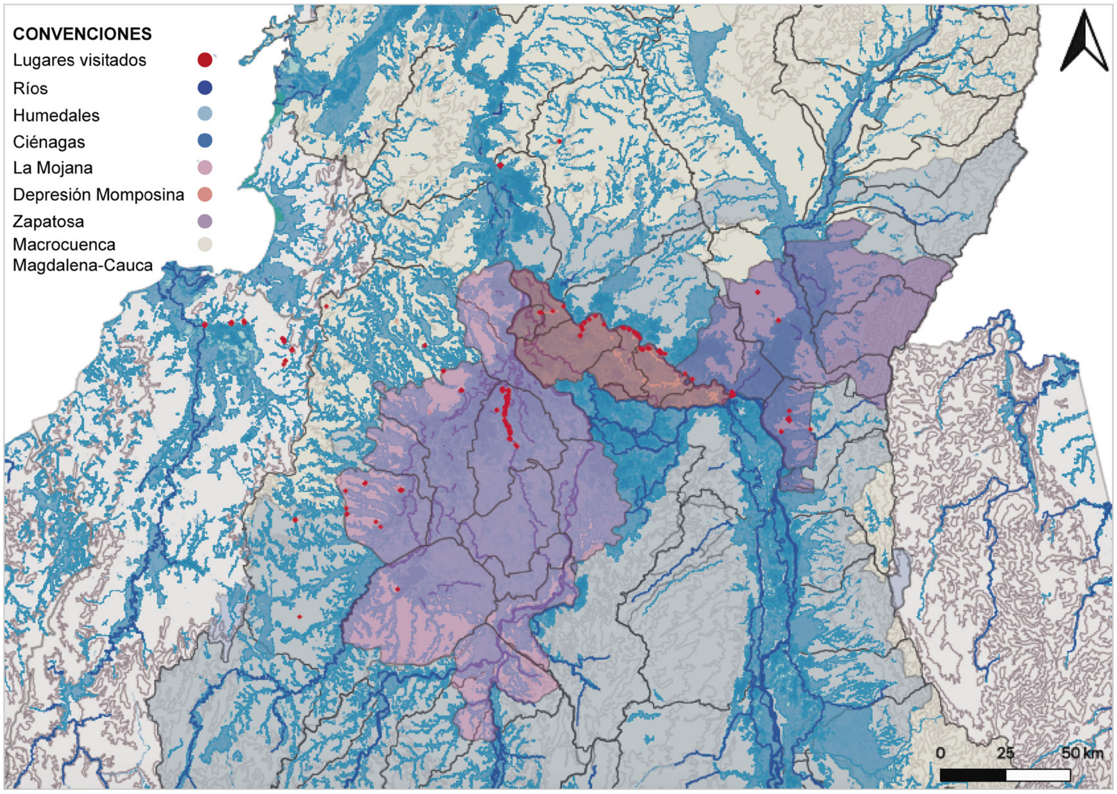

Figure 3. Route made in the GDC. Source: Preparation by María Camila Ramos Zapata.

stability (Rivera-Cediel, 2024). There are numerous studies and related regulations such as (de Nieto & Falchetti, 1981; Aguilera-Díaz, 2004; Aguilera-Díaz, 2011; OSSO Corporation, 2013; Vargas et al., 2023; Pan American Health Organization [PAHO] and World Health Organization [WHO], 2023; Torres Solórzano, 2023), but their approach is still centralist (Billon et al., 2020) selective or fragmented, in a complex region. Indeed, sometimes, the implications of water cycles or the factors that impede facing the challenges related to economic interests and armed conflict are not understood (Diz Diz, 2021).

Specific solutions have also been given that are adapted to types of infrastructure and housing (Palencia Mendoza, 2019; García-Reyes Röthlisberger & Fajardo, 2019; Mosquera-Torres & Calderón-Franco, 2022), which shows the need for more significant multiscale efforts that integrate natural dynamics and community knowledge as leading actors in the handling of these ecosystems (Smardon, 2006).

The research project aims to promote actions that rebalance socio-ecosystem relationships, strengthening the capacity to respond to change (Nguyen et al., 2022) and improving communities' quality of life and social mobility. It seeks to promote comprehensive attention to the ecoregion and its macro-basin, which counteracts the centrality in managing the territory and its ecosystem (Jaimes Pereira & Zerbone Alves de Albuquerque, 2022). The line presented in the article focuses on living practices and architecture, documenting evidence of adaptation and resilience (Coscia & Voghera, 2022) to current conditions. This enabled the generation of preliminary inputs to support locally adapted, co-produced, and located interventions within a self-management and community governance framework to formulate effective public policies at the territory's national, regional, and local management levels.

METHODOLOGY

This began with a bibliographic review, looking at the documentation and socio-ecosystemic characterization in the three zones: La Mojana, the Momposina Depression, and La Zapatosa (Figures 2 and 3). Representative cases were chosen using intentional sampling, semi-structured interviews, life stories, and participant observation.

The information was analyzed using socio-ecosystemic characterization sheets (Figure 4), divided into the categories of ecosystem, ways of living, architecture, conflicts and threats, adaptation, and resilience indicators.

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Figure 4. Characterization tool. Source: Preparation by the authors.

RESULTS

LIVING PRACTICES

The significant biodiversity of these ecosystems provided by the water pulses in rivers, streams, lagoons, swamps, marshes, and forests (Camacho, 2015), has historically led communities to settle on their banks, forcing them to adapt to hydrological dynamics, with a calendar to meet their needs (Figure 5). The architecture and the way of occupying the territory reflect these dynamics. Constructive and productive practices such as fishing, agriculture, and hunting respond to the climate, the water bodies, and the periods of the year marked by growth from January to October with abundant fishing. Then comes the summer season that fertilizes the land for planting, and although fishing decreases, it is when the fish spawn, preparing for the next season. In addition, the fresh pastures of the dry season are used for livestock migration from the savannas, establishing a close relationship between the highlands and the wetlands.

Each period implies the availability of resources for food security, construction, and the trade of surpluses, which has historically generated very close ties with the riparian populations and those around them. Figure 6 shows the two moments in each of the microhabitats.

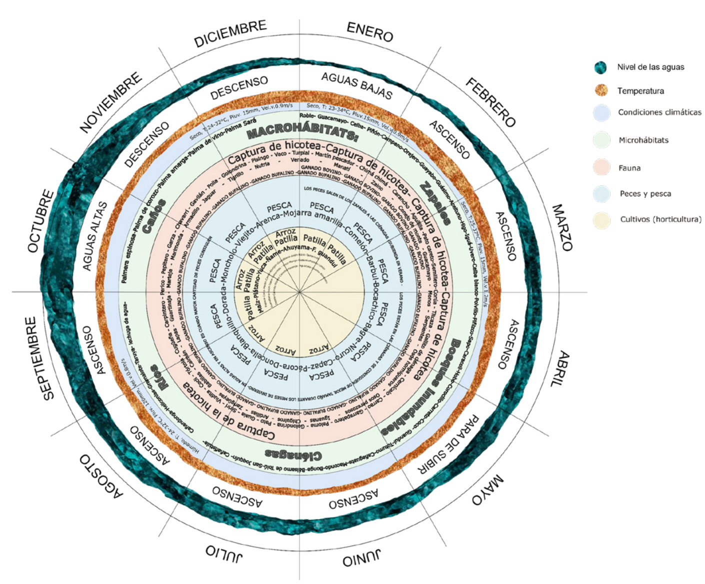

Figure 5. Ecological calendar of the GDC. Source: Preparation by the authors.

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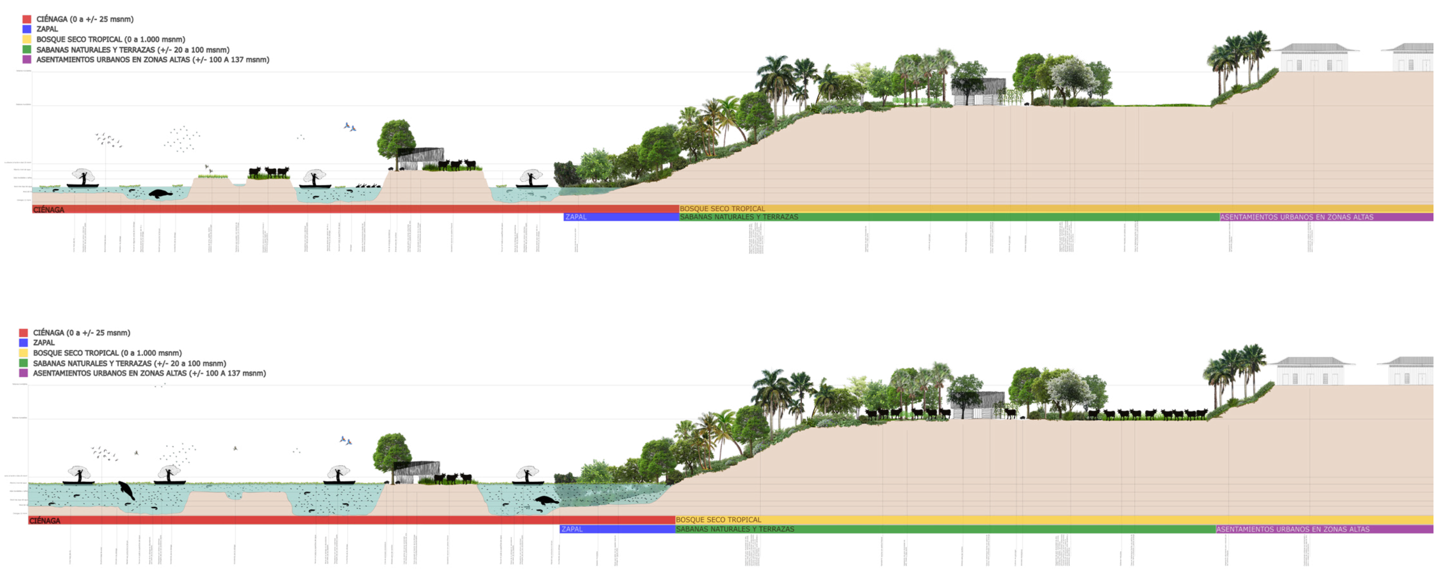

Figure 6. Ways of living in the natural savanna, natural tropical dry forest, marsh, and swamp intersection in high and low waters. Source: Preparation by the authors.

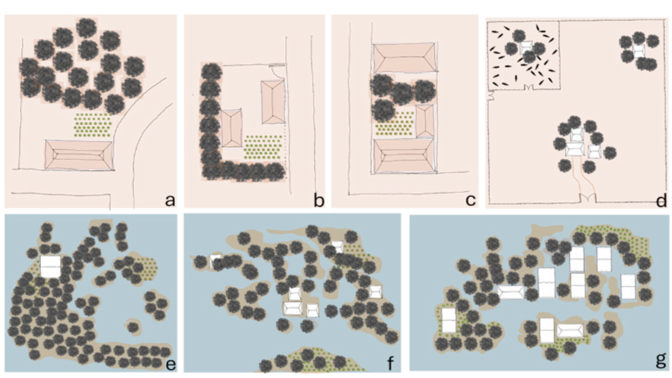

Figure 7. Types of layout: a, b, and c urban; d. rural productive; e, f, and g in the marsh. Source: Preparation by the authors

HABITAT AND ARCHITECTURE

Traditional architecture and layout are maintained, with extended single-volume constructions generally using non-attached volumes (Figure 7, a-g). In the productive properties, the grouped construction is surrounded by infrastructure for complementary activities such as livestock and horticulture (d).

In most cases, they have one floor and, exceptionally, two or more, especially in urban buildings that show the wealth of other times, such as in Sucre, San Marcos, and El Banco. The building is always accompanied by low, medium, and high vegetation to provide shade and, in some cases, food, often complemented by subsistence crops (Camacho Segura & Robledo Escobar, 2020), even in urban areas (Figure 8).

Figure 8. Setup in productive (above), urban (in the center), and swamp (below) areas. Source: Preparation by the authors.

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Each ecosystem involves the use of the available surrounding materials and suitable bioclimatic response, adapted to the water cycles, with predominantly masonry, half-timbered, and embedded adobe in rural or urban dry areas, half-timbered in American oil palm and sometimes wood constructions in flood zones. Each has a rod foundation in the ground, except for masonry that rises on large stones. Zinc roofs also stand out, replacing those of savannah and Macauba palm, modifying the dwelling's comfort, which is complemented by the surrounding vegetation (Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, Figure 14, and Figure 15).

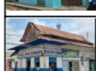
CARACTERIZACIÓN DEL HÁBITAT Y LA ARQUITECTURA TRADICIONAL EN LA DEPRESIÓN MOMPOSINA					
TIPOLOGÍA		CARACTERÍSTICAS CONSTRUCTIVAS			
		CERRAMIENTOS		CUBIERTAS Y ENTREPISOS	
REGISTRO	TIPO	SISTEMA	MATERIALES	SISTEMA	MATERIALES
a. Urbana					
	Terrestre- A nivel del suelo	Bahareque con envarado vertical	Madera	Par, hilera y solera	Madera
			Nepa de corozo		Palma amarga y de vino
					Madera
					Teja de zinc
		Bahareque embutido	Madera	Par, hilera y solera	Madera
			Nepa de corozo + barro		Palma amarga y de vino
					Madera
					Teja de zinc
		Entramado	Madera	Par, hilera y solera	Madera
					Palma amarga y de vino
					Madera
					Teja de zinc
		Mampostería simple	Ladrillo	Par, hilera y solera	Madera
					Teja plana
					Madera
					Teja de barro
					Madera
					Teja de zinc
b. Rural					
	Terrestre-A nivel del suelo	Bahareque con envarado vertical	Madera	Par, hilera y solera	Madera
			Nepa de corozo		Palma amarga y de vino
					Madera
					Teja de zinc
		Bahareque embutido	Madera	Par, hilera y solera	Madera
			Nepa de corozo		Palma amarga y de vino
					Madera
					Teja de zinc
		Entramado	Madera	Par, hilera y solera	Madera
					Palma amarga y de vino
					Madera
					Teja de zinc

Figure 9. Technical characterization of the architecture in the three zones. Source: Preparation by the authors.

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Figure 10. Traditional urban masonry house. El Banco. Source: Preparation by the authors.

Figure 11. Urban masonry houses, Sucre. Source: Preparation by the authors.

Figure 12. Traditional urban half-timbered house, San Marcos. Source: Preparation by the authors.

Figure 13. Traditional urban house using American oil palm, Santiago Apostol. Source: Preparation by the authors.

Figure 14. Traditional rural house in embedded adobe, La Zapatosa. Source: Preparation by the authors.

Figure 15. Traditional house in the marsh using American oil palm, San Marcos. Source: Preparation by the authors.

CONFLICTS AND THREATS

The socio-ecological balance of the macro-basin and the GDM wetlands has been altered by the changing water cycles due to upstream infrastructure works such as dams, dikes, and highways, among others, making it unsustainable (Greco & Larsen, 2014). Climate change has adjusted cycles and their duration, as has pollution (Meza-Martínez et al., 2020) and water sedimentation caused by mining activities (Urango-Cárdenas et al., 2024); the use of agrochemicals (Camacho, 2017) and monoculture, which put communities at risk (Marrugo-Negrete et al., 2024). The desiccation of the land for productive and extractive purposes, the abandonment of practices in rhythm with the water, and the replacement of traditional architecture in flood zones are also observed, which generates impacts on the territory and communities, as well as environmental and humanitarian emergencies, especially in multi-annual climate cycles (Figure 16 and Figure 17).

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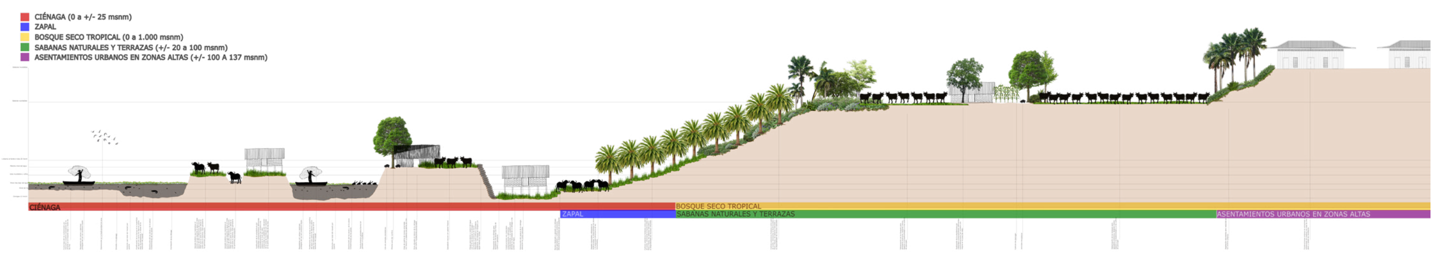

Figure 16. Identification of habitat conflicts. Source: Preparation by the Authors.

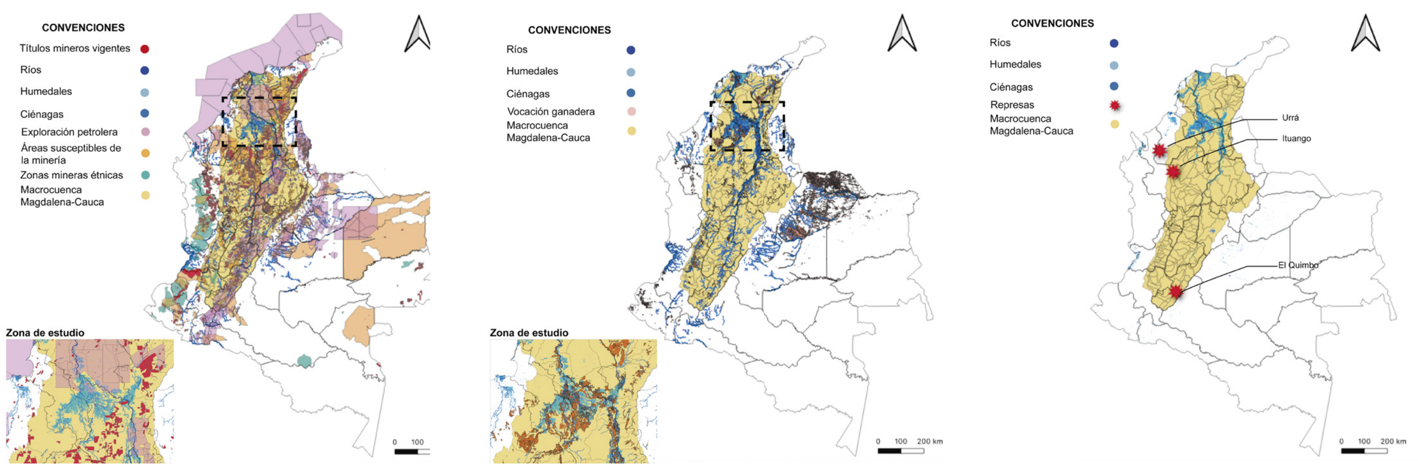

Figure 17. Regional conflicts: mining, livestock, and dams. Source: Preparation by María Camila Ramos Zapata.

Figure 18. Road fragmenting the marsh. Source: Preparation by the authors.

Figure 19. Houses for residents affected by floods. Source: Preparation by the authors.

Interventions encouraging this way of life and territory management have added to this. This has caused developments that run against the region's nature. These proposals intensify conflicts by action or omission, such as those in Figure 18 and Figure 19.

ADAPTATION AND RESILIENCE INDICATORS

Resilient and adaptation initiatives to current conditions that appeal to ecological wisdom were found (Liao et al., 2016). These promote associativity, ecosystem awareness for all generations, the recognition of the local, and safeguarding one's own (Figure 20). This is manifested in maintaining rhythms based on water pulses, traditional architecture, and knowledge associated with gastronomy, horticulture, fishing, and the production of objects. Reforestation, ecosystem recovery, and protection of local fauna are also promoted as a basis for their food security and the development of new sources of work and economy based on trade, tourism, and environmental services. Although there are few initiatives to address the broad needs of a complex region, the characterization shows the relics and survival of knowledge and practices in

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ways of living that can be enhanced by recognizing the importance of this region and these socio-ecosystems for the country and the world.

MULTISCALE GUIDELINES

The information analysis allowed identifying the potential to understand and relearn how to work alongside the rhythms of water and the challenges to be faced in this region. These propose multiscale guidelines that guide public policy in its management (Table 1), considering the fundamental role of community and landscape planning in controlling anthropogenic impacts.

Due to the characteristics of the challenges, the urgency of intervention at the national level in the macro basin, regionally in the GDC, and locally in each of its three subregions is evident, which implies further development of its characterization. At the same time, elements were found in the local context that can provide solutions through the recovery of living practices and traditional architecture adapted to restore balance in the socio-ecological relationship. This can be the basis for a community process that, from the surviving knowledge, guarantees appropriate and equitable solutions outlined from the local needs and capacities. This consolidates inputs for the analysis, planning, and definition of policies and projects focused on the region that respects local particularities, promoting their conservation and supporting the necessary adaptation processes to the growing impacts of climate change on the hydraulic dynamics of the region.

Figure 20. Adaptation initiatives, from left to right environmental recovery and ways of living in Antequera, recovery of Zenú hydraulic knowledge in Purísima, and ecotourism initiative in La Rinconada. Source: Preparation by the authors.

Table 1. Summary of the DOFA and CAME analysis. Source: Preparation by the authors.

WEAKNESSES	NATIONAL	REGIONAL	LOCAL
	CORRECT		
Small municipalities. Deficient conservation and sustainable use efforts. Dispersed and absent administrative, economic, and management dependence.	Update the administrative policy framework considering their needs, decentralizing, and respecting the local dynamics.	Comprehensive territory management based on knowledge, conservation, and sustainable use of regional natural and cultural capital, focusing on resilience and adaptation.	
Limited socio-ecological management. Limited approach to resilience and adaptation. Poor accessibility and high cost of transportation. Low availability of services and infrastructure. High rates of poverty and inequality. Low quality of life, social mobility, migration, and disrespect of traditional cultural practices.	Including the region in the national framework guarantees the prevalence of socio-ecological needs.	Improve infrastructure, service provision, education, health, culture, transport, roads and media.	
Limited technical capacities for territorial management and planning. Fragmented and small-scale studies and interventions. Low recognition and valuation of the socio-ecosystem.	Focus efforts on the ecoregion's development, overcoming conflicts, and increasing the presence of the state.	Encourage interdisciplinary study and recognition of the region on a multiscale scale, from participatory scenarios, accompaniment, and technical and academic assistance.	

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WEAKNESSES	NATIONAL	REGIONAL	LOCAL
	CORRECT		
Low support for organized communities and low level of partnership.	Prioritize policies to strengthen associativity.	Empower communities and strengthen associativity and cooperativism as forms of empowerment, participation, governance, and self-management.	
Lack of knowledge of the ecosystem characteristics associated with water.	Sensitize public officials and new inhabitants about the particular local conditions around water, the environmental role, and the possible solutions adapted from the region and not the other way around.		
Contamination from external sources.	Strengthen environmental and economic policies and regulations for prevention and correction.		
OPPORTUNITIES	EXPLOIT		
Survival of knowledge on adaptation to water.	Prioritize local knowledge over foreign interventions in formulating public policy and projects.	Identify, recognize, and value the surviving knowledge to promote its appreciation.	
Traditional knowledge balanced with nature.			
Biodiversity that promotes food security.		Promote knowledge, sustainable practices, and ecosystem conservation, which guarantee its defense and contribute to its protection.	
Freshwater reserve.			
Ecosystem with restoration potential.			
Ecotourism and cultural potential.		Consolidate points and routes of cultural and ecotourism tourism about local milestones, encouraging local communities to manage it.	
Unexplored, little studied, and valued cultural and identity potential			
Agricultural and fish farming potential.	Encourage sustainable agro-industrial development for food security, good living, and social mobility by integrating locally produced regional products into the market.		
The habitat and the traditional architecture respond adequately to the challenges of climate change.	Promote the appreciation and value of local practices and their regulatory acceptance.		
STRENGTHS	MAINTAIN		
Flood cycles generate rich food security and biodiversity.	Use clear and coherent interventions to raise awareness of the region's specific characteristics.	Guarantee the safeguarding and protection of knowledge about the region's ecosystem management.	
		Encourage efficient but sustainable agricultural and fishing practices that are not extractivist and controlled.	
Great cultural diversity.	Promote the region and its recognition, especially its ecological character. This would expand the offer of tourist services complementary to those already recognized.		
Survival of knowledge related to traditional ways of living and architecture.	Raise awareness about this knowledge's value and promote its learning as an input for regional and global intervention in similar situations.		
	Support local and regional cultural and tourism developments.		
Local communities committed to conservation.		Encourage the formation of groups interested in their recognition, safeguarding, and promotion with accompaniment and technical assistance.	
THREATS	FACE		
Centralized policies of little scope in the territory.	Ensure decentralization and equity in the management of the region's resources.	Consolidate regional efforts that cooperate in the management and injection of resources.	
Climate change.	Sustainable development strategies in all fields. Policies and plans for reforestation and soil recovery, comprehensive water resources management, agricultural adaptation, and ecological restoration in degraded areas.		
Annual and multi-annual flood rates.	Identify the particularities of the ecosystem to promote recognition and learning of how it works as an input for interventions that recognize its own dynamics.		
Development outside the natural dynamics of water.			
Regional inequality of access to resources with significant extractivism.	Strengthen environmental and economic policies and regulations for prevention and correction, which encourage appropriation for the defense and conservation of their ecosystem wealth.		
Deficient environmental policies that allow important transformations in the territory (containment or diversion of water, savannization, deforestation, and desiccation).			
Local environmental conflicts and other river sectors (mining, dams, livestock, intensive crops, deforestation).			
Armed conflict, drug trafficking, illegal mining.			
Promotion of foreign ways of living and architecture without suitable environmental response	Recognize, document, value, and promote their protection.		

These are nodes of intervention that can contribute to sensitizing the local and foreign populations to the urgent need to respect and adapt to water cycles. This implies a different approach to managing the territory based on water and not against it, revealing the importance of multiscale work.

DISCUSSION

The bibliographic review revealed many studies and regulations on the basin and the GDC, which show the relationship between conflicts at the basin level and the impacts on the wetlands. However, the problems are enormous and profound, given the lack of knowledge about local phenomena, which reflects a lack of instruments for such centralized territory management. It is impossible to solve problems only from the central or local context without establishing communication channels and participation at the different levels. Thus, the interventions proposed must be consistent with regional needs. This project line showed the importance of recognizing and recovering the living practices and adapting them to the new environmental and social conditions, which reference the knowledge linked to architecture, the ecosystem, and local urbanism.

This project complements previous efforts by preliminarily characterizing some indicators of adaptation and resilience of communities. This information is essential to formulate solutions to the socio-environmental challenges of the region. The characterization will serve as input for the next stage, where the communities have agreed upon socio-ecological restoration nodes. These promote empowerment and rooting, strengthening local capacities based on indigenous knowledge without invasive interventions and encouraging participation in public policies.

Assessing the ways of living allows keeping, conserving, and relearning relationships with water, resilience, and adaptation to contemporary challenges. This leaves open the need to continue the recognition process in other areas of the region and activate new points of work for recovery, conservation, and safeguarding.

CONCLUSIONS

The three subregions of the GDC are vital for human ecology and sustainability. Despite their cultural and ecosystem differences, they suffer from similar problems that threaten survival, causing adverse impacts that take the socio-ecosystem to the point of no return, as is already evident in some sectors. Their communities' quality of life and social mobility are at risk, which requires adaptation, resilience, understanding, and relearning how to work with water and its rhythms in this region.

The recovery of forms of life and their adaptation to new conditions through knowledge linked to local architecture and urbanism requires joint work between the parties to strengthen communities from their knowledge.

Conceiving management with a socio-ecological approach can counteract the external pressures currently affecting the region. Given its socioeconomic and environmental relevance, this promotes a more efficient self-management of the territory as a viable and necessary alternative, integrates efforts, and increases the country's and the world's representativeness.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, A.C.S.; Data curation, A.C.S.; Formal analysis, A.C.S.; Acquisition of funding A.C.S.; Research, A.C.S. and E.G.A.; Methodology, A.C.S.; Project management, A.C.S.; Resources, V.I.E.F.A.; Supervision, A.C.S.; Validation, A.C.S.; Visualization, A.C.S. and M.C.R.Z.; Writing - original draft, A.C.S.; Writing - revision and editing, A.C.S.

ACKNOWLEDGMENTS

Thanks are given to the communities of the El Pozuelo-Bolívar marsh, the Manatí-Antequera Foundation, Apropapur-Purísima, Antonio Herazo-Sincelejo, Edith González Afanador for building the environmental component of the research María Camila Ramos Zapata for drawing the maps, and the Vice-Dean of Research and Outreach of the Faculty of Arts for financing the project.

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 112 - 125
https://doi.org/10.22320/07190700.2024.14.02.09

Recibido 26/11/2024
Aceptado 12/12/2024

BIOCOMPOSITE OF BANANA FIBER, PEANUT SHELLS FROM MANABÍ (ECUADOR), AND RECYCLED EXPANDED POLYSTYRENE

BIOCOMPUESTO DE FIBRA DE BANANEIRA, CÁSCARA DE AMENDOIM DE MANABÍ (ECUADOR) Y POLIESTIRENO EXPANDIDO RECICLADO

BIOCOMPOSTO DE FIBRA DE BANANEIRA, CASCAS DE AMENDOIM DE MANABÍ (ECUADOR) E POLIESTIRENO EXPANDIDO RECICLADO

Eddie Efrén Echeverría-Maggi
Master's degree in Geomatics
Professor, Faculty of Engineering, Industry and Construction
University Laica Vicente Rocafuente, Guayaquil, Ecuador
https://orcid.org/0000-0002-4634-5675
eecheverriam@ulvr.edu.ec

Vicente Flores-Alés
Doctor in Chemistry
Professor, Architectural Construction II Department , Higher Technical School of Building Engineering
University of Seville, Seville, Spain
https://orcid.org/0000-0003-4329-0020
vflores@us.es (corresponding author)

Juan Jesus Martin-del-Rio
Doctor in Chemistry
Professor, Architectural Construction II Department , Higher Technical School of Building Engineering
University of Seville, Seville, Spain
https://orcid.org/0000-0003-1935-5437
jjdelrio@us.es

ABSTRACT

This research involves the development of a thermoplastic polymer biocomposite in a matrix of recycled expanded polystyrene reinforced with banana pseudostem fiber and crushed peanut shells. Six models were produced with different doses, of which the one that obtained the best result was the last one, with a content of 63% EPS, 25% banana fiber (40 mm), and 12% crushed peanut shells (1 to 3 mm). In the bending test, it achieved an MOR of 12 N/mm2 and an MOE of 55 N/mm2; the compressive strength was 8.60 N/mm2; moisture absorption was 10%; and in the thermal conductivity test, it had a value of 0.095 W/m·k, which means it has an adequate insulating capacity. The values obtained comply with the Ecuadorian standard INEN 3110 for particleboards. This work shows the capacity of the materials used to produce different light, resistant, insulating components that can be used in buildings.

Keywords
recycling, natural fibers, panel, expanded polystyrene

RESUMEN

Esta investigación consiste en el desarrollo de un biocompuesto polimérico termoplástico en una matriz que se obtiene de la disolución del poliestireno expandido (EPS) reciclado, reforzado con fibra del pseudotallo de plátano y cáscara de cacahuete. Se elaboraron 6 modelos con los materiales, de los cuales el que obtuvo el mejor resultado fue la última dosificación, con un contenido del 63% de EPS diluido, 25% de fibra de plátano en tiras (40 mm) y 12% de cáscara de cacahuete triturado (1 a 3 mm). En la prueba de flexión alcanzó un MOR de 12 N/mm2 y un MOE de 55 N/mm2; la resistencia a la compresión fue de 8,60 N/mm2; 10% de absorción de humedad; y en el ensayo de conductividad térmica tuvo un valor de 0,095 W/m·k que le otorga la propiedad de material aislante. Los valores alcanzados cumplen con las normas ecuatorianas INEN 3110 para tableros de partículas. Este trabajo evidencia la capacidad de los materiales utilizados para la manufactura de diversos componentes ligeros, resistentes y aislantes que se pueden emplear en las edificaciones.

Palabras clave
reciclado, fibras naturales, panel, poliestireno expandido

RESUMO

Esta pesquisa envolve o desenvolvimento de um biocompósito de polímero termoplástico em uma matriz de poliestireno expandido reciclado reforçado com fibra de pseudocaule de bananeira e cascas de amendoim trituradas. Foram produzidos seis modelos com diferentes doses, dos quais o que obteve o melhor resultado foi o último, com um teor de 63% de EPS, 25% de fibra de banana (40 mm) e 12% de casca de amendoim triturada (1 a 3 mm). No teste de flexão, alcançou um MOR de 12 N/mm2 e um MOE de 55 N/mm2; a resistência à compressão foi de 8,60 N/mm2; a absorção de umidade foi de 10%; e no teste de condutividade térmica, apresentou um valor de 0,095 W/m·K, o que significa que tem uma capacidade de isolamento adequada. Os valores obtidos estão em conformidade com a norma equatoriana INEN 3110 para painéis de partículas. Este trabalho mostra a capacidade de materiais utilizados para produzir diferentes componentes leves, resistentes e isolantes que podem ser empregados em edificações.

Palavras-chave:
reciclagem, fibras naturais, painel, poliestireno expandido

INTRODUCTION

Bananas are one of the most representative crops in the world, covering an area of 5,557,060 ha in 2020. The largest producer is India (31,504,000 t), and the largest exporter is Ecuador (7,039,839 t) (FAOSTAT, n.d.). Industries can use a significant amount of fiber extracted from the pseudostem for various applications (Balda et al., 2021). Researchers have conducted several studies on the uses of these fibers, such as in the reinforcement of mortar (Akinyemi & Dai, 2020); in the pharmaceutical and food industries (Kumar et al., 2022); in wastewater treatment, where they act as absorbents for environmental pollutants such as heavy metals, dyes, and pesticides, among others (Ahmad & Danish, 2018); as reinforcements in composite materials, including epoxy resin, vinyl ester, polyester, polypropylene and polyethylene (Ogunsile & Oladeji, 2016). The structure of banana fiber (BF) consists of 60-65% cellulose, 19% hemicellulose, 5% lignin, 2.5% pectin, and a moisture content of 10%. It has a microfibrillar angle of 11°, a fiber diameter of 173 μm, and a density of 1,350 g/ cm^3. Its high cellulose content gives it high mechanical strength; the modulus of elasticity ranges from 27 to 32 GPa, and the tensile strength has a range of 529 to 914 N/mm^2, and the percentage of elongation of the cultivated banana is 21.26%. These values are higher than those of bamboo, coconut, and sisal fibers (Balda et al., 2021; Senthilkumar et al., 2018; Jayaprabha et al., 2011; Chattaviriya et al., 2022; Addis et al., 2023). Banana pseudostem fiber is suitable for reinforcing polymer composites to replace synthetic fibers due to its excellent mechanical strength (Kalangi et al., 2022).

Research has shown that incorporating natural fibers improves mechanical properties as well as thermal and acoustic insulation. Studies show that banana fiber has a noise reduction coefficient of 0.55-0.89 at frequencies from 250 to 6300 Hz (Chattaviriya et al., 2022; Mendes & de Araújo Nunes, 2022). In hybrid composites, it has a thermal conductivity of 0.003 W/m·K (Saravanan et al., 2020), while in polymer composites, it achieves tensile strength of 21-93 N/ mm^2, flexural strength of 48-55 N/mm^2, and impact resistance of 7-18 J (Immanuel Durai Raj et al., 2023; Kalangi et al., 2022).

Banana fiber can be treated with chemicals to improve its mechanical performance, as in the work of T. A. Nguyen and T. H. Nguyen, who developed a composite of 30 mm long banana fiber treated with sodium hydroxide (NaOH) at 10%, 15%, 20% and 25% by mass, achieving high performance with a ratio of 80% epoxy resin and 20% banana pseudostem fiber (Nguyen & Nguyen, 2021). Treatment of the fibers improves load transfer and delays crack propagation after shear failure (Chenrayan et al., 2023).

However, controlling the fiber length, orientation, and volume is essential. Excessive amounts can create voids in the matrix, weakening the interfacial bond and reducing the strength (Prem Chand et al., 2021; Addis et al., 2024; Wongsa et al., 2020; Korniejenko et al., 2016). Sandwich composites have also been developed by hand, using overlapping layers of fiber and polymer (Ramprasath et al., 2020).

Peanut shells consist of 45% cellulose, 32.8% lignin, 23-30% hemicellulose, and 4.9% protein, with a moisture content of 8-10% (Binici & Aksogan, 2017a; Gatani et al., 2010; Zaaba & Ismail, 2018). Currently, there is research based on the use of peanut shell ash and its derivatives in construction components as a replacement for cement in concretes and mortars, using mainly ground nutshell ash obtained at temperatures ranging from 400°C to 800°C, the ideal temperature being 500°C (Gatani et al., 2010; Abd-Elrahman et al., 2023). It has been used as a stabilizer for earthen materials and has applications as a fine aggregate in concrete blocks and masonry (Sathiparan et al., 2023). Manufacturers have also used peanut shells as a component in the production of thermal and acoustic insulation materials (Binici & Aksogan, 2017b).

Peanut shells have also been used in manufacturing particleboard using urea-formaldehyde as a binder, with particle sizes ranging from 0.5 to 3 mm (Guler et al., 2008; Akindapo et al., 2015). Prabhakar et al. investigated the properties of an epoxy composite reinforced with peanut shell powder, using fibers treated with NaOH at concentrations of 2, 5, and 7 w/v %, and three shell dosages of 5, 10, and 15 wt% (Prabhakar et al., 2015). S. Ramu et al. worked with a hybrid composite in an epoxy matrix with peanut shell and rice husk, treated with NaOH (1-2 hours) to improve their mechanical properties (Ramu et al., 2023). R. Girimurugan et al. (2022) carried out an experimental study on the compressive properties of a hybrid composite of high-density polyethylene, nano-alumina, and peanut shell, in a ratio of 95: 2.5: 2.5 respectively, which is the ratio that gave the highest values of mechanical strength (Girimurugan et al., 2022). Sada et al. (2013) used peanut shells as a substitute for fine aggregate (sand) with a size no larger than 4.76 mm; as the amount of peanut shell increases, the workability decreases, and the density decreases (Sada et al., 2013).

Expanded polystyrene (EPS) is an inert, non-biodegradable material that does not contain chlorofluorocarbons (CFCs), so it cannot contaminate environmental vectors, but it can cause problems if it is not recycled. One ton of discarded polystyrene is equivalent to 200 m3 and takes up a lot of space, comprising 98% air and 2% polystyrene. Thermal and chemical techniques are used to recycle this product. Chemical options involve the use of solvents. Other

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 112 - 125
https://doi.org/10.22320/07190700.2024.14.02.09

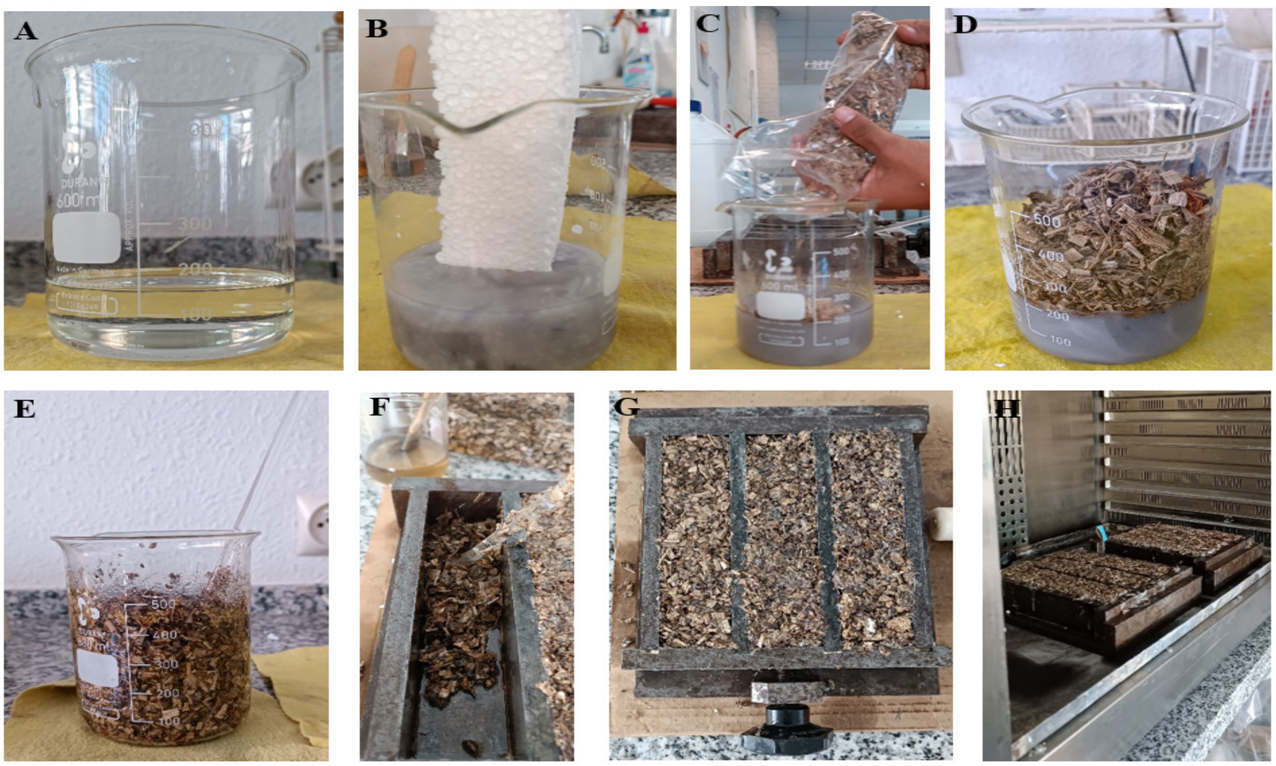

Figure 1. Prototyping procedure. (a) universal solvent; (b) expanded polystyrene solution (EPS); (c) and (d) a blend of the natural aggregates with the binder; (e) mixing of the components; (f) placement in the mold; (g) compaction in mold and resting for 48 hours; (h) drying in the oven. Source: Prepared by the authors

processes, like hot air shrinking and frictional heat compression (Martínez & Laines, 2013), can incorporate additional materials, such as wood flour (Poletto et al., 2011). Plastic recycling is an alternative to avoid environmental pollution and emission of toxic gases from incineration and consists of collection, storage, and reprocessing to obtain new products (Segura, Noguez & Espín, 2007.).

The general objective of the research is to develop a material, using banana peels and peanut shells from agricultural waste, that can be used to make an architectural panel. This panel should be sufficiently durable and have insulating properties. This process is expected to help reduce the carbon footprint associated with the construction and manufacture of the material. The combined use of the two plant residues and the recovery of EPS is the central element of this research.

MATERIALS AND METODOLOGY

Banana fibers and peanut shells were collected from agricultural residues in the rural area of Carrasco, located in Manabí (Ecuador). The fibers were selected after harvesting, sun-dried for seven days, and then transported to the Universidad Laica Vicente Rocafuerte laboratories in Guayaquil. Expanded polystyrene from household appliance packaging was also collected.

The fibers underwent chemical treatment in a NaOH solution to clean and improve their physical and mechanical performance. They were then dried in the sun for seven days and in an oven for 48 hours at a temperature of 100°C. Once dried, the banana fibers were cut into strips measuring 40 mm by 2 mm and 20 mm by 2 mm. The EPS was diluted in solvent, resulting in a whitish-grayish viscous substance. The fibers were mixed with the conglomerate (diluted EPS) for 15 minutes, then placed in metallic molds previously lubricated with a release agent, accompanied by 50 percussion strokes, to eliminate air bubbles and improve its coupling. The substance remained in the mold for seven days; then, it was removed and left to dry in the environment for 14 additional days (Figure 1).

To prepare the specimens, the specimen model outlined in the *UNE-EN 196-1:2018 standard*, initially designed for cement testing, was utilized solely to establish the dimensions of the 40 mm x 40 mm and 160 mm specimens. Six different types of dosages of their components were established, and three prototypes were prepared for each dosage to calculate the average value (Table 1, Figure 2). The workability of the final batch was verified by testing the consistency of fresh mortar on a vibrating table.

The models underwent a characterization process involving physical and mechanical tests, with analysis conducted following the particleboard specifications

Table 1. Prototype composition. Source: Prepared by the authors

Sample average	BF (g)	CPS (g)	EPS (g)	Solvent (ml)	Fibers
1 (I, II, III)	0	54	60	150	CPS_5 mm
2 (IVV, V, VI)	54	0	60	150	BF_40 x 2 mm
3 (VII, VIII, IX)	20	34	70	180	BF_ 40 x 2 mm CPS_1 a 3 mm
4 (X, XI, XII)	20	40	60	150	BF_ 40 x 2 mm CPS_ 1 a 3 mm
5 (XIII, XIV, XV)	20	40	60	150	BF_ 20 x 2 mm CPS_1 a 3 mm
6 (XVI, XVII, XVIII)	40	20	100	250	BF_ 40 x 2 mm CPS_ 1 a 3 mm

outlined in the European standard UNE-EN 312:2010 and the Ecuadorian standard INEN 3110 (Aguillón et al., 2024). In the physical properties, density was determined based on the UNE-EN 323: 1994 standard (Benítez et al., 2013), moisture absorption based on the UNE-EN 317:1994 standard (Preethi & Murthy, 2013), and thermal transmittance based on ISO 8302:1991. In the mechanical tests, flexural strength was assessed by determining the modulus of rupture (MOR) and modulus of elasticity (MOE), following the guidelines of *UNE-EN 310:1994)*. Finally, compressive strength was evaluated according to UNE 56535:1977 (2017). The mechanical tests were performed on a Shimadzu UH-F500kNX universal testing machine.

The basic statistical parameters have been considered for the different properties studied.

Figure 2. Specimens of 40 x 40 x160 mm used for physical and mechanical tests (the numbers are the designation assigned to the specimens). Source: Prepared by the authors

RESULTS AND DISCUSSION

DENSITY

Banana fibers and peanut shells, like most lignocellulosic biomass (Karuppuchamy et al., 2024), have a low density (Akcali et al., 2006). This intrinsic property is transferred to the new composite material and its derivatives. The fibers' incorporation in the composite may generate additional porosity in the matrix and be followed by a density decrease, as Belkadi et al. studied. (Belkadi et al., 2018). To determine the density of the prismatic models, from the physical relationship between mass and volume, an average value of 0.53 kg/m^3 was obtained with a composition of 60% EPS and 40% natural aggregates (Table 2). Model I, made only with crushed peanut shells, accounting for 47% of its volume, had the lowest density. On the other hand, the hybrid model VI, consisting of 37% natural fibers and 63% EPS, had the highest density. The fibers' incorporation in the composite may generate additional porosity in the matrix, followed by a decrease in density. Peanut shells are less dense than banana fibers.

Table 2. Density of the prototypes. Source: Prepared by the authors

Sample average	Density (kg/m³)	Standard deviation
1	0.49	0.3321
2	0.52	0.6996
3	0.50	0.2356
4	0.55	0.9555
5	0.50	0.4545
6	0.64	0.1822

ABSORPTION

The moisture test was carried out following the UNE-EN 317:1994 standard. The samples with less expanded polystyrene and more natural fibers absorbed a higher percentage of moisture (Table 3). The use of EPS significantly reduces water absorption¸ however, when used as natural fibers, the morphological parameters must be taken into account in terms of their ability to absorb water (Kesikidou & Stefanidou, 2019). Sample VI achieved the lowest percentage of absorption of all the samples, with a value of 10%, following the Ecuadorian standard INEN 3110 for particleboards in humid environments, which sets a maximum value of 12%. The higher dose of EPS traps the fibers inside and protects them from external agents.

THERMAL CONDUCTIVITY

The thermal conductivity test follows ISO 8302:1991 using the hot plate method, which measures thermal conductivity in the range of 0.002 to 2500 W/m·K. The tests can be carried out over a temperature range of 10°C to 40°C, with a 15° difference between the plates. Samples measuring 200 x 200 x 30 mm were prepared for this test. All samples showed low thermal conductivity, demonstrating the insulating potential of the material. A higher fiber content resulted in a lower heat transfer rate (Table 4). Air voids within the matrix improve the insulation properties, but may reduce the material's mechanical strength.

A clear relationship between density and thermal conductivity coefficient is observed, confirming the influence of dosage and shell/fiber typology on this property. Other research confirms that vegetable fibers and polymer addition reduced thermal conductivity (Mo et al., 2017; Zouaoui et al., 2021).

FLEXURAL STRENGTH

The bending test was carried out following the UNE-EN 310:1994 standard. This test makes it possible to determine the modulus of rupture (MOR), which is the maximum stress the specimen can withstand before fracturing, thus evaluating the plastic properties of the composites. The modulus of elasticity (MOE) was also determined, which is the average force the specimen can withstand without breaking and returning to its original state, expressing the elastic property of the material. (Table 5). It is important to note that fiber and matrix treatments tend to improve the mechanical behavior of cementitious matrix composites (Laverde et al., 2022).

The highest flexural strength value obtained was 12 N/mm^2. This result complies with the Ecuadorian standard INEN 3110 for particleboard, which establishes a minimum strength value of 9 N/mm^2; the MOE value reached 55 N/mm^2, demonstrating its elastic property before deformation.

MOR is the property that has shown the most significant variation in results.

COMPRESSIVE STRENGTH

Following UNE 56535:1977, the compression test obtained the highest compressive strength of 8.60 N/mm^2 with dosage 6. This sample contains a higher percentage of

Table 3. Moisture absorption. Source: Prepared by the authors

Sample average	Absorption (%)	Standard deviation
1	16	0.9631
2	20	0.2655
3	25	0.7851
4	21	0.0236
5	19	0.5999
6	10	0.1222

Table 4. Thermal conductivity. Source: Prepared by the authors.

Sample average	Density (kg/m^3)	Thermal conductivity (W/m·K)	Standard deviation
1	0.49	0.062	0.2555
2	0.52	0.065	0.3694
3	0.50	0.083	0.9563
4	0.55	0.081	0.5844
5	0.50	0.085	0.2411
6	0.64	0.093	0.4922

Table 5. Flexural strength. Source: Prepared by the authors.

Sample average	MOR (N/mm^2)	Standard deviation	MOE (N/mm^2)	Standard deviation
1	4.20	0.9631	41.00	0.9102
2	5.10	1.0265	73.00	0.0658
3	4.26	0.9452	21.00	0.3599
4	4.60	1.1532	34.00	0.8425
5	4.85	0.9620	66.50	0.2261
6	12.00	1.2002	55.00	0.3102

Table 6. Compressive strength. Source: Prepared by the authors.

Sample average	Compressive strength (N/mm2)	Standard deviation
1	4.99	0.8864
2	5.00	0.9541
3	4.12	0.7500
4	4.44	0.8674
5	3.97	0.8551
6	8.60	0.8999

banana fiber (25%). The higher percentage of banana fiber and the reduced peanut shell size probably influenced the higher axial strength (Table 6).

The results obtained provide sufficient values for the performance expected of a material of this type (Attia et al., 2022). Some research confirms that alkaline pre-treatment improves the mechanical performance of the fiber in the compression test (Lamichhane et al., 2024), improving the mechanical properties of mortar with short and thin banana fibers: A sustainable alternative to synthetic fibers (Ali et al., 2022; Lamichhane et al., 2024).

Combining the two types of plant residue allows the granular effect of the peanut shell to be combined with the fibrous effect of the banana residue, thus reinforcing each other's influence on the mechanical behavior of the prototypes.

CONCLUSIONS

The product developed in this work differs from other products created in previous research by using a completely autonomous process that avoids using resins and sophisticated equipment or tools. This innovation allows communities to implement the production process locally. The test results meet the standards and demonstrate the potential of the material.

The specimens made with banana fibers and peanut shells, agglomerated with an EPS solution, achieved a suitable consistency for the tests. They easily conformed to the shape of the mold, indicating that the final composite could take on different shapes. The natural fibers were pretreated in a NaOH solution to remove impurities and increase the mechanical strength of the final product.

The percentage of water absorption ranges from 10 to 25%. The models with more natural fibers and less binder have a high percentage of water absorption. Model 6 has the lowest percentage of water absorption. The thermoplastic content in the composite can protect and insulate the natural fibers from moisture, contributing to the material's durability.

Thermal conductivity ranged from 0.062 to 0.093 W/m·k. The higher number of natural fibers incorporated in the matrix decreases heat conduction. Model 6 achieves a conductivity value of 0.093 W/m·k compared to the other samples. This value achieved is within the range of materials with insulating properties. It is important to highlight the influence of the fibers on this property.

Specimen 6 gave the best results of all the samples, achieving in the flexure test a MOR of 12 N/mm^2, which determines the resistance to flexural stress before fracture, the degree of plasticity, and a MOE of 55 N/mm^2, which determines the elastic capacity of the material before deformation. The compressive strength was 8.60 N/mm^2. The flexural strength exceeds this value, possibly due to a disaggregation effect during the test, the length of the fibers, and the reduction in the particle size of the peanut shell. Increasing the polymer content resulted in a water absorption rate of 10%, thereby improving the encapsulation and protection of fibers.

The fibers exhibit robust interfacial bonding with the polymer (dissolved EPS), but air bubbles were observed within the specimens. The presence of air bubbles was reduced by incorporating the peanut shell in smaller particle sizes, thus improving the molecular cohesion in the matrix. It is recommended to apply a constant load during the drying process. In addition, the application of heat contributes to the consolidation of the material, although this was not one of the research objectives.

The test results demonstrate the effectiveness of the components used, including the EPS waste, which was dissolved to form the matrix conglomerate reinforced with banana and peanut shell fibers. The values obtained comply with the Ecuadorian INEN 3110, based on the UNE EN 312 standard, for particleboards. This allows us to consider that lightweight, durable construction components with insulating properties can be produced.

AUTHOR CONTRIBUTIONS CRediT

Conceptualization, E.E.M., V.F.A., J.J.M.D.R.; Data Curation, E.E.M.; Formal Analysis, E.E.M., V.F.A., J.J.M.D.R.; Funding Acquisition; Research, E.E.M., V.F.A., J.J.M.D.R.; Methodology, V.F.A., J.J.M.D.R.; Project Management, V.F.A., J.J.M.D.R.; Resources, E.E.M., V.F.A., J.J.M.D.R.; Software, E.E.M.; Supervision, V.F.A., J.J.M.D.R.; Validation, V.F.A., J.J.M.D.R.; Visualization; Writing - original draft, E.E.M.; Writing - revision and editing, E.E.M., V.F.A., J.J.M.D.R.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to CITIUS at the University of Seville for the use of their laboratories for the characterization analyses.

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 122 - 133
https://doi.org/10.22320/07190700.2024.14.02.10

Recibido 27/09/2024
Aceptado 13/12/2024

INFLUENCE OF SOLAR SHADING DESIGN PARAMETERS ON ENERGY EFFICIENCY IN COLD ARID TEMPERATE CLIMATES, MENDOZA, ARGENTINA

INFLUENCIA DE LOS PARÁMETROS DE DISEÑO DE PROTECCIONES SOLARES EN LA EFICIENCIA ENERGÉTICA EN CLIMAS ÁRIDOS TEMPLADOS FRÍOS, MENDOZA, ARGENTINA

INFLUÊNCIA DOS PARÂMETROS DE DESIGN DAS PROTEÇÕES SOLARES NA EFICIÊNCIA ENERGÉTICA EM CLIMAS ÁRIDOS FRIOS E TEMPERADOS, MENDOZA, ARGENTINA

Alicia Betman
Arquitecta
Becaria Doctoral del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0000-0001-6765-8323
abetman@mendoza-conicet.gob.ar (Autor de Correspondencia)

Julieta Balter
Doctora en Arquitectura
Investigador Asistente del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0000-0002-7785-8465
jbalter@mendoza-conicet.gob.ar

Stella Maris Donato
Doctora en Ciencias Matemáticas
Profesional Asistente del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET),Mendoza, Argentina
https://orcid.org/0009-0003-2435-1358
sdonato@mendoza-conicet.gob.ar

Carolina Ganem
Doctora en Arquitectura
Investigadora Independiente del Instituto de Ambiente, Hábitat y Energía (INAHE)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Mendoza, Argentina
https://orcid.org/0000-0002-1431-1219
cganem@mendoza-conicet.gob.ar

RESUMEN

El sector de la construcción tiene un impacto significativo en el consumo energético global y en las emisiones de carbono. A pesar de los avances tecnológicos y de materiales, el rendimiento energético de los edificios depende principalmente de las decisiones de diseño arquitectónico. Este estudio evalúa cómo las configuraciones de sistemas de protección solar afectan los consumos energéticos de calefacción, refrigeración e iluminación en un box de estudio ubicado en un clima árido templado frío. Los resultados muestran que la proporción ventana-pared (WWR) y la orientación absoluta son factores determinantes en el consumo energético. Se observó un incremento del 16% en el consumo de refrigeración y del 13% en iluminación con el aumento progresivo del WWR. Además, la demanda de calefacción aumentó en torno al 18% según la orientación. Estos hallazgos destacan la importancia de ajustar las variables de diseño para optimizar la eficiencia energética de los edificios.

Palabras clave
protecciones solares, simulación paramétrica, eficiencia energética, clima árido templado frío

ABSTRACT

The construction sector has a significant impact on global energy consumption and carbon emissions. Despite technological and material advances, the energy performance of buildings primarily depends on architectural design decisions. This study evaluates how solar protection system configurations affect energy consumption for heating, cooling, and lighting in a study box in an arid, temperate, cold climate. The results show that the window-to-wall ratio (WWR) and absolute orientation are key factors in energy consumption. A 16% increase in cooling consumption and a 13% increase in lighting were observed with the progressive increase of the WWR. Additionally, depending on the orientation, heating demand increased by approximately 18%. These findings highlight the importance of adjusting design variables to optimize the energy efficiency of buildings.

Keywords
solar shading, parametric simulation, energy efficiency, cold temperate arid climate

RESUMO

O setor de construção exerce um impacto significativo no consumo global de energia e nas emissões de carbono. Apesar dos avanços em tecnologia e materiais, o desempenho energético dos edifícios depende principalmente das decisões de projeto arquitetônico. Este estudo avalia como as configurações de sistemas de proteção solar afetam os consumos de energia de aquecimento, resfriamento e iluminação em um box de estudo localizado em um clima árido temperado frio. Os resultados mostram que a proporção janela-parede (WWR) e a orientação absoluta são fatores determinantes no consumo energético. Um aumento de 16% no consumo de resfriamento e de 13% em iluminação foi observado com o aumento progressivo da WWR. Além disso, a demanda de aquecimento aumentou em cerca de 18%, dependendo da orientação. Essas descobertas destacam a importância de ajustar as variáveis de projeto para otimizar a eficiência energética dos edifícios.

Palavras-chave:
proteção solar, simulação paramétrica, eficiência energética, clima árido temperado e frio

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https://doi.org/10.22320/07190700.2024.14.02.10

INTRODUCTION

The building sector is one of the areas most responsible for energy consumption and carbon emissions, aggravating the global environmental crisis. This impact, which will reach 68% by 2050, according to the International Energy Agency [IEA] (2021), is intensified due to the projected population growth. This increase generates a greater demand for energy resources, putting pressure on existing infrastructures (IPCC, 2023). Buildings with thermally inefficient envelopes consume more energy to achieve thermal comfort conditions, contributing to increased global emissions and dependence on non-renewable resources. A critical aspect is the thermal performance of the openings, which influences heat gains and losses. In addition to fulfilling aesthetic roles and allowing ventilation and lighting, windows are key construction systems for controlling solar radiation. The entry of solar radiation can reduce the energy consumption associated with heating in cold climates and improve the thermal and visual comfort of the occupants (Ghosh & Neogi, 2018). However, an inadequate design can lead to glare, increased cooling demand, or increased dependence on artificial lighting. This highlights the importance of designing optimized windows and solar protection systems adapted to each region's climatic conditions (Kaasalainen et al., 2020; Kirimtat et al., 2016). In this context, solar protection and advanced radiation control technologies are fundamental to efficiently managing the flow of solar energy.

Within sustainable architecture, passive strategies for the design of envelopes are key to improving the energy performance of buildings. These strategies, which consider parameters such as windows and solar protections, seek to identify optimal configurations through energy simulations and observational studies (Bustamante & Encinas, 2012). Simulation tools make it possible to systematically evaluate the impact of different parameters on the thermal behavior of buildings, which provides critical information for decisions from the initial stages of architectural design. Correlation analysis, a robust statistical methodology, helps understand how design parameters influence the energy consumption of buildings. Unlike sensitivity analysis, which evaluates the response to changes, correlation allows quantifying the intensity and direction of the relationships between variables without implying causality (Zou et al., 2003). This approach facilitates the identification of patterns between variables, such as the percentage of the glazed area (WWR) and the orientation of the windows, which provide valuable information for bioclimatic design strategies (Alanis-Navarro et al., 2017). These methodologies are fundamental tools when evaluating how factors interact in energy efficiency.

Although several studies have explored the design of windows and solar protections using computer simulations, the use of correlation analysis to identify complex relationships between design parameters and energy consumption remains limited. Research such as that by Koç and Maçka Kalfa (2021), Dabbagh and Krarti. (2022), Khidmat et al. (2021), Mangkuto et al. (2021), and Nazari et al. (2023) have provided valuable perspectives, but do not look closely into the identification of relationships between multiple variables. Betman et al. (2023) analyzed how given geometric parameters affect energy demands and obtained encouraging first approximations. This article will address additional methodologies that explore a specific correlation approach, expanding upon the work in this area, focusing mainly on the city of Mendoza, located in central-western Argentina.

Correlation analysis can significantly contribute to optimizing design parameters such as WWR and solar protection. It provides an in-depth understanding of how these elements impact energy requirements by facilitating the development of strategies adapted to local climatic conditions. In addition, it strengthens buildings' capacity to face environmental challenges, such as climate change and the shortage of renewable resources.

The Metropolitan Area of Mendoza (32° 40' South Latitude, 68° 51' West Longitude), categorized as BWk (cold arid temperate) according to the Köppen classification, has an average annual temperature of 17°C. Its summers are hot and dry, with temperatures up to 39°C, and cold winters, with lows of -6°C. The daily thermal variations, which range between 10°C and 20°C, and a high annual solar radiation highlight the need for a detailed climate analysis to design buildings that respond to the region's climatic and social particularities.

Future climate projections suggest an increase in average temperatures, especially in summer, which highlights the urgency of implementing mitigation and adaptation measures, such as passive shading strategies and cooling technologies to reduce dependence on mechanical systems (National Directorate of Scenarios and Energy Planning, 2019; National Meteorological Service, 2023; IPCC, 2023).

Based on this, this paper explores the relationship between building design parameters and the factors influencing energy behavior in cold temperate arid climates, such as Mendoza. It uses a correlation analysis to identify and quantify how the design parameters of windows and solar protections impact the energy requirements for cooling, heating, and lighting to optimize their performance.

METHODOLOGY

DEFINITION OF THE SIMULATION MODEL AND STUDY PARAMETERS

A project is proposed with an indoor space whose dimensions align with the housing units of the Provincial Housing Institute's development plan for Mendoza, a typology widely reproduced in the last 10 years. It consists of a duplex on two floors. The setting chosen for this study is the bedroom. Thus, the box is formed in an area of 3.00 m by 3.00 m with a height of 2.70 m.

Table 1 outlines the thermo-physical characteristics of typical materials used in construction in the region. During dynamic energy modeling in the EnergyPlus software, the building pattern is associated with these materials and is connected to a single thermal zone. It is marked off by one of the walls in contact with the outside, which includes a window. The rest of the horizontal and vertical thermal envelope is considered adiabatic. This approach allows the analysis of indoor spaces in high-rise buildings. In Table 1, the walls, floor, and ceiling materials are characterized. The window can be opened, has an aluminum frame, and 3mm single glazing. U = 5.8 W/m^2 K.

This study uses solar control devices comprising sunshades formed by vertical and horizontal slats. The parameters evaluated are defined below:

- Window-to-wall ratio (WWR): This represents the percentage of glazed area compared to the total area of the facade. For this analysis, a WWR range between 30% and 90% was considered, with 10% intervals. Values under 30% were not included, as they would limit the evaluation of the impact of variables related to lighting.
- Orientation: Orientations receiving direct solar radiation were analyzed, including three main angles: 0° for the north, 90° for the east, and -90° for the west. Two intermediate positions were also considered: +45° (northeast) and -45° (northwest).
- Arrangement of the slats: The solar protection system includes equidistantly spaced modular slats. Two configurations were proposed: slats arranged horizontally (value of 0 in the software) and vertically (value of 1 in the software).
- Slat tilt angle: Three configurations were evaluated: horizontal position (0°), intermediate tilt (15°), and steep tilt (30°). The value of 0° acts as a basic barrier against solar radiation. The 15° inclination offers a balance between solar efficiency and aesthetics. Finally, the 30° inclination provides greater shading, improving solar protection without affecting functionality or visual design.
- Depth of the slats: The Climate Consultant software shading graph was used for this (Figure 1). The solar angle for 12:00 solar

Table 1. Thermo-physical characteristics of the study model. Source: Preparation by the authors.

MASS MATERIALS							NON-MASS MATERIALS
Construction	Layers	Roughness	Thickness (m)	Conductivity (W/m°C)	Density (Kg/m3)	Specific Heat (J/kg °C)	Thermal Resistance (m2-K/W)
Outside wall	Plaster	Rough	0.025	1.16	1800	1000	
	Brick	Medium-rough	0.2	0.81	1600	835	
	Plaster	Rough	0.025	1.16	1800	1000	
	Gypsum	Soft	0.02	0.4	800	840	
Floor	Subfloor	Rough	0.12	0.78	1600	780	
	Coating	Rough	0.12	0.78	1600	780	
Roof	Membrane						0.55
	Coating	Rough	0.12	0.78	1600	780	
	Mineral wool	Medium-rough	0.05	0.031	50	750	
	Tongue and Groove board	Medium-rough	0.25	0.11	600	1380	

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https://doi.org/10.22320/07190700.2024.14.02.10

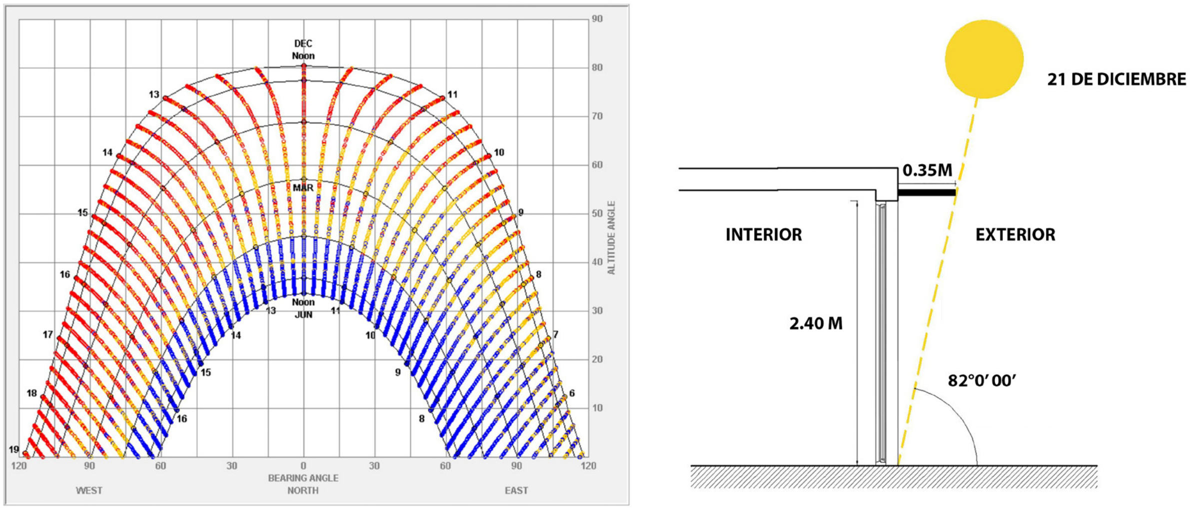

Figure 1. (a) Solar angles for the locality of Mendoza using the Climate Consultant software, (b) Calculation of the solar angle. Source: Preparation by the authors.

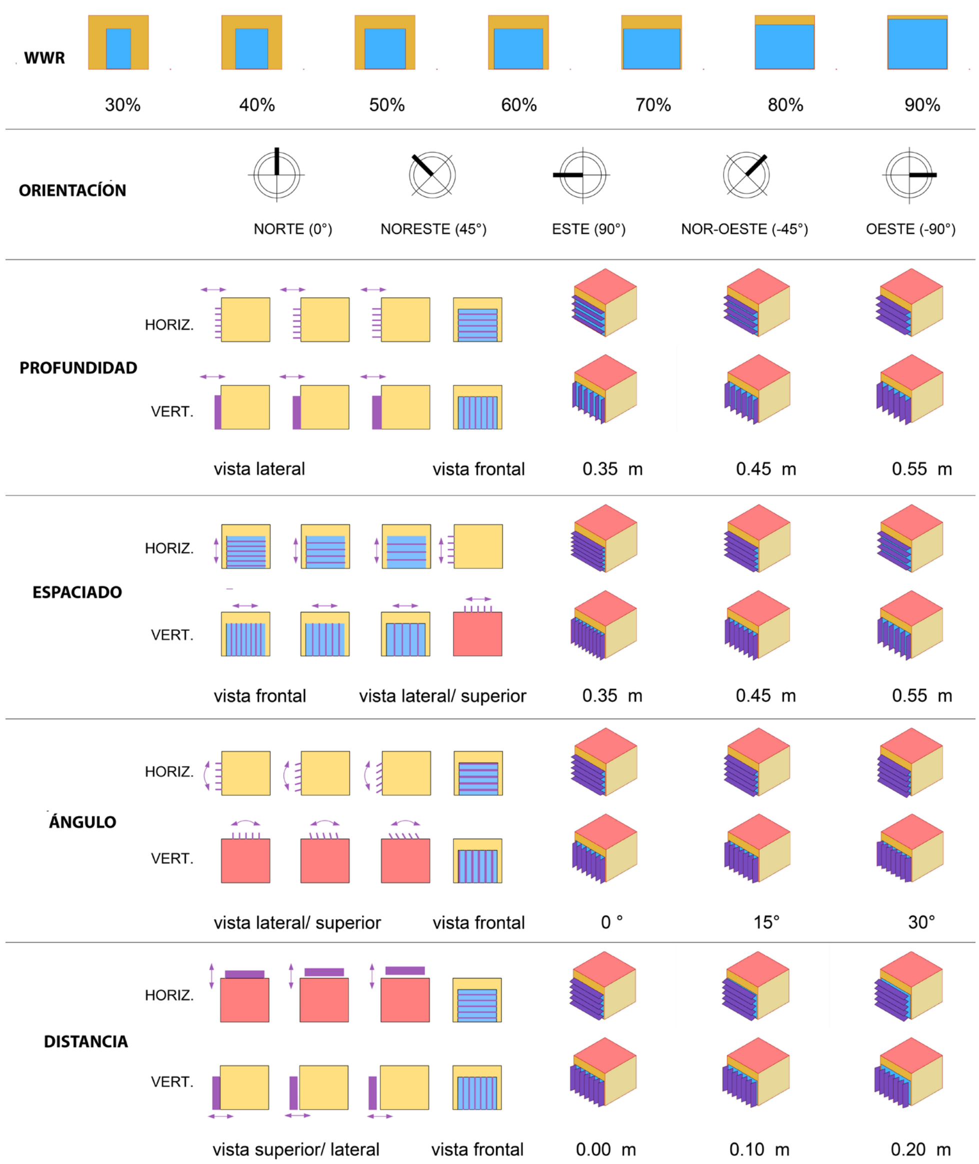

Figure 2. Variable conditions of the model. Source: Preparation by the authors.

Table 2. Fixed conditions of the studied model. Source: Preparation by the authors.

Fixed condition	Parameter	Description	Values	Comments
	Winter Thermostat	Temperature established as per ASHRAE 55	21°C	Standard winter clothing (0.9 clo) for sedentary activities
	Summer Thermostat	Temperature established as per ASHRAE 55	26°C	Standard summer clothing (0.5 clo) for sedentary activities
	Lighting Demand	Lighting setpoint at a central point, 0.80 m from the ground	500 lx	Daily use (08:00-23:00) with 4W/m2, without considering internal gains
	Infiltration rate	Air changes per hour	1 change per hour	Constant

time on December 21st was chosen to know the maximum solar height and, therefore, the minimum depth requirement of the protection. For Mendoza, the value of this angle is 82°. Considering the most unfavorable situation, the corresponding calculation was made, represented by an opening with a WWR of 90%. The result yielded an initial depth of 0.35 m, which was increased in ranges of 0.10 m, reaching a maximum of 0.55 m, following aesthetic and functional criteria.

- Spacing between slats: The spacing values were proportional to the depth to maintain aesthetic and functional criteria.
- Distance of solar protection from glazing: Three scenarios were evaluated: (1) the device next to the glass (distance of 0.00 m), (2) an intermediate distance of 0.10 m, and (3) a maximum distance of 0.20 m.

Figure 2 presents a graphical layout of the input variables used in the parametric analysis, allowing the different design configurations to be evaluated.

To create the model, the Grasshopper parametric design software was used with the Rhinoceros 3D visualizer on a three-month educational license. The Ladybug and Honeybee add-ons were integrated for the energy analysis. These allow climate data to be imported from Energy Plus Weather Data (EPW) files and enable running calculations using recognized engines such as EnergyPlus, Daysim, and Radiance. The OpenStudio graphical interface was also used. This connects the three-dimensional model with the simulation tool library, which assigns the properties the 3D model needs to make the simulations. Once the thermostats and setpoints were configured, the goal was to determine the energy demands for cooling, heating, and lighting, expressed in (kWh/m^2/year).

Table 2 presents the fixed conditions used for the model's energy simulation. These conditions include winter and summer thermostats, considerations for lighting demand, and the air infiltration rate.

CORRELATION STUDY

This study seeks to identify and quantify the relationships between different input variables and their impacts on the system outputs. The TTToolbox plugin was used to automate the iteration of the analysis—i.e., the repetition of the process—and record all the values of the possible combinations. The plug-in made it possible to evaluate all possible combinations, a total of 5670, and analyze the incidence of each variable using a correlation analysis. This analysis was performed using the R software and subsequently processed in Microsoft Excel.

The correlation analysis was carried out for the horizontal and vertical sunshade axes. The suitability of the chosen correlation measure was evaluated by checking the distribution of quantitative variables on each axis to verify whether they fit a multivariate normal distribution.

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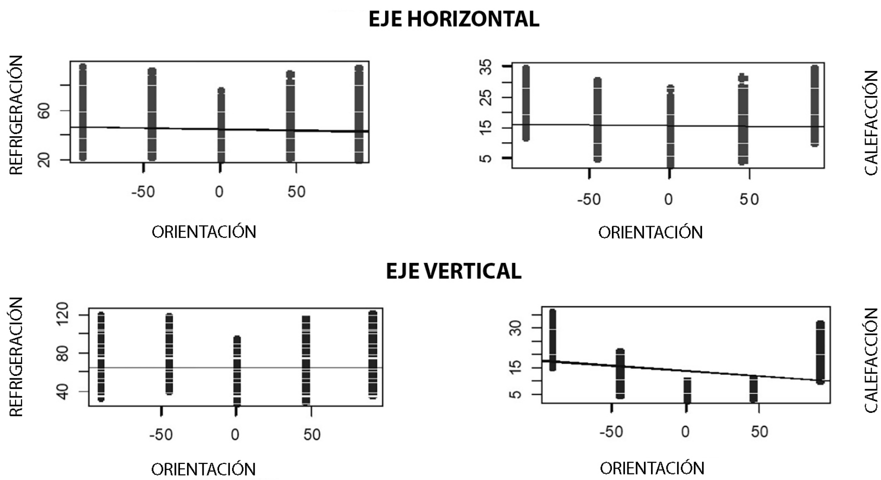

Figure 3. Correlation values of the orientation parameter. Source: Preparation by the authors.

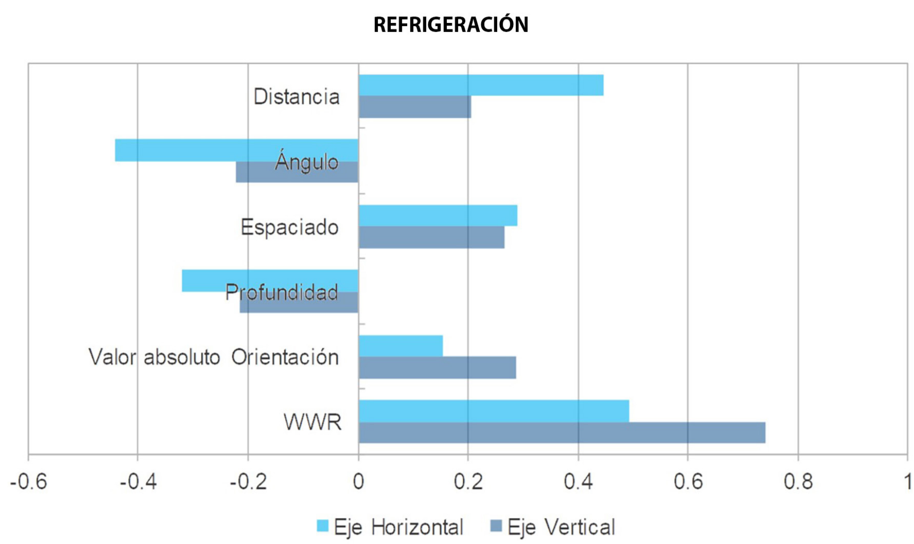

Figure 4. Cooling correlation study. Source: Preparation by the authors.

The Mardia (1970), Henze & Zirkler (1990), and Doornik & Hansen (2008) tests were performed to evaluate compatibility with this distribution. The results of these tests indicate that the variables studied do not follow a joint normal distribution, suggesting that the assumptions necessary to apply parametric tests based on normality are not met. This lack of normality questions the validity of tests such as Student's t or the analysis of variance (ANOVA), which usually require distributed data. Therefore, Spearman's correlation coefficient (1961) was used to evaluate the relationships between the variables of interest (cooling, heating, and lighting) and the parameters defined in the study (WWR, orientation, depth, spacing, angle, and distance). This coefficient does not depend on assumptions about the data distribution and is suitable for non-normally distributed data.

RESULTS AND DISCUSSION

First of all, it is essential to note that, during the process of analyzing the study parameters, a particular situation with the orientation was observed. A significant pattern was evident in the heating and cooling requirements: both extremely high and extremely low values of the orientation (i.e., in the East and West orientations) resulted in an increase in the building's energy requirements. This phenomenon manifests itself through weak correlations that highlight the importance of considering the orientation's absolute value when studying its impact on energy demand. This can be seen in Figure 3.

By focusing on the absolute value of the orientation, a noticeable increase in the magnitude of the estimated

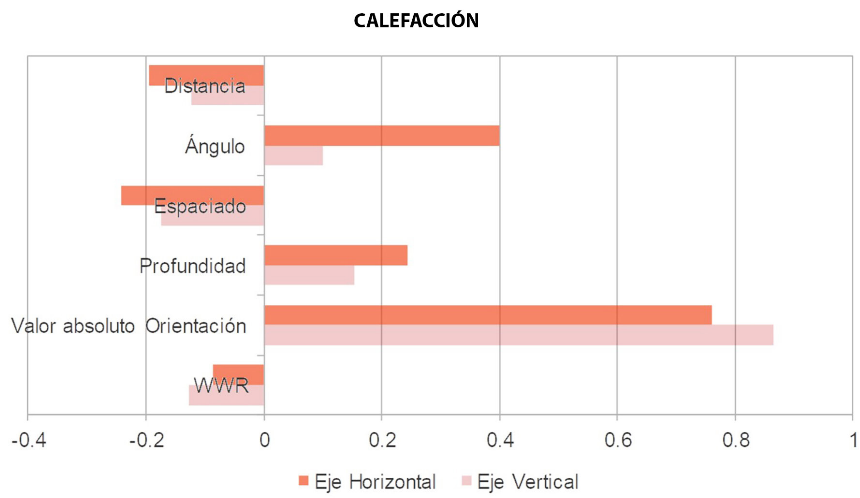

Figure 5. Heating correlation study. Source: Preparation by the authors.

coefficients is observed, accompanied by a sign change. This implies that both cooling and heating, the latter even more markedly, tend to increase as the orientation moves towards the extreme values, i.e., when it moves to the right (approaching 90) in the positive range [0-90] and when it moves to the left (approaching -90) in the negative range. These findings underline the significant influence of orientation on the building's energy requirements. For example, buildings facing east (with orientations in the range of [0-90]) or west (with orientations in the range of [-90-0]) have higher heating and cooling needs compared to those facing north (orientation close to 0).

The results of the correlation study are presented below. Figures 4, 5, and 6 show graphs for the cooling, heating, and lighting variables.

First of all, it is seen that in the iterations carried out, the arrangement of the sunshades, whether horizontal or vertical, does not affect the relationship between the parameters under study and the energy needs. For example, a higher window-to-wall ratio (WWR) increases energy demands in cooling, regardless of whether the sunshades are vertical or horizontal. As the depth of the devices increases, the demands decrease. These relationships are reflected in the correlations observed, whether positive or negative. However, each shading arrangement generates variations in the demands, as shown in the size of the corresponding bar. It is also seen that the heating and lighting variables coincide in the influence of the parameters on energy demands, while, for cooling, the influence is inverse. For example, an increase in the distance of the sunshades translates into higher energy requirements for heating and lighting, while, for cooling, the requirements decrease. This is because a greater distance allows more solar radiation to enter, reducing the need for artificial lighting and heating.

Another relevant aspect of the analysis is that the WWR parameter emerges as the most influential in cooling and lighting demands. An increase in the size of the windows leads to greater cooling requirements due to the greater inflow of solar radiation, while the demand for lighting decreases due to the greater inflow of daylight. This phenomenon suggests that large windows can significantly increase the cooling load during warmer months while reducing the need for artificial lighting during the day.

In addition, it is important to note that the relationship between absolute orientation and heating has a high correlation, which indicates a strong and direct connection between these factors. In contrast, the relationship between absolute orientation and cooling shows a moderate correlation with a downward trend, suggesting a less pronounced connection. Similarly, the relationship between absolute orientation and Illumination has a low correlation, indicating a weaker connection between these factors.

As for the design of the sunshades, several significant correlations compared to the cooling variable are highlighted both in the horizontal and vertical arrangement. In the horizontal arrangement, the cooling shows significant negative correlations with the tilt angle of the sunshades and the depth. These correlations suggest that increases in these design parameters of the sunshades are related to reductions in cooling requirements due to the

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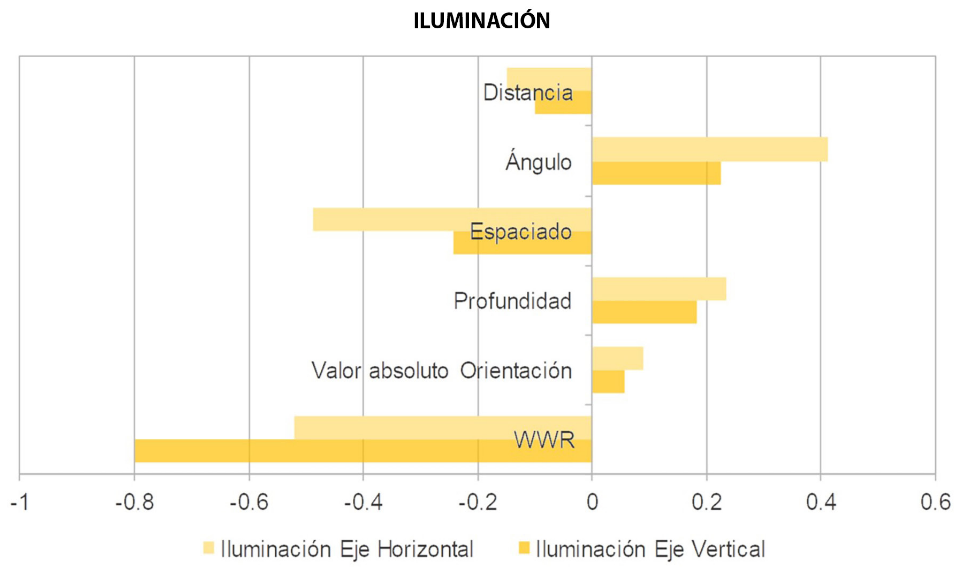

Figure 6. Lighting correlation study. Source: Preparation by the authors.

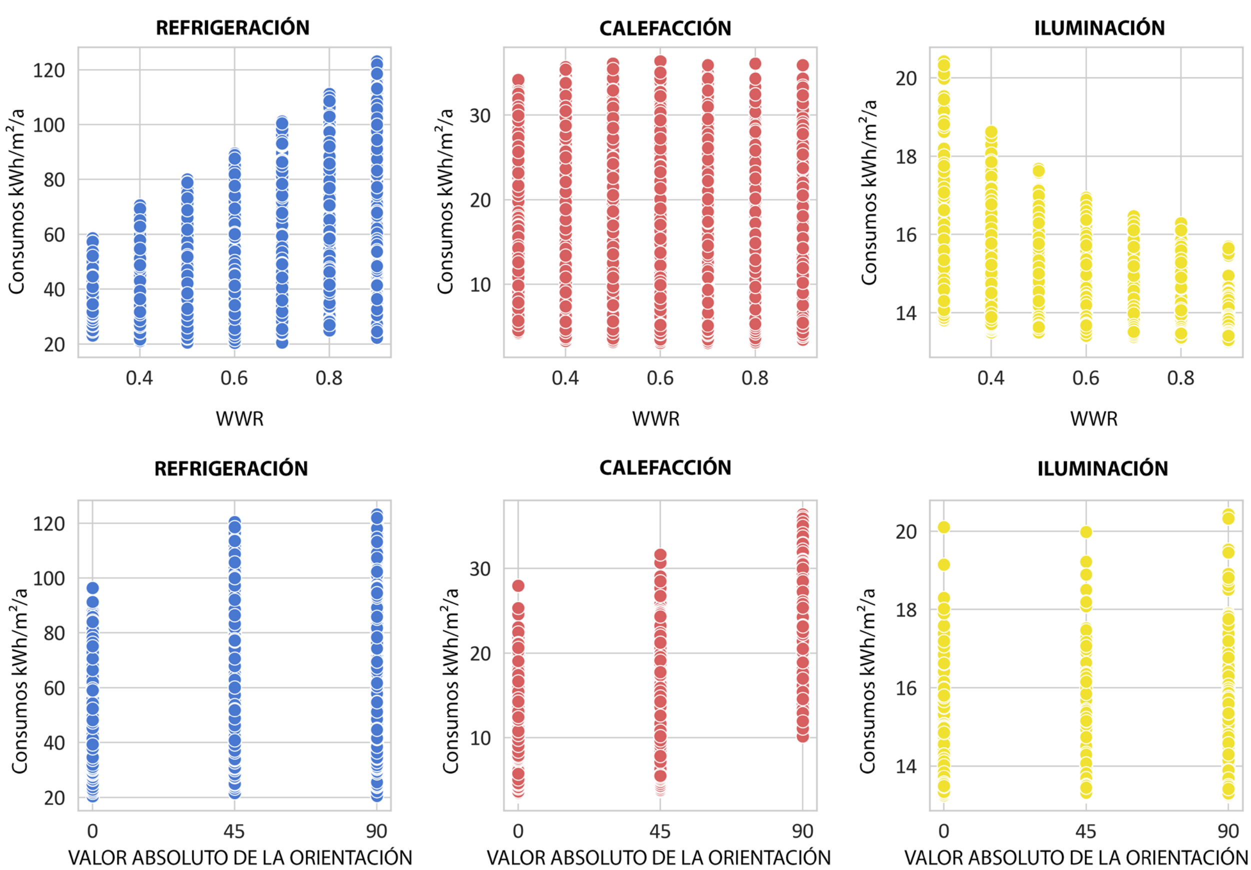

Figure 7. Energy consumption values of the most influential parameters. Source: Preparation by the authors.

greater shading they produce. For example, when the depth and angle of the sunshade slats increase, the shaded area is larger, and consequently, the cooling demand tends to be lower.

On the other hand, significant positive correlations are found between the cooling variable and the WWR, spacing, and distance of the sunshades' parameters, indicating that increases in these parameters are associated with increases in cooling requirements due to the decrease in the solar protection surface. For example, when the window area (WWR), the spacing between the sunshade slats, and the distance between the sunshade and the opening increases, the shading area tends to decrease, which increases the cooling demand because the solar radiation is not being blocked efficiently.

Finally, the heating and lighting variables show different correlations with several factors. Significant negative correlations with the window-wall ratio (WWR), orientation, spacing, and distance are highlighted, indicating that an increase in these variables leads to greater solar radiation input, resulting in a decrease in heating and lighting demands. In contrast, significant positive correlations with depth and angle are observed, indicating that increases in these variables are associated with increases in heating and lighting due to the increased shading area.

The analysis presented highlights the significant influence of the WWR (window-wall ratio) and the absolute orientation as determining variables in the energy requirements of buildings, particularly concerning the cooling, heating, and lighting demands. The graphs of Figure 7 show that an increase in the WWR causes a considerable increase in cooling energy consumption (kWh/m^2•y) due to a rise in solar gains, while simultaneously reducing the demand for artificial lighting due to the greater daylight penetration. This intensity in the WWR is related to a 16% increase in cooling and 13% in lighting. With regard to heating, there is an approximate 18% increase associated with the orientation. The lower graphs of the figure show that extreme orientations (±90°) are related to higher energy demands, while orientations close to 0° (north) have lower energy requirements.

CONCLUSIONS

In the context of the global environmental issue, understanding the correlations between the different energy requirements in the buildings of the city of Mendoza, Argentina is essential. This study reveals that the consumption patterns for heating and lighting are closely related, while cooling shows an inverse relationship. This dynamic suggests that adjustments in one area can significantly impact the others by affecting energy efficiency and total consumption. Although the analysis is based specifically on the climate of Mendoza, the methodology can be replicated in other regions to evaluate factors in different climatic contexts. These findings constitute the first steps towards more optimized designs, allowing progress in strategies that efficiently balance energy demands in buildings.

During the iterations carried out, it was observed that the horizontal or vertical shading arrangement does not alter the relationship between the design parameters and the energy needs. However, the strength of this relationship varies for each axis, as indicated by the coefficient values. As for orientation, energy requirements increase as they deviate from the ideal direction. Specifically, buildings facing east or west require more energy than those facing north. This adjustment directly affects the heating, cooling, and lighting systems, with the case of heating being particularly relevant. An approximate 18% increase in the interval associated with the orientation is observed, which shows that extreme orientations (±90°) are related to higher energy demands. In contrast, orientations close to 0° (north) have lower energy requirements.

The analysis of the design parameters reveals that the window-to-wall ratio (WWR) plays a crucial role in the cooling and lighting demands. A positive correlation is found between the WWR and the cooling demands, indicating that an increase in the window size expands the need for cooling due to a greater solar radiation input. However, this higher radiation reduces the need for artificial lighting, as daylight is better used, which evidences a negative correlation with lighting demands. These findings confirm the increase of 16% in cooling and 13% in lighting in the consumption intervals.

The negative correlations between the cooling demand and parameters such as the angle and depth of solar protections suggest that increasing these factors reduces the need for cooling by providing greater shade. In contrast, the positive correlations found between cooling and factors such as the WWR, the spacing, the distance of the sunshades, and the orientation of the latter indicate that an increase in these parameters is associated with increased cooling needs. This is because less solar protection allows more solar radiation to enter, increasing the cooling demand.

On the other hand, significant negative correlations were found between heating and lighting, the WWR, and the spacing and distance of the sunshades. These results indicate that an increase in these variables favors a greater solar radiation input, reducing the heating and lighting demands. In contrast, the positive correlations with the sunshades' absolute orientation, depth, and angle suggest that an increase in these parameters is associated with higher demands due to the increase in the shading area.

As for the limitations of the work, it is observed that although the study examines several factors of solar protection design, its focus is mainly geometric, which limits the consideration of material characteristics, such as those of glass and the protections themselves. This restriction opens the possibility of future studies that look closer at these material aspects.

In summary, this analysis in temperate climates with high solar exposure offers a solid basis for designing more sustainable buildings, reducing energy consumption and operating costs. It also provides valuable information for decision-making during the initial stages of the design process.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, B.A. and B.J.; Data Curation, D.S.; Formal analysis, B.A. and B.J.; Research, B.A. and B.J.; Methodology, B.A. and D.S.; Software, B.A. and D.S.; Supervision, B.J. and G.C.; Validation, D.S.; Visualization, B.A.; Writing - original draft, B.A.; Writing - revision and editing, B.A., B.J. and G.C.

ACKNOWLEDGMENTS

The authors are grateful to the following sources of funding: ANPCYT FONCYT PICT 2019-02752 (2021-2024) "Development of a standardized protocol of specific thermal and energy audit applicable for hot climates as a reliable, non-invasive, highly replicable and low-cost tool that contributes to the energy certification of homes"; CONICET PIP 11220200101711CO (2021-2023)"Sustainable habitat and resilience to Climate Change" and PUE INAHE 2017-0096 (2018-2025) "R+D+i in Energy and Environmental Efficiency of the Human Habitat".

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Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 134 - 147
https://doi.org/10.22320/07190700.2024.14.02.11

Recibido 12/11/2024
Aceptado 16/12/2024

THERMAL ANALYSIS OF LIGHTWEIGHT WATTLE AND DAUB WALLS FOR DIFFERENT DESIGN TEMPERATURES IN ARGENTINA

ANÁLISIS TÉRMICO DE MUROS DE QUINCHA ALIVIANADA PARA DIFERENTES TEMPERATURAS DE DISEÑO EN ARGENTINA

ANÁLISE TÉRMICA DE PAREDES DE PAU A PIQUE LEVE PARA DIFERENTES TEMPERATURAS DE PROJETO NA ARGENTINA

Maria Guadalupe Cuitiño-Rosales
Doctora en Ciencias Exactas
Investigador Adjunta del Instituto de Ingeniería y Ciencias Aplicadas a la Industria (ICAI)
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) - Universidad Nacional de Cuyo (UNCuyo), San Rafael, Argentina
https://orcid.org/0000-0002-0021-5648
gcuitino@mendoza-conicet.gob.ar (Autor de Correspondencia)

Alejandro Domínguez
Diseñador Gráfico
Subgerencia Operativa de Transferencia Tecnológica Gerencia de Desarrollo Tecnológico e Innovación.
Coordinador de la línea de trabajo de Bioarquitectura en el Área Tecnologías Sustentables
Instituto Nacional de Tecnología Industrial (INTI), San Martin, Argentina
https://orcid.org/0009-0005-2415-6741
adominguez@inti.gob.ar

Gabriel Vaccaro
Licenciado en Comunicación
Coordinador de la Mesa estratégica de cannabis medicinal y cáñamo industrial
Instituto Nacional de Tecnología Industrial (INTI), San Martin, Argentina
https://orcid.org/0009-0007-6906-7798
gvaccaro@inti.gob.ar

Victoria Di-Cesare
Diseñadora Industrial
Responsable del área de Diseño Industrial y Sustentable, Subgerencia Regional Cuyo
Instituto Nacional de Tecnología Industrial (INTI), San Martin, Argentina
https://orcid.org/0009-0002-3715-6490
vdicesare@inti.gob.ar

Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 134 - 147
https://doi.org/10.22320/07190700.2024.14.02.11

RESUMEN

Se analiza el comportamiento térmico de los muros de quincha liviana en distintas zonas bioclimáticas de Argentina, que surgen como una alternativa sustentable frente a otros materiales de construcción. Se determinaron experimentalmente las conductividades térmicas del relleno de quincha (0.07 W/mK) y del revoque (0.34 W/mK), obteniendo una transmitancia térmica global de 0.79 W/m²K para muros de 15.6 cm de espesor. A partir de mediciones in situ en una vivienda, se demostró la capacidad de los muros de quincha liviana para mantener estabilidad térmica interior, con amplitudes térmicas significativamente menores respecto del exterior. El análisis comparativo con ladrillos macizos y ladrillos huecos concluyó que los muros de quincha requieren menores espesores para alcanzar niveles de aislamiento óptimos, adaptándose a diversas zonas bioclimáticas. Esta técnica constructiva permite la replicabilidad en el contexto argentino, destacándose por su eficiencia térmica, sostenibilidad y confort interior, con oportunidades futuras para explorar su resistencia al fuego.

Palabras clave
quincha, conductividad térmica, confort interior.

ABSTRACT

The thermal performance of lightweight wattle and daub walls is analyzed in different bioclimatic zones of Argentina, presenting them as a sustainable alternative to other construction materials. The thermal conductivities of the wattle and daub (0.07 W/mK) and plaster (0.34 W/mK) infill were experimentally determined, yielding an overall thermal transmittance of 0.79 W/m²K for walls with a thickness of 15.6 cm. In situ measurements conducted in a dwelling demonstrated the ability of lightweight wattle and daub walls to maintain interior thermal stability with significantly lower thermal amplitude than outside. A comparative analysis with solid and hollow bricks concluded that wattle and daub walls require less thickness to achieve optimal insulation levels, making them suitable for different bioclimatic zones. This construction technique is replicable within the Argentinian context, with its thermal efficiency, sustainability, and indoor comfort standing out, with future opportunities to explore its fire resistance.

Keywords
wattle-and-daub, thermal conductivity, indoor comfort.

RESUMO

Analisou-se o desempenho térmico de paredes de pau a pique leve (em espanhol quincha alivianada) em diferentes zonas bioclimáticas da Argentina, que surgem como uma alternativa sustentável a outros materiais de construção. As condutividades térmicas do enchimento de pau a pique (0,07 W/mK) e do reboco (0,34 W/mK) foram determinadas experimentalmente, obtendo-se uma transmitância térmica geral de 0,79 W/m²K para paredes de 15,6 cm de espessura. Com base em medições in situ em uma casa, foi demonstrada a capacidade das paredes de pau a pique leve para manter a estabilidade térmica interna, com amplitudes térmicas significativamente menores em comparação com o exterior. A análise comparativa com tijolos maciços e tijolos ocos concluiu que as paredes de pau a pique exigem menos espessura para atingir níveis ideais de isolamento, adaptando-se a diversas zonas bioclimáticas. Esta técnica de construção permite a replicabilidade no contexto argentino, destacando-se por sua eficiência térmica, sustentabilidade e conforto interior, com oportunidades futuras para explorar sua resistência ao fogo.

Palavras-chave:
pau a pique, condutividade térmica, conforto interno.

INTRODUCTION

Thermal insulation in a house's perimeter walls has become increasingly important for sustainable and energy-efficient construction (Zhao et al., 2020; Sánchez Azócar, 2011). As Argentina covers regions with climates as diverse as the cold Patagonian ones and the hot ones of the Chaco region (Matteucci, 2012; IRAM 11603, 2012), the implementation of thermal insulation solutions becomes fundamental for occupant comfort and the energy efficiency[1]of the construction. The insulating capacity of opaque envelopes directly impacts the indoor thermal comfort[2] of the dwellings by retaining heat in winter and keeping them cool in summer. This behavior impacts energy consumption for heating and cooling, operating costs, and the carbon footprint of buildings (Muñoz et al., 2012). Therefore, analyzing the thermal conductivity[3] (λ) of materials is essential to reduce the environmental impact and improve the energy efficiency of buildings (Castillo et al., 2019). The thermal transmission coefficient (K) measures a material or a structure's ability to transfer heat (García León, Flórez-Solano. & Espinel Blanco, 2017). This is crucial in the context of walls because it determines how much heat is lost or gained through the envelopes. A low K value indicates that the wall is a good insulator with lower heat flow.

Numerous studies have investigated different strategies to improve the energy efficiency of buildings. Rey and Velasco (2006) in their work proposed practical strategies to improve this behavior through detailed audits and regulatory certifications, highlighting the importance of consumption analysis, optimization of systems and materials, and the implementation of sustainable technologies, which promote more efficient and environmentally responsible buildings (Rey Martínez & Velasco Gómez, 2006). Asdrubali et al. (2015) examined unconventional materials that promote energy efficiency in buildings, which underline their importance for climatically diverse areas (Asdrubali et al., 2015). In their work, Zhao et al. (2020) proposed using natural fibers as viable alternatives to plastics in insulation systems (Zhao et al.,2020). In contrast, Lakatos (2022) highlighted the potential of materials such as aerogels and vacuum panels for their high thermal performance. Zhovkva (2020) presented international experience in the design of sustainable multifunctional complexes, which highlights the fundamental principles of design aimed at achieving energy efficiency and respect for the environment (Zhovkva, 2020). These works show the importance of comprehensively addressing the different types of materials available on the market, which shows the importance of conducting research that compares the thermal conductivity of a wide range of construction materials and their combined impact on comfort and energy consumption.

A well-insulated house minimizes the heat flow between the inside and outside (Vanhoutteghem & Svendsen, 2014), which means that energy expenditure is significantly affected by the insulating capacity of the materials used in the construction. In cold climates, a good performance of the envelopes reduces the need for heating, while in hot climates, the need for cooling decreases. This translates into a reduction in the demand for resources. Buratti et al. (2021) highlight the relevance of integrating sustainable solutions in extreme climate contexts.

An indoor environment with good thermal regulation contributes to the physical and psychological well-being of the inhabitants (González Couret & Véliz Párraga, 2016). Thermal fluctuations can cause stress and health problems; in particular, well-insulated housing helps protect residents from extreme temperatures, which is crucial for vulnerable groups such as children, older adults, and people with pre-existing health conditions. A study in New Zealand (Howden-Chapman et al., 2007) showed that improving indoor air conditioning reduced respiratory problems and hospitalizations, especially in people with pre-existing conditions such as asthma or recurrent respiratory infections. Insulated dwellings also showed an improvement in residents' perception of general well-being. Research in South

1 Energy Efficiency: is the ability of a system, material or building to minimize heat losses and optimize energy use. It is related to thermal insulation, thermal transmittance and efficient design, reducing the energy consumption required for heating or cooling, and promoting thermal comfort and environmental sustainability (Kreith and Goswami, 2007).

2 Indoor Thermal Comfort: This is the perception of thermal well-being in a closed space, where people do not feel excessive cold or heat. A poorly insulated house can have extreme indoor temperatures, both cold in winter and hot in summer. This depends on factors such as air temperature, humidity, wind speed, thermal radiation, physical activity, and clothing, which are crucial for health, productivity, and well-being. (Forgiarini Rupp, Giraldo Vásquez & Lamberts, 2015)

3 Thermal conductivity: It is a physical, intrinsic property of materials, which measures the heat conduction capacity. (IRAM 11601, 2002)

Korea (Ham, Lee, & Kim, 2024) highlighted that building insulation standards significantly affect indoor temperatures and the risks of heat-related diseases; poorly insulated homes are more likely to exceed critical temperature thresholds, especially in rural areas and old buildings without maintenance controls. The World Health Organization WHO (World Health Organization [WHO], 2018) stresses that good thermal insulation not only improves indoor comfort but also reduces respiratory and cardiovascular diseases associated with extreme temperatures.

Research and development in the field of building materials are constantly advancing to find more durable and sustainable solutions. Natural materials are being rediscovered and adapted with new processing techniques to improve their insulating properties without compromising sustainability.

In Argentina, there are currently 60 Municipal ordinances that allow construction with earth using different techniques (Protierra Argentina Network, 2024). One of the most commonly used in envelopes is wattle and daub[4] in its diverse variants: prefabricated wattle and daub walls, filled with a mixture of a plastic consistency clayey slurry and vegetable fibers with a higher density than wet lightweight wattle and daub[5] (Cuitiño Rosales, Maldonado & Esteves Miramont, 2014), moist lightweight wattle and daub walls, where the filling comprises vegetable fiber immersed in a clayey earth slurry, commonly called slip slurry (Acevedo Oliva et al., 2017). The proposal to study the lightweight wattle and daub technique originated within the Alto Valle sustainable habitat participatory cycle in the north of the Patagonian region of Argentina. An inter-institutional collaboration and outreach agreement was signed between seven entities: Municipality of Allen (Río Negro), National Institute of Industrial Technology (INTI), National Institute of Agricultural Technology (INTA), National Council of Scientific and Technical Research (CONICET), National University of Río Negro, College of Architects of the Province of Neuquén, and the College of Architects of Río Negro.

Using natural materials when building walls has different advantages, especially thermal performance. The thermal conductivity of test cells built with the lightweight wattle and daub technique was determined using standardized tests. This data is relevant for conducting construction studies with this technique and thermally comparing lightweight wattle and daub enclosures with other industrialized materials commonly used in traditional construction.

OBJECTIVE

This work evaluates the thermal performance of lightweight wattle and daub walls as a sustainable alternative in house construction. It analyzes their thermal insulation capacity and compares them with solid bricks and hollow ceramic bricks. The thermal properties of the filler and plaster are also determined through standardized tests and on-site measurements in a house. The thicknesses of lightweight wattle and daub walls needed to comply with the thermal transmittance regulatory values are also defined[6] in several bioclimatic zones of Argentina to validate their viability.

METHODOLOGY

The methodology used in this work focuses on the thermal characterization of the components of the lightweight wattle and daub wall and its comparative analysis against conventional materials. First of all, standardized tests were carried out using the hot plate method to determine the thermal conductivity of the filler and the plaster. The test cells were manufactured with clay soil, vegetable fibers, and water mixtures, following controlled drying and hygrothermal conditioning processes. Subsequently, the wall's global thermal transmittance was evaluated theoretically following domestic regulations. A house built with this technique was also analyzed in Belén de Escobar, located 50 km north of the Federal Capital, Buenos Aires, Argentina, where hygrothermal measurements were recorded onsite. Finally, the wall thicknesses needed to comply with IRAM Standards in different bioclimatic zones were established to validate the system's thermal efficiency.

4 Wattle and daub: A construction system where the walls comprise a wooden structure, which, in turn, contains a reed fabric that is finally coated with mud (Cuitiño et al., 2015).

5 Moist lightweight wattle and daub: This is a wattle and daub with vegetable fibers immersed in a clayey earth slurry as a filler (slip), also known as lightened earth with straw or light mud-straw. (Acevedo Oliva et al., 2017)

6 Thermal transmittance: heat flow that passes per unit surface area of the element and per degree of temperature difference between the two environments separated by said element. It is expressed in W/(m2 x K). It is the thermal conductivity ratio of all the materials that the system comprises and their thicknesses. (Acevedo Oliva et al., 2017)

Figure 1: Test cell for the thermal test: a) Lightweight filler, b) Earth plaster. Source: Preparation by the authors.

Table 1. Thermal conditioning of the test cells. Source: Preparation by the authors.

Denomination	Drying time [Hs]	Test cell mass [Kg]			Relative change of the test cell mass [%]		
		M1	M2	M3	mr	mc	md
Lightweight filler test cell 1	216	9.20	7.25	7.31	26.90	25.85	0.83
Lightweight filler test cell 2		9.00	7.11	7.13	26.58	26.23	0.28
Plaster test cell 1	288	43.00	41.89	41.95	2.65	2.50	0.14
Plaster test cell 2		41.92	41.15	41.20	1.87	1.75	0.12

THERMAL CONDUCTIVITY ANALYSIS

To experimentally obtain the thermal conductivity values of the low-density straw filler and the heavier and higher-density earthen plaster, standardized tests were carried out in INTI (ISO 8302,1991); American Society for Testing and Materials [ASTM] C177 (2013); IRAM 11559 (1995). Two lightweight filler test cells and two plaster test cells were built, all 60 cm x 60 cm x 8 cm thick.

Both mixtures were prepared with a soil previously characterized in the laboratory, obtaining a composition of 17% sand, 40% silt, and 43% clay, a clay-silt soil. 50% of the characterized clay soil was mixed with 50% water to prepare the filler test cells. It was then allowed to hydrate for three days and mixed with an electric mixer until the lumps dissolved. This soil in a liquid state is called slip. Next, 72 liters of slip were mixed with a 13.16 kg bale of wheat stubble fibers, *Triticum aestivum*, until all the fibers were moistened and covered with the slip. However, when squeezed, the liquid should not run out, and it cannot contain clods of mud. Two wooden molds were filled with this mixture, and a little pressure was applied to compact them. The wooden mold was removed once the test cells were dry (Figure 1a).

The second part of the construction system uses earth plaster, the mixture responsible for covering the lightweight wheat straw filler as the wooden structure on both sides of the wall. The plaster comprises one part soil, one part water, two parts cut wheat stubble (maximum 5cm long), and two parts sand. With this slurry mixture, the mold was filled to 7.5 cm; then, it was filled up to an 8 cm thickness with a fine plaster finish to make the surfaces flat and parallel on both sides of the test cell so that the test plates could be supported correctly on the entire surface. To complete the fine finish, one part soil sieved by a 1mm x 1mm mesh, two parts sieved sand, and one part water was used, Figure 1b.

The four test cells were left to dry in the open for 20 days and then taken to the laboratory to run the test. They were placed in a temperature and humidity-controlled environment for hygrothermal conditioning. The initial weight of the test cell was taken (M1). The drying process was started at 60 °C until the constancy in the mass was confirmed (M2). Then, it was allowed to acclimatize at 23°C in the oven (M3) until a hygrothermal balance was reached.

CHANGE OF MASS

The relative mass change of the test cell after the drying process was calculated (m_r) (Equation 1). After this, a more complex conditioning treatment was applied (m_c) (Equation 2), and finally, the relative mass change was due solely to thermal conditioning (m_d) (Equation 3). The results of Table 1 were obtained according to the following expressions.

$$m_r = \frac{M_1 - M_2}{M_2}$$

(Equation 1)

$$m_c = \frac{M_1 - M_3}{M_3}$$

(Equation 2)

$$m_d = \frac{M_3 - M_2}{M_2}$$

(Equation 3)

It was seen that, in the case of the filler test cells, 216hr were required to achieve the hygrothermal conditioning. The variation of the mass is around 26%. This variation is because, in the drying process, the test cells remove the remaining moisture from the slip incorporated into the straw mixture at the beginning of the process. For the plaster test cells, variations in the masses were smaller because a higher-density material was used with less moisture incorporation. So, during the conditioning stages in the drying oven, there was less moisture loss compared to the initial mass. Then, during the conditioning at room temperature, they did not absorb that much moisture to achieve the hygrothermal balance.

The test cell's thermal conductivity was determined under the steady-state heat transfer method using a thermal flow meter, following the guidelines established in the ISO 8302 (1991), ASTM C177 (2013), and IRAM 11559 (1995) standards. The hot plate system was used to measure the thermal resistance of the lightweight filler and plaster test cells. This consists of horizontally placing the two test cells with a hot plate in the middle, a cold plate above the upper sample, and another cold plate below the lower sample, leaving the entire perimeter of the panel insulated to avoid heat losses through the periphery. For the thermal conductivity analysis, an average hot plate temperature of 32°C and cold plate temperature of 8°C was used. The results are shown in Table 2

With the data obtained from the test, Fourier's Law for heat conduction was applied (Equation 4), obtaining the material's conductivity:

$$\frac{\Delta q}{\Delta t} = k * A * \frac{T_f - T_c}{e}$$

(Equation 4)

From this approach, and since the test involves two panels, the following calculation was made to obtain the conductivity value of the tested materials (Equation 5), (Equation 6), (Equation 7), (Equation 8):

$$\Delta Q = \left[k * A * \frac{T_{f1} - T_{c1}}{e_1}\right] + \left[-k * A * \frac{T_{f2} - T_{c2}}{e_2}\right]$$

(Equation 5)

Factoring:

$$\Delta Q = k * A * \left(\frac{\Delta T_1 * e_2 + \Delta T_2 * e_1}{e_1 * e_2}\right)$$

(Equation 6)

$$Q = k * A * \left(\frac{\Delta T_1 * e_2 + \Delta T_2 * e_1}{e_1 * e_2}\right)$$

(Equation 7)

Table 2. Test temperatures and test cell dimensions. Source: Preparation by the authors.

		Filler test cell	Plaster test cell
Top/bottom hot plate temperature		32.0°C / 32.0°C	32.0°C / 31.9°C
Top/bottom cold plate temperature		8.0°C / 8.0°C	8.3°C / 7.8°C
Difference between plates		24°C	23.7°C / 24.1°C
Test average		20°C	20.1°C / 19.9°C
Average power supplied to the heating element	Voltage	6.97V	14.37V
	Current	0.62A	1.29A
Top panel thickness		0.074 m	0.0853
Bottom panel thickness		0.074 m	0.0852
Heat flow		4.273 W	18.125 W
Mean density		276.7 Kg/m^3	1354.7kg/m^2
Room temperature		22.5°C	24.4°C
Relative Humidity		50%	63%

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https://doi.org/10.22320/07190700.2024.14.02.11

Finally:

$$k = \frac{Q}{A} * \frac{e_1 * e_2}{(\Delta T_1 * e_2 + \Delta T_2 * e_1)} \quad \text{(Equation 8)}$$

Where:
Q: Thermal power; V*I*N [W]
V: Voltage supplied [V].
I: Current supplied [A].
N: Hot plate equipment calibration factor: 0.985
k_{1-2}: Thermal conductivity of the top and bottom panels, respectively [W/m²°C]
A: Hot plate area: 0.3078 m x 0.3078 m = 0.0948 m².
ΔT_{1-2}: Temperature delta for the top and bottom panels, respectively [°C].
e_{1-2}: Thickness of the top and bottom panels, respectively [m].

To analyze the thermal behavior of the wattle and daub wall as an enclosure wall, it was necessary to verify the maximum admissible thermal transmittance values for the winter season, following the provisions of IRAM 11601 (2002); IRAM 11603 (2012); IRAM 11605 (1996). The global thermal transmittance values were obtained (Equation 10) using the thermal resistance values obtained, the external 0.13 m²K/W and internal 0.04 m²K/W surface thermal resistance values provided in IRAM 11601 (2002), and using Equation 9. With these data from the experimental tests and based on the winter design guidelines established in IRAM 11603 (2012) and IRAM 11605 (1996), a comparative analysis was made about the wall thicknesses needed to obtain the same thermal transmittance in walls with different construction materials, such as fired brick and hollow ceramic brick, compared to the lightweight wattle and daub wall.

$$R_{Total} = \frac{e_{rev1}}{\lambda} + \frac{e_{rell}}{\lambda} + R_{Sext} + R_{Sint} + \frac{e_{rev2}}{\lambda} \quad \text{(Equation 9)}$$

$$K_{global} = \frac{1}{R_{Total}} \quad \text{(Equation 10)}$$

Where:
e_{rev1-2} = Thickness of the inner and outer plaster of the wattle and daub wall [m]
e_{rell} = Thickness of the lightweight filling of the wattle and daub wall [m]
λ = Thermal conductivity of the wattle and daub wall [W/m K]
R_{Sext} =External surface thermal resistance, IRAM 11.601 [0.13 m² K/W]
R_{Sint} =Internal surface thermal resistance, IRAM 11.601 [0.04 m² K/W]

CASE STUDY

With the global thermal transmittance data, a house in a wetland area of Escobar, Buenos Aires Province, belonging to the warm temperate bioclimatic zone IIIa of the IRAM 11603 Standard (1996), was measured on-site. The records were made during July. For this purpose, dataloggers were arranged at a height of 2.20 m from the finished floor level, taking readings every 15 minutes on the temperature of the indoor and outdoor environments. The criterion for choosing the environments (main room, office, and games room) was that they did not use auxiliary heating systems during the

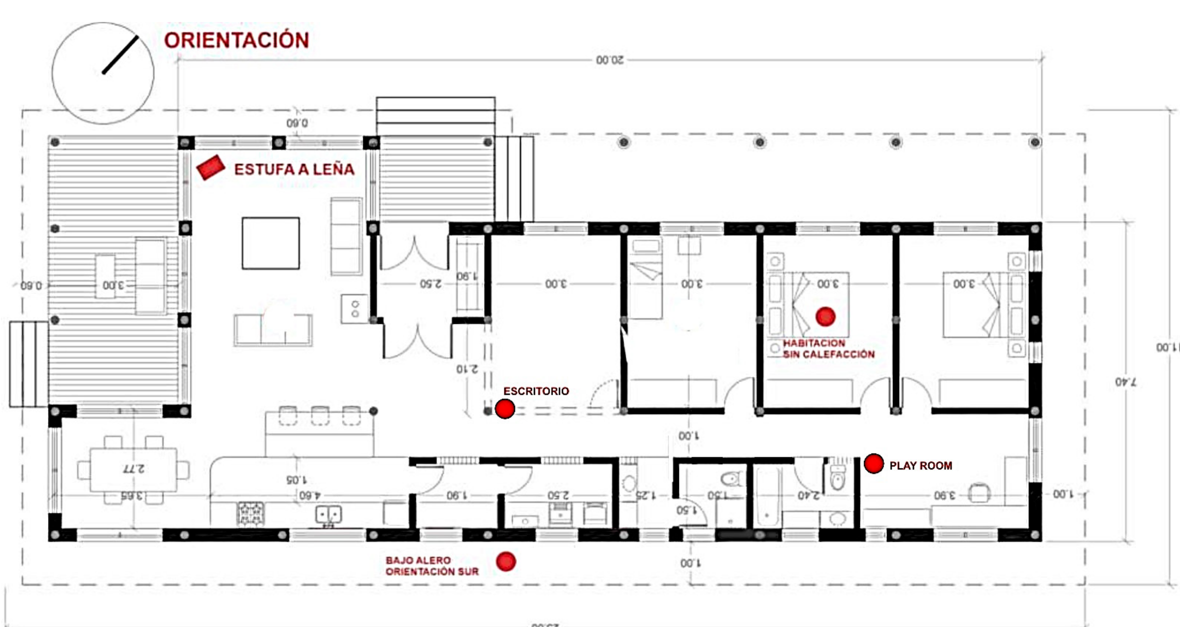

Figure 2: Architecture plan of the dwelling being measured. Source: Preparation by the Authors.

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https://doi.org/10.22320/07190700.2024.14.02.11

Figure 3: Housing construction process - Escobar. Source: Preparation by the authors.

measurement stage. The results generated a curve for each environment, which allowed seeing the insulating capacity of the lightweight wattle and daub walls and the daily thermal amplitudes (Figure 2).

The house in Figure 3 has a covered surface area of 157m^2. It has reinforced concrete pilots for the foundations on which a wooden platform was supported and raised 0.50m from the natural terrain. The main structure is a portico system of round *eucalyptus grandis* posts, approximately 0.18m in diameter. The walls have a framework of 1”x1/2” eucalyptus slats to contain the filling, comprising a wheat straw and slip mixture with an average dry density of 400 kg/m^3 (in situ). To mix the 0.05m thick plaster, 2 parts wheat stubble with 2 parts sand and 1 part earth were used. For the pre-fine plaster, 2 parts sand were used with 1 part earth, and the fine plaster was made with 2 parts sand, 1 part Kaolin clay AF200 + ¼ part cooked paste. The experimentally tested mixture compositions described in the first part of this work were used for both the filling and the plaster. This way, the tested thermal properties obtained 0.28 m thick finished walls. The joinery comprised PVC with hermetic double glazing. Like the floor, the roof is a lightweight 2” x 8” slash pine frame with an 18mm phenolic plate on the top, an 18mm phenolic plate on the bottom, a 200µm nylon vapor barrier, and 100mm glass wool thermal insulation. The inverted roof comprises 10 cm polyethylene foam, 750 µm plastic membrane, 150g geotextile mantle, and an 8cm thick wood chip and vegetation-lightened substrate.

COMPARATIVE ANALYSIS BETWEEN BIOCLIMATIC ZONES

The lightweight wattle and daub construction system can be adapted to build the opaque envelopes of houses in any of the six bioclimatic zones of Argentina (IRAM 11603,1996). For this, the thicknesses of the lightweight filler needed for the lightweight wattle and daub wall for each design temperature for winter and the associated maximum permissible transmittance were calculated from Equation 11. The solid brick and hollow ceramic brick wall thicknesses, which would be needed for each of the localities in Argentina, were obtained similarly using Equation 13. The plaster thicknesses remained constant data for both the lightweight wattle and daub (e_{rell-Q}) and the different brick walls (e_L). In the case of the earth plasters, a 0.05 m thickness was defined for both sides of the wall ($e_{rev\ ext}$, $e_{rev\ int}$), and in the case of walls with cementitious plasters ($e_{r.int}$, and$_{r.ext}$), 0.02 m of plaster was contemplated for each face, and the joints (e_j) between 0.015m bricks, where N_{L-1} is the number of joints needed to join the N_L bricks for the entire wall, with the surface resistances (R_{yes}, R_{it}) provided in IRAM 11601 (2002). The total wall thicknesses were obtained using Equations 12 and 14, and the conductivity and thermal resistance values are shown in Table 3.

$$e_{rell-Q} = \Big(\frac{1}{K_{\max adm}} - \frac{e_{rev\,ext}}{\lambda_{rev\,ext}} - \frac{e_{rev\,int}}{\lambda_{rev\,int}} - R_{si} - R_{s}$$

(Equation 11)

$$e_{muro\ Q} = e_{rev\,int} + e_{rell-nec} + e_{rev}$$

(Equation 12)

$$e_L = \Big(\frac{1}{K_{\max adm}} - \frac{e_{r.int}}{\lambda_{r.int}} - \frac{N_{L-1*}e_j}{\lambda_j} - \frac{e_{r.ext}}{\lambda_{r.ext}} - R_{si} - R_{se}$$

(Equation 13)

$$e_{muro\ L} = e_{rev.int} + N_{L-1} * e_j + N_L * e_L + e_r$$

(Equation 14)

Table 3. Conductivity and surface resistance values of the materials used. Source: Preparation by the authors.

Conductivity (W/mK)							Surface resistance (m²K/W)	
$\lambda_{ext\ plas}$	$\lambda_{int\ plas}$	$\lambda_{ext\ r}$	$\lambda_{int\ r}$	$\lambda_{fill\text{-}Q}$	$\lambda_{Solid\ Brick}$	$\lambda_{Hollow\ Brick}$	R_{si}	R_{se}
0.34	0.34	1.16	0.91	0.07	0.91	0.42	0.13	0.04

Table 4. Thermal response of the lightweight wattle and daub panels. Source: Preparation by the authors.

Designation	Characteristics		Thermal response	
	Thickness [m]	Density [kg/m3]	Thermal Resistance [mK/W]	Thermal Conductivity [W/mK]
Filler	0.074	276.7	14.29	0.07
Plaster	0.0852	1354.7	2.94	0.34

Table 5. Comparative analysis of wall thicknesses and thermal transmittance. Source: Preparation by the authors.

Author	Thickness [m]	Global Thermal Transmittance [W/m2K]
INTI	0.156	0.79
Acevedo Oliva et al.	0.156	1.03 0.73
Cuitiño Rosales, Maldonado & Esteves Miramont.	0.10	1.82
Adec	0.145	1.14

RESULTS AND DISCUSSION

EXPERIMENTAL TEST IN TEST TUBES

Using the equations of Fourier's Law for heat transmission (Equation 8), the value of thermal conductivity for the lightweight filler is k1= 0.07W/mK (Equation 15), and for earth plaster, it is k_2= 0.34W/mK (Equation 16), which can be seen in Table 4.

$$k_1 = \frac{6.97V * 0.62A * 0.985}{0.0948\ m^2} * \frac{0.074m * 0.074m}{(24\ K * 0.074m + 24K * 0.024m)} = 0.07\ \frac{W}{mK}$$

(Equation 15)

$$k_2 = \frac{14.37V * 1.29A * 0.985}{0.0948\ m^2} * \frac{0.0853m * 0.0852m}{(23.7\ K * 0.0853m + 24.1K * 0.0852m)} = 0.34\ \frac{W}{mK}$$

(Equation 16)

The global thermal transmittance of a lightweight wattle and daub wall is determined by Equations 9 and 10. The value obtained for a 0.156m thick wall (equivalent to the one used in the tests by the Protierra Chile team) consisting of 0.05m thick plaster and 0.05m thick filler is 0.79W/m²K. In the tests carried out by the Protierra Chile Team (Acevedo Oliva et al., 2017)) for a 0.156 m thick wet lightweight wattle and daub wall, a thermal transmittance of 1.03W/m²K was obtained. The same study was made for a lightweight dry[7] wattle and daub wall where the thermal transmittance was 0.73W/m²K. In the work of Cuitiño Rosales, Maldonado, and Esteves Miramont (2014), in the experimental test in 0.10 m thick wet wattle and daub test cells[8], thermal transmittance of 1.82 W/m²K was obtained. Finally, in the work of the Agency for the Economic Development of the City of Córdoba (Adec, 2019), for a 0.145m thick wall, a thermal transmittance value of 1.14W/m²K was

7 Dry Lightweight Wattle and Dab: This is a wattle and daub that only uses dry vegetable fibers as its filler, without any soil, clay, or water content (Acevedo Oliva et al., 2017).

8 Wet wattle and daub: This is wattle and daub with a filling of a mixture of clay in a plastic state (clayey earth plus water) with vegetable fibers of a higher density than lightweight wet wattle and daub (Acevedo Oliva et al., 2017).

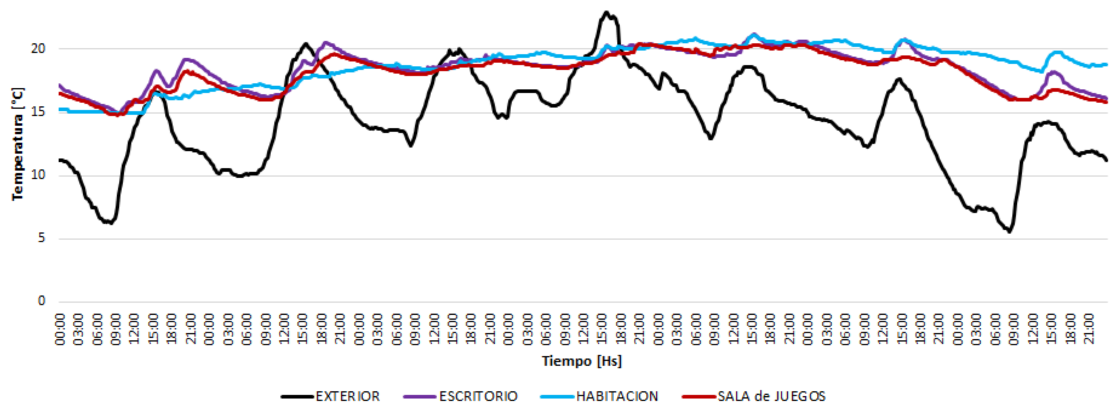
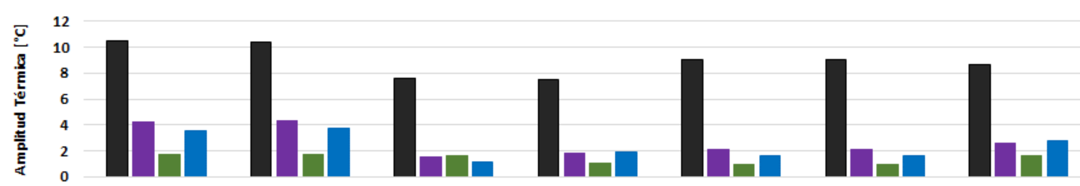


Figure 4: Thermal behavior curves of the house under study. Source: Preparation by the authors.



	1-07	2-07	3-07	4-07	5-07	6-07	7-07
EXTERIOR	10.5	10.4	7.6	7.5	9	9	8.7
ESCRITORIO	4.2	4.3	1.5	1.8	2.1	2.1	2.6
HABITACION	1.7	1.7	1.6	1	0.9	0.9	1.6
SALA DE JUEGOS	3.5	3.7	1.1	1.9	1.6	1.6	2.8

Figure 5: Daily thermal amplitude for the case study. Source: Preparation by the authors.

obtained. It can be seen that the lightweight fiber wall tested by the INTI has a better insulating response than the other walls. These data can be seen in Table 5.

MEASUREMENTS INSIDE THE HOUSE

Argentina has six bioclimatic zones: zone I: very warm, zone II: warm, zone III: warm temperate, zone IV: cold temperate, zone V: cold, and zone VI: very cold. In the cold bioclimatic zones of Argentina, it was necessary to use wattle and daub walls with thicknesses between 0.25m and 0.30 m to verify the conditions of the maximum permissible thermal transmittance level A given in Table 1 of IRAM 11605 (1996), which follows the winter design temperature established in IRAM 11603 (2012). This study has a thermal transmittance of 0.30W/m^{2}K for a lightweight straw wall comprising 0.05 m thick plaster for each side of the wall plus 0.20 m thick lightweight straw filling mixed with slip.

Figures 4 and 5 show the temperature data obtained in July. The external measurement curve is taken as a reference, where the daily thermal amplitude is observed[9], with values between 7.6°C and 10.5 °C. Despite this outdoor thermal variability, inside, there is less variation between the daily thermal amplitudes, where the maximum values recorded in the case of the desk are 4.3°C, in the bedroom, it is 1.7°C, and in the games room, it is 3.7°C, which shows a stable thermal behavior, which favors housing comfort. The house has a wood-burning stove in the living room if a higher comfort temperature is needed. However, no auxiliary heating system was used during this data recording stage.

COMPARATIVE ANALYSIS BETWEEN BIOCLIMATIC ZONES

The lightweight wattle and daub construction technique, Figure 6 a, can be adapted to be built in any bioclimatic zone of Argentina. However, the wall thicknesses must be analyzed to verify the maximum admissible thermal transmittance condition stated by IRAM 11605 (1996).

9 Thermal amplitude: Difference between the maximum and minimum temperature that is recorded in a place in a given period of time (IRAM 11549, 2002).

Table 6. Required and total wall thicknesses. Source: Preparation by the authors (2024)

Data		Lightweight wattle and daub wall [m]		Solid brick wall [m]			Hollow ceramic brick wall [m]		
Ext. design temp.	Level A $K_{max\ adm}$ [W/m2K]	Required thickness	Total Thickness	Required thickness	Total Thickness	Solid brick units N_{LM}	Required thickness	Total Thickness	Hollow brick units N_{LH}
-15	0.23	0.27	0.37	3.50	3.73	19	1.68	1.78	9
-14	0.23	0.27	0.37	3.50	3.73	19	1.68	1.78	9
-13	0.24	0.26	0.36	3.33	3.73	19	1.61	1.78	9
-12	0.25	0.25	0.35	3.19	3.535	18	1.54	1.59	8
-11	0.25	0.25	0.35	3.19	3.535	18	1.54	1.59	8
-10	0.26	0.24	0.34	3.07	3.34	17	1.48	1.59	8
-9	0.27	0.23	0.33	2.95	3.15	16	1.42	1.59	8
-8	0.28	0.22	0.32	2.83	3.15	16	1.37	1.39	7
-7	0.29	0.21	0.31	2.74	2.95	15	1.32	1.39	7
-6	0.3	0.20	0.30	2.63	2.95	15	1.27	1.39	7
-5	0.31	0.19	0.29	2.55	2.76	14	1.23	1.39	7
-4	0.32	0.19	0.29	2.46	2.76	14	1.18	1.39	7
-3	0.33	0.18	0.28	2.39	2.56	13	1.15	1.20	6
-2	0.35	0.17	0.27	2.23	2.56	13	1.08	1.20	6
-1	0.36	0.16	0.26	2.17	2.37	12	1.04	1.20	6
> 0	0.38	0.15	0.25	2.05	2.17	11	0.98	1.20	6

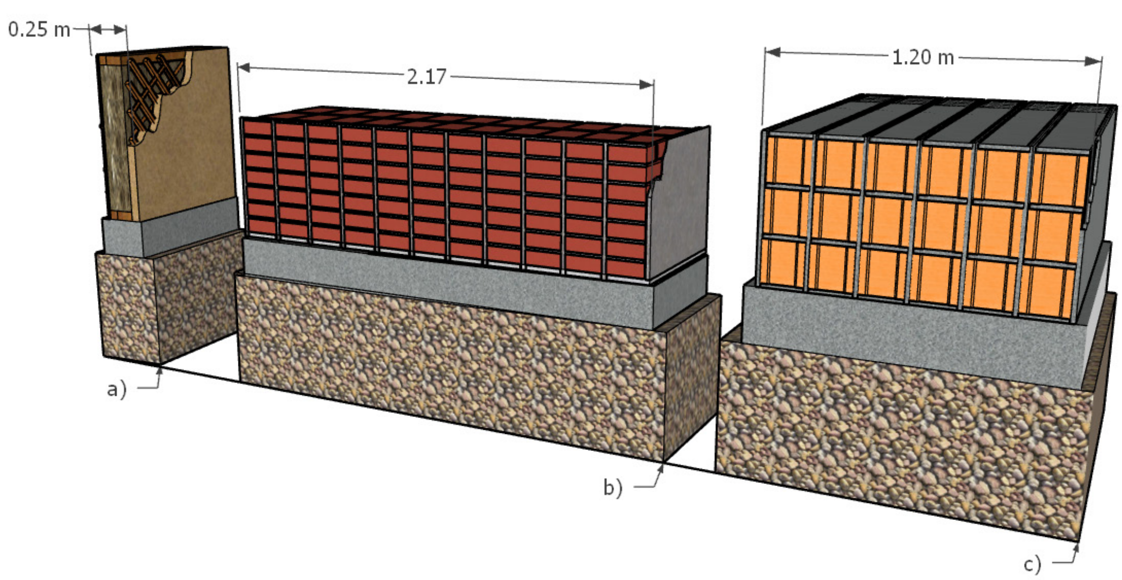


Figure 6: Details of the walls: a) Lightweight Wattle and Daub, b) Solid brick, c) Hollow brick. Source: Preparation by the authors (2024)

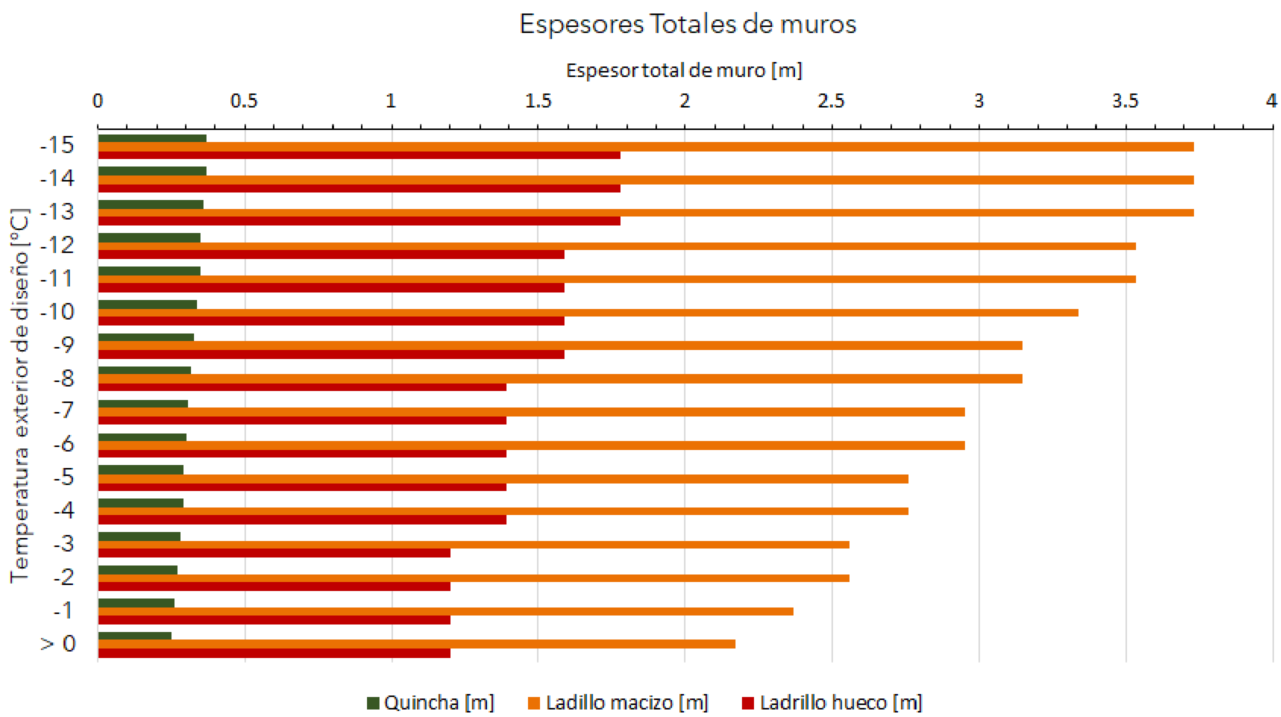


Figure 7: Comparative table of wall thicknesses of study materials for different exterior design temperatures. Source: Preparation by the authors (2024).

From what is described in the methodology (Equation 11-12-13 and 14), in Table 6, the wall thicknesses needed to comply with the maximum admissible thermal transmittance level A for each of the winter design temperatures were obtained, and then the total wall width that would comply with said regulations. In the case of wattle and daub, the data variable to be obtained was the thickness of the lightweight filler, and in the other two cases, the variable to be analyzed was the width of the brick wall. In all cases, the plaster is fixed data. Figures 6 a, b, and c show the proposed case studies.

Figure 7 shows the total wall thicknesses for each case study. In the wattle and daub walls with straw filler and plaster on both sides, the total wall thickness represents between 10% and 12% of the required wall thickness. The solid brick wall and the hollow solid brick represent between 21% and 23% of the total thickness. It can also be seen that faced with the same thermal transmittance demand, solid brick walls and hollow ceramic walls require a high amount of masonry to form the wall, as can be seen in Figure 6, where the last situation has been represented with a design temperature higher than 0°C, and a maximum permissible transmittance of 0.38W/m^{2}K, requiring a 0.15 m filler for wattle and daub and a finished wall thickness of 0.25m. 11 blocks would be needed for the solid brick wall giving a finished wall of 2.17m. In contrast, 6 were needed for the hollow ceramic brick, resulting in a 1.20 m wall. For the solid brick and hollow brick, it is not feasible to build walls with the obtained values due to the large dimensions required to reach the K_{maxadm} levels. In these cases, it is necessary to reduce the wall thicknesses and compensate for this reduction by incorporating insulating materials (Mac Donnell, 2014).

CONCLUSIONS

The parameters needed to conduct the hygrothermal study of the houses built with the lightweight wattle and daub wall plaster and filler technique were obtained with the thermal conductivity values obtained in their tests. As a result, an optimal response regarding thermal behavior was obtained, compared with similar studies in opaque envelopes for housing.

The thermal conductivity obtained from the filler was 0.07 W/m.K, and from the earth plaster, 0.34 W/m.K. The formation of a 0.156 m thick wall, with 0.05 m plaster on each side and 0.056 m thick filler, results in an overall thermal transmittance of 0.79 W/m^{2}K, compared with the wattle and daub tested in Protierra Chile (Acevedo Oliva et al., 2017), where a wall of the same thickness (0.156 m) gives a thermal transmittance of 1.03 W/m²k.

In the studied house, lightweight wattle and daub walls with thicknesses between 25 cm and 30 cm were used, and the hygrothermal behavior could be verified with a thermal transmittance of 0.30 W/m²K. From the on-site measurements in July 2023, it was obtained that, despite the external thermal amplitudes varying between 7.5°C and 10.5°C, the interior has thermal stability throughout the measurement, with amplitudes between 4.3°C and 0.9°C, which is reflected in the interior comfort, because it was not necessary to resort to auxiliary heating systems.

The data obtained in this study allowed making the theoretical calculations to determine the different thicknesses required according to Argentina's thermal transmittance needs for each bioclimatic zone. In this way, for an optimal level of thermal transmittance, it could be concluded that, for all cases, the lightweight wattle and daub wall complies with Level A with considerably lower wall thicknesses compared to a solid brick wall and a hollow ceramic brick wall.

It should be noted that the behavior of lightweight wattle and daub walls continues to be investigated for implementation in both bioclimatic and seismic areas. With this information, the fire resistance of this construction system will be studied, following IRAM 11950 (2010), "Fire resistance of construction elements—Test method."

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, M.G.C.R., A.D., G.V. and V.D.; Data curation, A.D. and G.V.; Formal analysis, M.G.C.R. and V.D.; Acquisition of A.D. and G.V. financing; Research, M.G.C.R., A. D., G.V. and V.D.; Methodology, M.G.C.R.; Project management, A.D. and G.V.; Resources, M.G.C.R., A.D., G.V. and V.D.; Software. M.G.C.R.; Supervision, A.D. and G.V.; Validation, M.G.C.R. and V.D.; Visualization, G.V. and V.D.; Writing - original draft, M.G.C.R., A.D, G.V. and V.D.; Writing - revision and editing, M.G.C.R., A.D., G.V. and V.D.

ACKNOWLEDGMENTS

The authors would like to thank the Municipality of Allen, Río Negro, and the National Institute of Industrial Technology for their support in conducting the tests needed for this publication.

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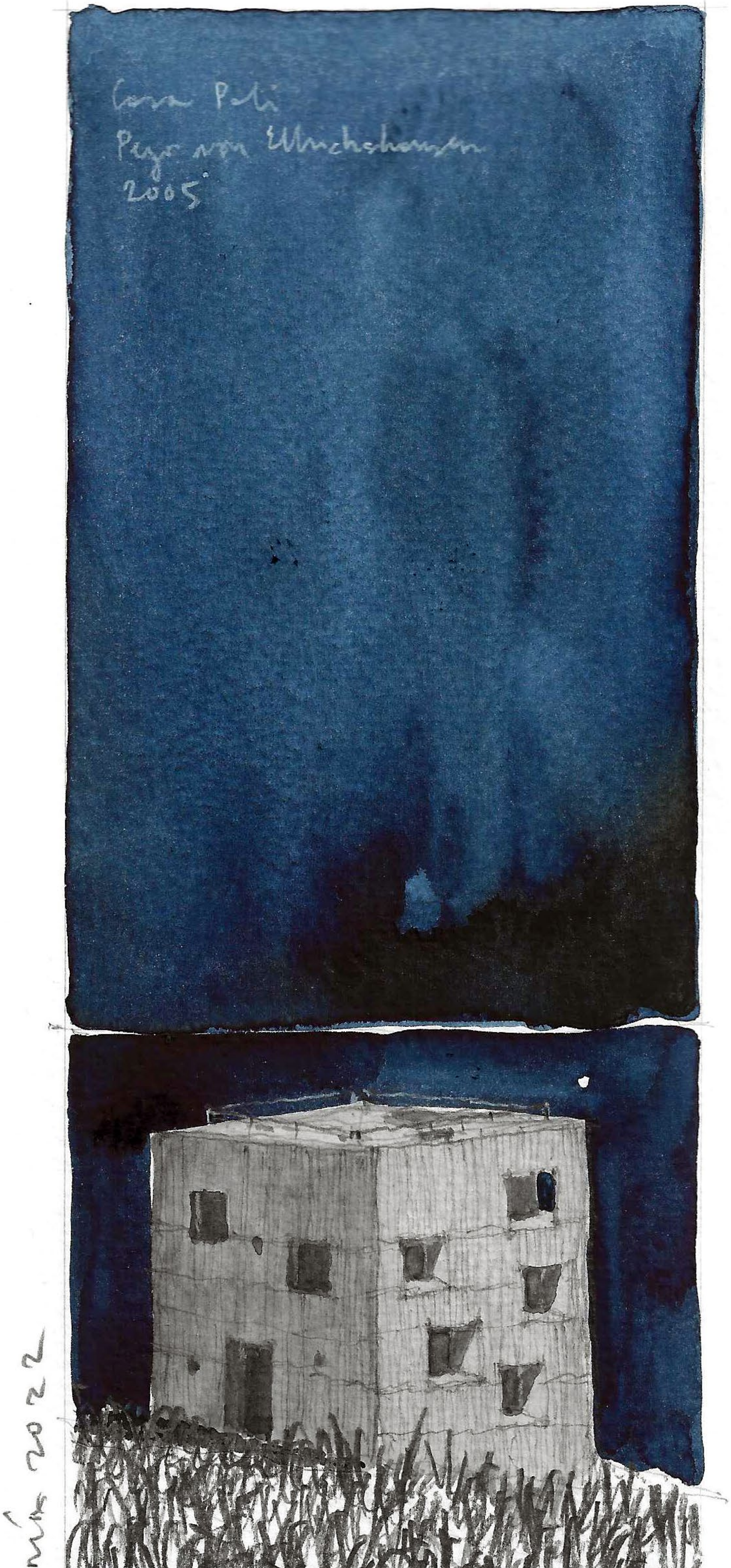

Objeto singular Columna