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EDITORIAL

El contexto actual de la publicación científica

Cuando se habla de productividad académica, se hace referencia a la generación e implementación de conocimiento que aporta de manera significativa al desarrollo de una disciplina. Como indican Gordillo-Salazar et al. (2020), esta productividad puede manifestarse en diversos productos académicos, como publicaciones científicas, patentes, entre otros.

Según el *Ranking Nature Research Leaders 2024* elaborado por *Nature Index* (2024), que clasifica a los países con los mejores desempeños en investigación, Chile ocupa el puesto número 33 a nivel mundial y el segundo lugar en América Latina, registrando un alza del 4,7%. Solo es superado por Brasil, que se encuentra en el puesto 24, aunque con un descenso del 12,4%. Iberti (2024), en el diario *La Tercera*, sostiene que este crecimiento en la productividad académica chilena responde tanto a un mayor acceso a fondos concursables nacionales e internacionales como a un fortalecimiento del trabajo colaborativo entre instituciones académicas. Un ejemplo de ello es la Universidad del Bío-Bío, que entre 2019 y 2023 ha alcanzado 2.324 publicaciones, reflejando un crecimiento sostenido gracias a colaboraciones estratégicas, desarrollo tecnológico y políticas de financiamiento en investigación que han robustecido sus capacidades científicas.

Como todo proceso de expansión, tanto en contextos nacionales como internacionales, este crecimiento trae consigo beneficios y desafíos. El ámbito de la investigación no es la excepción. En esta línea, Bajpai (2015) relata que fue Beall quien, en 2010, acuñó por primera vez el término "*predatory publishers*", es decir, editoriales o revistas científicas "depredadoras". Tal como lo describe Beall (2012), este concepto se refiere a publicaciones que imitan el nombre, diseño y formato de revistas de acceso abierto consolidadas y reconocidas en sus respectivos campos, pero que no poseen relación con ellas. Estas prácticas buscan engañar a investigadores incautos para que publiquen en plataformas carentes de rigurosidad en la revisión por pares, sin estándares científicos reconocibles y, además, con altos costos de publicación ocultos. Es importante subrayar que la existencia de estas revistas no solo es atribuible a quienes las promueven, sino también a investigadores que, por diferentes razones, acceden a estos atajos poco éticos para incrementar artificialmente su productividad académica.

Revistas depredadoras: una amenaza a la ciencia

Entre las características más comunes que permiten identificar a las revistas depredadoras —según lo señalado por Richtig et al. (2018) y Abad-García (2019)— se encuentran: procesos de evaluación nulos o insuficientes que resultan en publicaciones extremadamente rápidas; uso de títulos similares a los de revistas legítimas y prestigiosas; inclusión de consejos editoriales falsos sin el consentimiento de las personas referenciadas; uso de métricas e índices de impacto inexistentes o falsificados; información de contacto inválida que imposibilita una comunicación efectiva con los editores; temáticas excesivamente amplias y dispersas; vulneración de principios éticos en la publicación e investigación científica; afirmaciones engañosas sobre su indexación en bases reconocidas como *Web of Science*, *Scopus* o *PubMed*; artículos publicados con errores ortográficos, tipográficos o enlaces rotos; y el uso de correos electrónicos para la recepción de manuscritos en lugar de plataformas editoriales profesionales.

El valor de la publicación científica diamante

El acceso abierto, como modelo de difusión del conocimiento, tuvo un hito fundacional en la *Conferencia de Budapest* en 2001, aunque adquirió mayor notoriedad con la *Conferencia de Berlín* y la *Declaración de Bethesda* en 2003 (Zedda, 2025; Klebel et al., 2025). A partir de entonces, se impulsó la idea de que las investigaciones financiadas con fondos públicos deberían estar disponibles para toda la sociedad, reduciendo barreras económicas, legales y tecnológicas para su consulta.

Según Klebel et al. (2025), se reconocen cinco tipos principales de acceso abierto:

- Gold Open Access (OA): acceso inmediato y gratuito al contenido, con costos de publicación generalmente cubiertos por los autores o sus instituciones.
- Green OA: autoarchivo de una versión del artículo en repositorios abiertos, usualmente tras un periodo de embargo.
- Hybrid OA: revistas por suscripción que ofrecen acceso abierto opcional a ciertos artículos mediante pagos adicionales.
- Bronze OA: acceso gratuito otorgado por la editorial, sin licencias abiertas explícitas.
- Diamond OA: acceso libre e inmediato tanto para lectores como para autores, financiado por instituciones académicas, consorcios u otras entidades sin fines de lucro.

En el informe de la *Segunda Conferencia de Acceso Abierto Diamante*, realizada en México en 2023, Saenen et al. (2024) describen este modelo como una forma de comunicación académica que garantiza que los resultados de la investigación estén disponibles de manera inmediata y sin restricciones, a través de licencias abiertas y sin costos asociados. Este enfoque equitativo no solo democratiza el acceso al conocimiento, sino que también promueve la participación activa de todas y todos los involucrados en su creación, difusión, reutilización y preservación. Además, se centra en asegurar la calidad de los contenidos y en garantizar el derecho de todos los ciudadanos a beneficiarse de los avances científicos y sus aplicaciones.

El rol de Hábitat Sustentable en este ecosistema

En este escenario de transformación vertiginosa de la comunicación científica, la revista *Hábitat Sustentable* reafirma su compromiso con una ciencia abierta, ética, rigurosa y socialmente relevante. Nuestra línea editorial no solo adhiere a los principios del acceso abierto diamante, sino que también se proyecta como un espacio de publicación para investigaciones que aborden la sustentabilidad desde perspectivas críticas e interdisciplinarias, especialmente desde y para el Sur Global.

Publicamos sin cobrar a autores ni lectores, con procesos rigurosos de revisión por pares, en tres idiomas, y con una política editorial orientada a fortalecer comunidades académicas emergentes. Frente a las amenazas que representan las revistas depredadoras y la creciente mercantilización del conocimiento, *HS* se posiciona como una plataforma segura, ética y profesional. Esto lo hace no solo para investigadores consolidados, sino también para autoras y autores noveles que buscan publicar bajo altos estándares de calidad.

Asimismo, *HS* busca promover un pensamiento científico comprometido con los desafíos sociales y ambientales de nuestros territorios. La sustentabilidad, entendida de manera integral —ambiental, social, económica y cultural—, requiere enfoques abiertos, colaborativos y transdisciplinares. En ese sentido, valoramos especialmente aquellas contribuciones que promueven nuevas formas de comprender la relación entre hábitat, tecnología y sociedad.

Invitamos a nuestras lectoras y lectores, así como a académicos, profesionales y estudiantes, a ser parte activa de este proyecto editorial. Ya sea como autoras, revisores o lectores críticos, su participación es esencial para construir colectivamente una ciencia más abierta, confiable y pertinente.

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EDITORIAL

The current context of scientific publishing

When discussing academic productivity, we refer to the generation and application of knowledge that make significant contributions to the advancement of a discipline. As indicated by Gordillo-Salazar et al. (2020), this productivity can be manifested in various academic products, including scientific publications and patents, among others.

According to the *Nature Research Leaders 2024* ranking, prepared by Nature Index (2024), which ranks countries by their research performance, Chile ranks 33rd worldwide and second in Latin America, registering a 4.7% increase. It is only surpassed by Brazil, which ranks 24th, although with a decrease of 12.4%. Iberti (2024), in the *La Tercera* newspaper, argues that the growth in Chilean academic productivity is a response to both increased access to domestic and international competitive funds and a strengthening of collaborative work between educational institutions. An example of this is the Universidad del Bío-Bío, which between 2019 and 2023 published 2,324 works, reflecting sustained growth thanks to strategic collaborations, technological development, and research financing policies that have strengthened its scientific capabilities.

Like any expansion process, both in domestic and international contexts, this growth brings with it benefits and challenges. The field of research is no exception. Along these lines, Bajpai (2015) mentions that it was Beall who, in 2010, first coined the term "*predatory publishers*", i.e., "predatory" scientific publishers or journals. As described by Beall (2012), this concept refers to publications that imitate the name, design, and format of established and recognized open-access journals in their respective fields, but have no relation to them. These practices aim to deceive unsuspecting researchers into publishing on platforms that lack rigorous peer review, fail to adhere to recognizable scientific standards, and, furthermore, incur high hidden publication costs. It is essential to note that the existence of these journals is not solely attributable to those who promote them, but also to researchers who, for various reasons, utilize these unethical shortcuts to artificially inflate their academic productivity.

Predatory journals: a threat to science

Among the most common characteristics that allow identifying predatory journals — as pointed out by Richtig et al. (2018) and Abad-García (2019)— there are: null or insufficient evaluation processes that result in extremely fast publications; use of titles similar to those of legitimate and prestigious journals; inclusion of false editorial boards without the consent of the referenced people; use of non-existent or falsified metrics and impact indexes; invalid contact information that makes effective communication with editors impossible; excessively broad and dispersed topics; violation of ethical principles in publishing and scientific research; misleading claims about their indexing on recognized platforms such as *Web of Science*, *Scopus* or *PubMed*; articles published with spelling, typographical errors or broken links; and the use of e-mails for the receipt of manuscripts instead of professional editorial platforms.

The value of the diamond scientific publication

Open access, as a model of knowledge dissemination, reached a foundational milestone with the *Budapest Conference* in 2001, although it gained greater notoriety with the *Berlin Conference* and the *Bethesda Declaration* in 2003 (Zedda, 2025; Klebel et al., 2025). From then on, the idea was promoted that publicly funded research should be made available to the entire society, thereby reducing economic, legal, and technological barriers to its consultation.

According to Klebel et al. (2025), five main types of open access are recognized:

- Gold Open Access (OA): Immediate and free access to the content, with publication costs usually covered by the authors or their institutions.
- Green OA: Self-archiving of a version of the article in open repositories, usually after an embargo period.
- Hybrid OA: Subscription journals that offer optional open access to specific articles for additional payments.
- Bronze OA: Free access granted by the publisher, without explicit open licenses.
- Diamond OA: Free and immediate access for both readers and authors, funded by academic institutions, consortia, or other non-profit entities.

In the report of the *Second Diamond Open Access Conference*, conducted in Mexico in 2023, Saenen et al. (2024) describe this model as a form of academic communication that ensures that research results are available immediately and without restrictions, through open licenses and without associated costs. This equitable approach not only democratizes access to knowledge, but also promotes the active participation of all those involved in its creation, dissemination, reuse, and preservation. In addition, it focuses on ensuring

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the quality of content and guaranteeing the right of all citizens to benefit from scientific advances and their applications.

The role of Hábitat Sustentable in this ecosystem

In this scenario of vertiginous transformation in scientific communication, the journal *Hábitat Sustentable* reaffirms its commitment to open, ethical, rigorous, and socially relevant science. Our editorial line not only adheres to the principles of diamond open access, but also serves as a publication space for research that addresses sustainability from critical and interdisciplinary perspectives, particularly from and for the Global South.

We publish without charging authors or readers, with rigorous peer-review processes, in three languages, and with an editorial policy that aims to strengthen emerging academic communities. In the face of the threats posed by predatory journals and the growing commodification of knowledge, *HS* is positioned as a safe, ethical, and professional platform. This makes it not only for established researchers, but also for new authors seeking to publish under high-quality standards.

Additionally, *HS* aims to foster a scientific mindset dedicated to addressing the social and environmental challenges of our territories. Sustainability, understood in an integral way—encompassing environmental, social, economic, and cultural aspects—requires open, collaborative, and transdisciplinary approaches. In this sense, we especially value those contributions that promote new ways of understanding the relationship between habitat, technology, and society.

We invite our readers, as well as academics, professionals, and students, to be an active part of this editorial project. Whether as authors, reviewers, or critical readers, their participation is essential to collectively build a more open, reliable, and relevant science.

EDITORIAL

O contexto atual da publicação científica

Quando discutimos a produtividade acadêmica, nos referimos à geração e à aplicação de conhecimentos que fazem contribuições significativas para o avanço de uma disciplina. Conforme indicado por Gordillo-Salazar et al. (2020), essa produtividade pode se manifestar em vários produtos acadêmicos, incluindo publicações científicas e patentes, entre outros.

De acordo com a classificação Nature Research Leaders 2024, elaborada pelo Nature Index (2024), que classifica os países por seu desempenho em pesquisa, o Chile ocupa a 33ª posição mundial e a segunda na América Latina, registrando um aumento de 4,7%. Só é superado pelo Brasil, que ocupa a 24ª posição, embora com uma queda de 12,4%. Iberti (2024), no jornal La Tercera, argumenta que o crescimento da produtividade acadêmica chilena é uma resposta tanto ao maior acesso a fundos competitivos nacionais e internacionais quanto ao fortalecimento do trabalho colaborativo entre instituições educacionais. Um exemplo disso é a Universidad del Bío-Bío, que entre 2019 e 2023 publicou 2.324 trabalhos, refletindo um crescimento sustentado graças a colaborações estratégicas, desenvolvimento tecnológico e políticas de financiamento de pesquisa que fortaleceram suas capacidades científicas.

Como em qualquer processo de expansão, tanto em contextos nacionais quanto internacionais, esse crescimento traz consigo benefícios e desafios. O campo da pesquisa não é exceção. Nesse sentido, Bajpai (2015) relata que foi Beall quem, em 2010, cunhou pela primeira vez o termo "predatory publishers", ou seja, editoras ou periódicos científicos "predatórios". Conforme descrito por Beall (2012), esse conceito refere-se a publicações que imitam o nome, o design e o formato de periódicos de acesso aberto estabelecidos e reconhecidos em seus respectivos campos, mas não têm relação com eles. Essas práticas buscam enganar pesquisadores desavisados para que publiquem em plataformas sem revisão rigorosa por pares, sem padrões científicos reconhecíveis e com altos custos de publicação ocultos. É importante ressaltar que a existência dessas revistas não se deve apenas àqueles que as promovem, mas também aos pesquisadores que, por diferentes motivos, acessam esses atalhos antiéticos para aumentar artificialmente sua produtividade acadêmica.

Periódicos predatórios: uma ameaça à ciência

Entre as características mais comuns que nos permitem identificar os periódicos predatórios - de acordo com Richtig et al. (2018) e Abad-García (2019) - incluem: processos de avaliação inexistentes ou insuficientes que resultam em publicações extremamente rápidas; uso de títulos semelhantes aos de periódicos legítimos e de prestígio; inclusão de conselhos editoriais falsos sem o consentimento dos indivíduos referenciados; uso de métricas e índices de impacto inexistentes ou falsificados; informações de contato inválidas que impossibilitam a comunicação efetiva com os editores; assunto excessivamente amplo e disperso; violação de princípios éticos na publicação e na pesquisa científica; alegações enganosas de indexação em bancos de dados reconhecidos, como Web of Science, Scopus ou PubMed; artigos publicados com erros ortográficos e tipográficos ou links quebrados; e o uso de e-mails para envio de manuscritos em vez de plataformas editoriais profissionais.

O valor do diamante da publicação científica

O acesso aberto, como modelo de disseminação do conhecimento, teve um marco fundamental na Conferência de Budapeste em 2001, embora tenha ganhado maior visibilidade com a Conferência de Berlim e a Declaração de Bethesda em 2003 (Zedda, 2025; Klebel et al., 2025). A partir de então, foi promovida a ideia de que a pesquisa financiada com recursos públicos deveria ser disponibilizada para toda a sociedade, reduzindo as barreiras econômicas, legais e tecnológicas à sua consulta.

De acordo com Klebel et al. (2025), são reconhecidos cinco tipos principais de acesso aberto:

- Gold Open Access (OA): acesso imediato e gratuito ao conteúdo, com os custos de publicação geralmente cobertos pelos autores ou suas instituições.
- Verde OA: autoarquivamento de uma versão do artigo em repositórios abertos, geralmente após um período de embargo.
- Híbrido OA: periódicos por assinatura que oferecem acesso aberto opcional a determinados artigos mediante o pagamento de taxas adicionais.
- Bronze OA: acesso gratuito concedido pelo editor, sem licenças abertas explícitas.
- Diamond OA: acesso gratuito e imediato para leitores e autores, financiado por instituições acadêmicas, consórcios ou outras entidades sem fins lucrativos.

No relatório da Segunda Conferência Diamante de Acesso Aberto, realizada no México em 2023, Saenen et al. (2024) descrevem esse modelo como uma forma de comunicação acadêmica que garante que os resultados da pesquisa estejam disponíveis imediatamente e sem

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restrições, por meio de licenças abertas e sem custos associados. Essa abordagem equitativa não apenas democratiza o acesso ao conhecimento, mas também promove a participação ativa de todos os envolvidos em sua criação, disseminação, reutilização e preservação. Ela também se concentra em assegurar a qualidade do conteúdo e garantir o direito de todos os cidadãos de se beneficiarem dos avanços científicos e de suas aplicações.

O papel da Habitat Sustentable nesse ecossistema

Nesse cenário de vertiginosa transformação da comunicação científica, a revista Habitat Sustentable reafirma seu compromisso com a ciência aberta, ética, rigorosa e socialmente relevante. Nossa linha editorial não apenas adere aos princípios do acesso aberto diamante, mas também se projeta como um espaço de publicação de pesquisas que abordam a sustentabilidade a partir de perspectivas críticas e interdisciplinares, especialmente do e para o Sul Global.

Publicamos sem cobrar dos autores ou leitores, com processos rigorosos de revisão por pares, em três idiomas e com uma política editorial que visa fortalecer as comunidades acadêmicas emergentes. Diante das ameaças representadas pelas revistas predatórias e da crescente mercantilização do conhecimento, a HS se posiciona como uma plataforma segura, ética e profissional. Isso faz com que ela não seja apenas para pesquisadores estabelecidos, mas também para novos autores que buscam publicar com altos padrões de qualidade.

O HS também busca promover o pensamento científico comprometido com os desafios sociais e ambientais de nossos territórios. A sustentabilidade, entendida de forma integral - ambiental, social, econômica e cultural -, exige abordagens abertas, colaborativas e transdisciplinares. Nesse sentido, valorizamos especialmente as contribuições que promovem novas formas de entender a relação entre habitat, tecnologia e sociedade.

Convidamos nossos leitores, bem como acadêmicos, profissionais e estudantes, a serem parte ativa deste projeto editorial. Seja como autores, revisores ou leitores críticos, sua participação é essencial para construirmos coletivamente uma ciência mais aberta, confiável e relevante.

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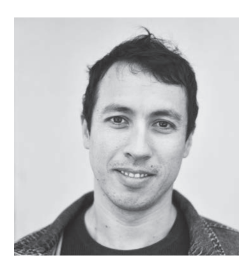

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DRIVING THE DEVELOPMENT OF ENERGY COMMUNITIES IN COLOMBIA: CHALLENGES AND OPPORTUNITIES FOR A DECENTRALIZED ENERGY TRANSITION

IMPULSANDO COMUNIDADES ENERGÉTICAS EN COLOMBIA: RETOS Y OPORTUNIDADES PARA UNA TRANSICIÓN ENERGÉTICA DESCENTRALIZADA

ESTÍMULO AO DESENVOLVIMENTO DE COMUNIDADES ENERGÉTICAS NA COLÔMBIA: DESAFIOS E OPORTUNIDADES PARA UMA TRANSIÇÃO ENERGÉTICA DESCENTRALIZADA

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ABSTRACT

Energy communities represent a transformative paradigm for democratizing access to renewable energy, decentralizing power systems, and fostering economic sustainability. This study analyzes their global development, with an emphasis on developing countries such as Colombia. The research employs a systematic literature review in Scopus and a keyword co-occurrence analysis to identify trends; in addition, Colombian regulatory documents were examined to contextualize the findings. The discussion addresses distributed generation, peer-to-peer (P2P) energy trading, and regulatory frameworks that drive local energy transitions. Although the opportunities are significant in Colombia, challenges persist in infrastructure, regulation, and social acceptance, particularly in the Caribbean region. The article proposes context-specific strategies from international experiences to overcome these barriers and consolidate decentralized energy systems that accelerate the country's energy transition and sustainable development.

Keywords
electricity, energy policy, energy resources

RESUMEN

Las comunidades energéticas representan un paradigma transformador para democratizar el acceso a energías renovables, descentralizar los sistemas energéticos y fomentar la sostenibilidad económica. Este estudio analiza su desarrollo global, con énfasis en países en vías de desarrollo como Colombia. La investigación utiliza una revisión sistemática en Scopus y un análisis de co-ocurrencia de palabras clave para identificar tendencias; además, se revisaron documentos regulatorios colombianos para contextualizar los hallazgos. Se abordan la generación distribuida, el comercio entre pares (P2P) y los marcos regulatorios que impulsan transiciones energéticas locales. En Colombia, aunque las oportunidades son significativas, persisten retos de infraestructura, regulación y aceptación social, especialmente en el Caribe. Este artículo propone estrategias adaptadas basadas en experiencias internacionales para superar dichas barreras y consolidar sistemas descentralizados que aceleren la transición energética y el desarrollo sostenible del país.

Palabras clave
energía eléctrica, política energética, recursos energéticos

RESUMO

As comunidades energéticas representam um paradigma transformador para democratizar o acesso à energia renovável, descentralizar os sistemas energéticos e promover a sustentabilidade econômica. Este estudo analisa seu desenvolvimento global, com ênfase em países em desenvolvimento, como a Colômbia. A pesquisa emprega uma revisão sistemática da literatura no Scopus e uma análise de coocorrência de palavras-chave para identificar tendências. Além disso, documentos regulatórios colombianos foram examinados para contextualizar os resultados. A discussão aborda a geração distribuída, o comércio de energia ponto a ponto (P2P) e os marcos regulatórios que impulsionam as transições energéticas locais. Embora as oportunidades sejam significativas na Colômbia, persistem desafios em infraestrutura, regulamentação e aceitação social, particularmente na região do Caribe. O artigo propõe estratégias específicas para o contexto, a partir de experiências internacionais, para superar essas barreiras e consolidar sistemas energéticos descentralizados que acelerem a transição energética e o desenvolvimento sustentável do país.

Palavras-chave:
energia elétrica, política energética, recursos energéticos

INTRODUCTION

In the global energy transition context, clean energy sources have emerged as a fundamental solution to challenges associated with climate change, energy security, and sustainable development. Characterized by minimal environmental impact, these sources aim to reduce greenhouse gas emissions and promote more resilient and decentralized energy systems. According to Andoni et al. (2019), blockchain and other advanced technologies are transforming traditional energy models by enabling decentralized management and peer-to-peer (P2P) energy trading. Mollah et al. (2021) highlight that blockchain-enabled smart grids address security concerns in transactions and facilitate the integration of renewable resources into decentralized systems. The integration of distributed energy resources (DERs) has further catalyzed the adoption of renewables and the creation of energy communities, fostering prosumer participation in local energy markets (Morstyn et al., 2019). These innovations contribute not only to environmental sustainability but also to social cohesion and local economic development (Siano et al., 2019), marking a clear path toward the global energy transition.

The transition toward sustainability requires not only renewable sources but also advanced technologies that optimize resource use. In this context, P2P energy has emerged as a key mechanism, enabling direct transactions between prosumers and consumers within energy communities. This approach democratizes access and facilitates a decentralized, flexible energy market (Wang et al., 2019). P2P systems reduce energy costs and promote efficient use of renewables. For instance, Zia et al. (2020) show how local transactions facilitate renewable integration into microgrids, while Siano et al. (2019) demonstrate how distributed ledger technology (DLT) enables secure energy transactions through smart contracts, optimizing supply-demand balance. Mollah et al. (2021) note that decentralization is central to future smart grids, integrating Blockchain to overcome technical barriers.

However, adopting these systems presents regulatory and technical challenges, especially in regions where centralized structures still dominate. Andoni et al. (2019) and Soto et al. (2021) emphasize the need for regulatory clarity and robust infrastructure to implement P2P models in emerging regions effectively.

Energy communities play a crucial role in this transition, serving as catalysts for renewable technologies and autonomous governance mechanisms. They unite prosumers and consumers in dynamic markets, leveraging technologies like blockchain to ensure secure, transparent transactions (Gu et al., 2023; Wang et al., 2019). European implementation has shown that these initiatives can enhance energy resilience and reduce carbon emissions. where the integration of smart contracts enables process automation, improving both economic and environmental performance (Andoni et al., 2019; Mollah et al., 2021). Mollah et al. (2021) argue that combining Blockchain and smart grids is key to managing growing energy transactions efficiently.

Despite these benefits, energy communities still face regulatory, technical, and infrastructural barriers in developing countries. This underscores the need for further research to design adaptive models that reflect local conditions and ensure long-term viability (Gu et al., 2023; Siano et al., 2019).

OBJECTIVES OF THE LITERATURE REVIEW AND CONTRIBUTION TO THE FIELD

In the Colombian context, energy communities represent a strategic approach to addressing persistent challenges such as energy poverty, unreliable electricity supply, and regulatory barriers. The current legislative framework, promoted by the Ministry of Mines and Energy and the Energy and Gas Regulatory Commission (Comisión de Regulación de Energía y Gas – República de Colombia, 2011; Ministerio de Minas y Energía – República de Colombia, 2023b), allows the establishment of collective self-generators (AGRC, in Spanish) and collective distributed generators (GDC, in Spanish), fostering the adoption of non-conventional renewable energy sources (NCRES), including solar, wind, and biomass. These regulations, together with targeted incentives for projects in the Caribbean region, offer significant potential to improve energy access in areas affected by high tariffs and limited infrastructure.

At the global level, advanced technologies such as blockchain and smart contracts have transformed energy markets, permitting secure and transparent transactions between prosumers and consumers. Studies by Andoni et al. (2019) and Siano et al. (2019) have demonstrated how P2P trading democratizes access to renewable energy, reduces carbon emissions, and enhances local governance. These international experiences provide valuable insights for Colombia, particularly regarding integrating digital platforms that improve energy management and encourage community participation.

This literature review aims to analyze how energy communities, supported by technological innovations and adaptive regulatory frameworks, can contribute to a decentralized energy transition in Colombia.

METHODOLOGY

This study is grounded in identifying key trends and emerging patterns related to energy communities and their integration with advanced technologies such as

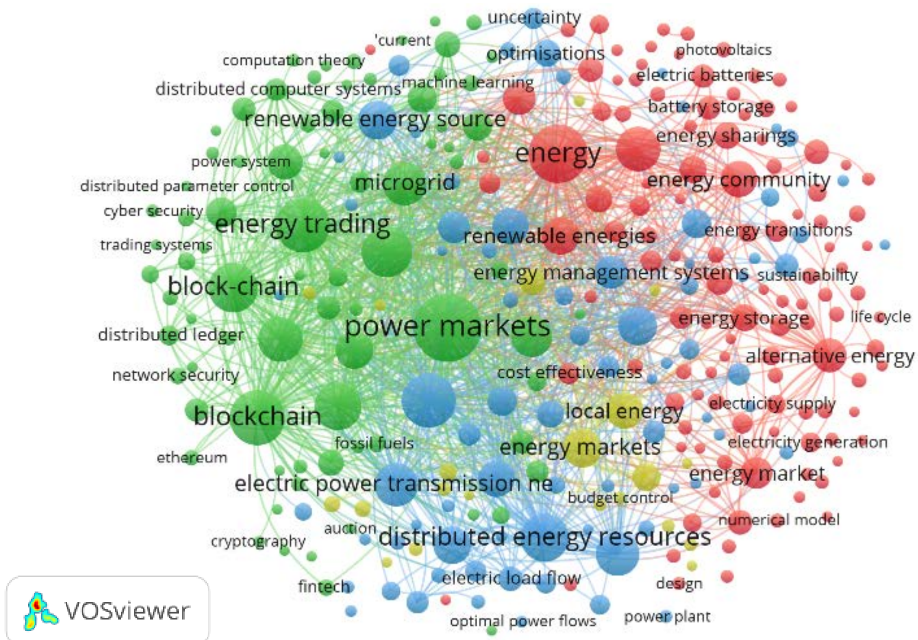

Figure 1. Co-occurrence map of keywords in the field of energy communities and associated technologies. Source: Prepared by the authors.

Blockchain and Smart Contracts. The Scopus database was used to ensure rigorous and representative analysis, as it includes peer-reviewed literature from high-impact journals (Codina, 2005). Search terms included "Energy communities", "Blockchain", "Smart contracts", and "Distributed energy markets."

The analysis followed several stages:

1. Initial screening and temporal delimitation. Titles and abstracts were assessed to identify studies aligned with the research focus. Articles had to include at least one of the predefined terms in the title, abstract, or keywords, using the Boolean operator OR. The timeframe extended from a seminal work (Andoni et al., 2019) to the most recent full year (2025), yielding 1,232 documents.
2. Application of exclusion criteria. Documents not in English, or not classified as scientific articles or reviews, were excluded. Publications unrelated to Engineering, Energy, or Computer Science were also removed, reducing the dataset to 609 documents.
3. Keyword co-occurrence analysis. To explore the conceptual structure of the literature, we used VOSviewer to identify relationships among frequent terms and uncover thematic clusters.
4. Thematic classification and prioritization. The remaining studies were classified into four key thematic categories to support a more focused and organized analysis: (i) implementation of digital technologies in energy communities (25 documents), (ii) regulatory and policy barriers (25), (iii) community governance models (25), and (iv) specific cases of renewable energy integration (25). Within each category, the most relevant studies were identified, prioritizing those with higher citation counts as an indicator of academic impact.
5. Final selection and in-depth analysis. A final subset of 13 scientific articles was selected for detailed review. The selection was based on their thematic alignment, methodological rigor, and scholarly influence. This final stage provided a robust foundation for the critical analysis of the most significant contributions in the field.

Additionally, the study incorporated regulatory and institutional perspectives to enhance contextual relevance. A distinctive feature was the inclusion of key regulatory documents (Ministerio de Minas y Energía – República de Colombia, 2023a) and reports (Comisión de Regulación de Energía y Gas – República de Colombia, 2011), which helped situate international trends within Colombia's context, especially in the Caribbean region, known for its high potential in non-conventional renewable energy sources.

RESULTS AND DISCUSSION

KEYWORD CO-OCCURRENCE ANALYSIS

This analysis uncovers the conceptual structure of the literature by identifying clusters of frequently co-occurring terms, thereby revealing key thematic relationships among the selected articles. Figure 1 presents a co-

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occurrence map, where nodes and links highlight thematic relationships among key concepts.

The keyword co-occurrence analysis identified three primary thematic clusters reflecting predominant research areas in energy communities and advanced technologies: Energy Transition and Energy Communities, Blockchain and Digital Technologies, and Energy Management and Efficiency. Below is a synthesis of the findings grouped by cluster, highlighting the main concepts and their context within the field.

- Energy Transition and Energy Communities (Red): This cluster focuses on research on creating sustainable energy generation and storage models. It emphasizes integrating renewable sources, active participation by energy communities, and the importance of decentralized energy markets. The strong connection between "energy sharing" and "energy community" highlights the crucial role of prosumers and local initiatives in the energy transition. The main concepts are "Energy community", "Alternative energy", "Energy storage", "Energy transitions", and "Energy sharing".
- Blockchain and Digital Technologies (Green): This group reflects the growing interest in deploying advanced technologies such as Blockchain and Smart Contracts. These tools enable decentralized energy trading, facilitate P2P transactions, and ensure local energy markets' security, transparency, and efficiency. The links between "Blockchain" and "Smart contracts" underscore their significant role as key enablers in developing modern, decentralized energy systems. The main concepts are "Blockchain", "Distributed ledger", "Peer-to-peer trading", "Energy trading", and "Smart contracts".
- Energy Management and Efficiency (Blue): This group reflects the growing interest in deploying advanced technologies. These tools allow decentralized energy trading, facilitate P2P transactions, and ensure local energy markets' security, transparency, and efficiency. The links between "blockchain" and "smart contracts" underscore their significant role as key enablers in developing modern, decentralized energy systems. The main concepts include "Renewable energy source", "Microgrid", "Distributed energy resources", and "Energy efficiency".

DEFINITION AND CHARACTERISTICS OF ENERGY COMMUNITIES

Energy communities are a transformative model for advancing sustainable and decentralized energy systems. They involve citizens, businesses, and local organizations that collaborate in producing, consuming, and trading renewable energy. Based on the principles of sustainability, local empowerment, and decentralized governance, these communities promote inclusive and participatory energy management (Soto et al., 2021).

A key feature of energy communities is their ability to operate autonomously within local markets, using technologies such as blockchain and smart contracts to enable secure and transparent peer-to-peer energy trading (Mollah et al., 2021; Wang et al., 2019). Many also implement microgrids to optimize distributed energy resources and improve resilience to environmental and regulatory risks (Zia et al., 2020).

Internationally, energy communities have helped address energy poverty and infrastructure deficits. In Europe, the 2019 Renewable Energy Directive has encouraged Renewable Energy Communities to enhance citizen participation and renewable adoption (Gjorgievski et al., 2021). In Latin America, particularly in rural and underserved areas, community microgrids offer reliable, sustainable electricity that supports social and economic development (Soto et al., 2021).

EVOLUTION OF THE CONCEPT OF ENERGY COMMUNITIES

The notion of Energy Communities has evolved significantly over recent decades, becoming a key driver in the shift toward more sustainable and decentralized energy systems. These communities, which bring together prosumers, local managers, and other stakeholders, aim to democratize energy production, consumption, and trading by implementing advanced technologies such as Blockchain and Smart Contracts. This model promotes environmental sustainability, strengthens social cohesion, and fosters local economic development (Gu et al., 2023; Stefan et al., 2020). Energy Communities leverage Non-Conventional Renewable Energy Sources (NCRES) such as solar and wind to reduce dependence on fossil fuels and increase resilience to climate and regulatory challenges (Zia et al., 2020).

Globally, Energy Communities have proven to be practical tools for addressing energy access issues and energy poverty. In local contexts, such as Colombia's Caribbean region, they present an opportunity to transform energy systems and advance social equity. Their development, propelled by technological advances and regulatory frameworks, allows citizen participation in energy markets. However, their implementation varies depending on each region's socioeconomic and climatic conditions, underscoring the importance of an adaptive approach to ensure success. Such adaptive approaches should be context-sensitive, integrating participatory governance, institutional collaboration, and appropriate technology selection based on local capacity. Successful models must consider not only technical feasibility but also cultural acceptance, affordability, and long-term community ownership to guarantee that energy communities are inclusive, resilient, and sustainable.

KEY STAKEHOLDERS: PROSUMERS, LOCAL MANAGERS, AND MARKET PARTICIPANTS

Key stakeholders in Energy Communities include prosumers, local managers, and market participants, each playing a critical role in ensuring the operation and sustainability of these systems.

- Prosumers: Individuals or entities that both produce and consume energy. According to Wang et al. (2019), prosumer engagement through decentralized platforms, such as those based on blockchain, facilitates reliable energy transactions and fosters the adoption of renewable energy technologies (Ariza et al., 2020).
- Local Managers: They coordinate the community's activities, including energy planning and mediation among members. Their role is crucial in implementing participatory governance models and ensuring compliance with regulatory standards. As Stefan et al. (2020) highlighted, this role is especially significant in local settings where energy needs and resources vary widely.
- Market Participants: This group comprises system operators, technology developers, and other actors providing critical infrastructure and services. They facilitate the integration of advanced technologies, such as Smart Contracts and real-time monitoring systems, to improve operational efficiency and transparency within the energy system (Mollah et al., 2021).

Figure 2 illustrates a conceptual model of P2P energy trading in Energy Communities. It highlights the main interactions among key actors: consumers, prosumers, and the utility company, all coordinated by an energy exchange manager.

These players can trade energy among themselves or with consumers, managing both generation and consumption. The utility company provides backup to the system, offering energy purchase and export prices to balance surpluses or shortages in community energy production. The energy exchange manager oversees energy transactions among participants, ensuring efficient fulfillment of energy needs while maintaining transparency and security in energy flows and financial agreements. Figure 2 highlights energy flows (represented by arrows) as well as energy trading transactions (labeled "Trading"). It underscores the significant role of prosumers in fostering a decentralized energy generation and consumption model.

ENABLING TECHNOLOGIES FOR ENERGY COMMUNITIES

The development of energy communities, driven by advanced technologies, facilitates the decentralization of energy systems and optimizes resource management. The leading tools used are Blockchain and Smart

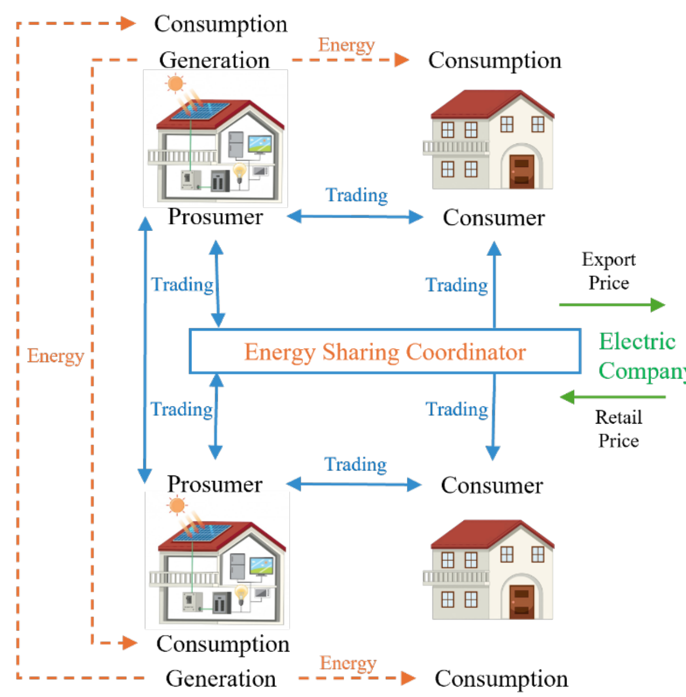

Figure 2. Conceptual Model of P2P Energy Trading in Energy Communities. Source: Adapted from Soto et al. (2021).

Contracts, which enable secure and transparent energy transactions while eliminating intermediaries and lowering operating costs (Andoni et al., 2019; Gu et al., 2023; Zia et al., 2020). These technologies allow prosumers and other market participants to actively engage in decentralized models, automating critical processes such as transaction settlements and energy asset management (Wang et al., 2019).

Transactive Energy is another key enabler, integrating economic and control mechanisms to balance supply and demand in real-time within microgrids and local energy markets (Siano et al., 2019; Zia et al., 2020). Such systems leverage digital and communication technologies to manage Distributed Energy Resources (DERs), fostering prosumer engagement in P2P markets. Successful examples include initiatives like Power Ledger and PROSUME, which demonstrate the transformative potential of these models in both local and international markets (Gjorgievski et al., 2021). Similarly, technologies such as the Internet of Things (IoT) and digitalization improve connectivity among smart devices in homes and businesses. Smart meters and real-time analytics platforms optimize energy generation and consumption, improving energy efficiency and promoting renewable energy adoption (Miglani et al., 2020; Mollah et al., 2021).

Finally, cases in Europe, Australia, and Latin America highlight how these technologies reshape energy markets. Pilot projects have demonstrated their capacity to integrate Renewable Energy, reduce emissions, and advance social cohesion in energy communities (Gjorgievski et al., 2021; Gu et al., 2023; Stefan et al., 2020).

Blockchain and smart contracts: the foundation of energy decentralization

Blockchain technology and Smart Contracts have emerged as pivotal elements in transforming and decentralizing modern energy systems. Blockchain provides a distributed, secure, transparent infrastructure for recording energy transactions, effectively removing intermediaries and reducing operating costs. On the other hand, smart contracts are digital tools that execute energy transactions automatically, reducing the need for intermediaries and minimizing errors (Kumari et al., 2022; Mollah et al., 2021).

In the energy context, these technologies facilitate the implementation of P2P markets, where prosumers can directly trade surplus renewable energy with other users. This encourages local community involvement and boosts economic and environmental sustainability. Examples like the Brooklyn Microgrid project in the United States and Power Ledger in Australia underscore the transformative impact of Blockchain in enabling decentralized energy resource management (Gjorgievski et al., 2021; Sousa et al., 2019). Blockchain also addresses critical challenges such as cybersecurity by employing advanced cryptographic mechanisms to protect user data and ensure the integrity of transactions.

Figure 3 illustrates the architecture of a decentralized energy management system comprising smart meters, data communication lines, and power infrastructure. Each household, including both consumers and prosumers, is equipped with a smart meter that monitors energy consumption or generation in real time. These meters are interconnected through secure digital networks with a central management platform, potentially supported by Blockchain and smart contracts, and communicate with the Distribution System Operator (DSO) infrastructure. The system allows peer-to-peer energy trading while maintaining coordination with the DSO to ensure grid stability and system reliability. Power flows are represented by orange dashed lines, while data flows are shown as solid blue lines. This integrated setup supports automated transactions, efficient load balancing, and increased resilience to local fluctuations in demand or supply. The figure highlights how physical infrastructure and institutional actors are connected through digital tools to activate secure and dynamic decentralized energy markets.

Transactive energy and P2P trading redefining local markets

Transactive Energy and P2P trading are reshaping energy markets by allowing direct exchanges between

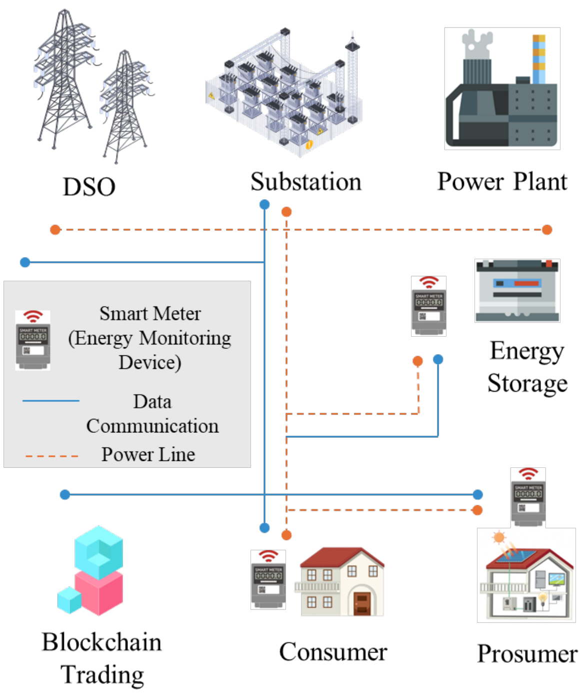

Figure 3. Concept of an Energy Trading System. Source: Prepared by the authors.

consumers and prosumers, eliminating traditional intermediaries, and fostering the decentralization of energy systems. These models harness technologies like blockchain and digital platforms, enabling efficient and transparent real-time trading of renewable energy (Soto et al., 2021). Transactive energy relies on advanced algorithms to dynamically balance supply and demand in local microgrids. These tools optimize energy flow, minimize losses, and support the integration of renewable sources such as solar and wind. Moreover, transactive controllers automatically adjust user consumption based on economic signals, enhancing system sustainability (Siano et al., 2019).

P2P trading, in turn, allows prosumers to maximize the use of their Renewable Energy resources and earn financial benefits by selling excess energy directly to other users. Studies in Colombia emphasize the potential of P2P trading to empower end-users and increase their engagement in the energy market. For instance, the "Transactive Energy Initiative Colombia" has identified user preference structures to design business models that integrate this type of transaction (Cárdenas-Álvarez et al., 2022). Nevertheless, these models face significant regulatory and technological challenges. In Colombia, the absence of specific legal frameworks to regulate decentralized energy transactions constitutes an obstacle to widespread implementation. Likewise, initial infrastructure costs, such as smart meters and digital platforms, limit adoption, particularly in rural and underdeveloped areas (González-Dumar et al., 2024).

In summary, transactive energy and P2P trading offer a unique opportunity to decentralize energy markets and empower consumers. However, to fully realize their potential, adaptive policies and strategic partnerships are critical to overcoming technological and regulatory barriers, especially in emerging contexts like Colombia (Zia et al., 2020).

USE CASES AND INTERNATIONAL EXPERIENCES

The selection of developed countries with very different contexts from Colombia, such as Germany, Denmark, Japan, or Australia, allows us to highlight specific contributions in different decentralized energy systems, providing valuable ideas for Colombia's energy transition as models to follow.

In Europe, Germany is at the forefront of renewable energy governance and citizen-driven initiatives. Its *Energiewende* policy advocates collaborative energy models that involve all stakeholders. Using blockchain technology, Germany is improving transparency and reducing operational costs, setting a benchmark for participatory governance and regulatory adaptation (Mollah et al., 2021). On the other hand, Denmark excels in market-driven energy innovation, particularly through peer-to-peer (P2P) trading platforms. These platforms allow prosumers to trade surplus energy, optimizing supply and demand dynamics and ensuring grid stability. Denmark's success provides a replicable model for the integration of distributed renewable energy systems in Colombia (Wang et al., 2019).

An example from the Asian continent is Japan. This country has been successful in deploying microgrids that integrate solar and distributed storage. These systems ensure continuity of power during emergencies, mitigating the vulnerabilities inherent in centralized grids. This approach is particularly instructive for disaster-prone regions (such as Colombia), highlighting the need for robust and adaptive energy infrastructure (Siano et al., 2019).

Finally, Australia's P2P energy trading platforms, exemplified by initiatives such as Power Ledger, enable direct transactions between prosumers. This model promotes inclusive and sustainable energy markets while reducing reliance on centralized grids. The country's experience aligns with Colombia's goal of empowering local energy communities through decentralized solutions (Wang et al., 2019).

By synthesizing Germany's governance framework, Denmark's market innovations, Japan's resilience strategies, and Australia's P2P systems, Colombia can formulate a comprehensive energy transition plan. This approach could address the country's regulatory, infrastructure, and socioeconomic challenges and open the door to a decentralized and sustainable energy future. International experiences have highlighted the effectiveness of combining advanced technologies, including blockchain and smart contracts, with cooperative models and inclusive regulations. These experiences also underscore the transformative role of emerging technologies in optimizing resource management and building trust among market stakeholders. For example, the use of blockchain in Europe has improved the traceability and security of energy transactions, reinforcing prosumer participation through peer-to-peer trading (Tkachuk et al., 2023).

CONCLUSIONS

Developing energy communities, including Colombia, has become a pivotal strategy for advancing sustainable and decentralized energy systems worldwide. This model democratizes energy access, reduces carbon emissions, and promotes socio-economic sustainability by integrating emerging technologies and adaptive regulatory frameworks.

In Colombia, energy communities offer a strategic opportunity to address long-standing challenges such as energy poverty and limited electrification in rural and non-interconnected regions. The Caribbean region has significant potential for distributed generation due to its abundant renewable resources (Ministerio de Minas y Energía – República de Colombia, 2024).

Nevertheless, the country faces regulatory, technical, and social barriers. Although Law 2099 of 2021 and CREG Resolution 701 of 2024 establish foundations for the creation of energy communities, greater regulatory clarity is needed, as are financing mechanisms to encourage the participation of small-scale prosumers (Ministerio de Minas y Energía – República de Colombia, 2023b). Pilot projects in the Department of Bolívar have demonstrated the viability of such initiatives, underlining the importance of adapting international models to local realities (Departamento Nacional de Planeación – República de Colombia, 2023; Molina et al., 2022). Based on this, we consider that the main strategies to achieve a sustainable energy transition in Colombia would be as follows:

- Strengthening the Regulatory Framework: Design inclusive regulations that incentivize private investment and reduce barriers to adopting emerging technologies.
- Fostering Education and Community Awareness Actions: Implement educational programs to raise awareness in local communities regarding the benefits of renewable energy and decentralized management.
- Developing Public-Private Partnerships: Encourage collaborations among universities, technology companies, and local governments to accelerate the adoption of innovative solutions. Universities

can play a crucial role in research, development, and technical training, ensuring communities have the tools and knowledge necessary to manage their energy resources.

- Investing in Infrastructure and Technology: Prioritize the deployment of smart meters, storage systems, and digital platforms to facilitate P2P trading and the efficient management of energy resources.

The transition toward energy communities in Colombia demands a comprehensive approach that combines technology, regulation, and citizen participation. Universities are called upon to spearhead technical training and public engagement initiatives, bridging technological development and local needs. Their involvement in pilot project design, alongside cooperation with the private and governmental sectors, will be pivotal for ensuring the feasibility and scalability of these initiatives.

In summary, energy communities are drivers of technological change and essential tools for strengthening social cohesion and cultivating a culture of sustainability. Their practical implementation requires a sustained commitment from all sectors, ensuring that the benefits of the energy transition are accessible for the entire Colombian population. Timely and decisive action remains essential to empower communities, strengthen institutional and technological capacities, and drive the transition toward a decentralized and inclusive energy future that guarantees long-term sustainability and social equity.

AUTHOR CONTRIBUTION CRediT

Conceptualization, M.F.M.R. & J.G.F.C.; Data Curation, M.F.M.R.; Formal Analysis, M.F.M.R.; Funding Acquisition, M.F.M.R.; Research, M.F.M.R.; Methodology, M.F.M.R.; Project Management, M.F.M.R. & J.C.M.S.; Resources, M.F.M.R.; Software, M.F.M.R.; Supervision, M.F.M.R. & J.C.M.S.; Validation, M.F.M.R. & J.G.F.C.; Visualization, M.F.M.R. & J.G.F.C.; Writing - review and editing, M.F.M.R., J.C.M.S. & J.G.F.C.

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IMPACT OF NEIGHBORHOOD MORPHOLOGY IN TROPICAL CLIMATES: A CASE STUDY OF THE TRADITIONAL NEIGHBORHOODS OF KANYAKUMARI, INDIA

IMPACTO DE LA MORFOLOGÍA DEL VECINDARIO EN EL CLIMA TROPICAL: UN ESTUDIO DE CASO DE LOS BARRIOS TRADICIONALES DE KANYAKUMARI, INDIA

IMPACTO DA MORFOLOGIA DOS BAIRROS EM CLIMAS TROPICAIS: UM ESTUDO DE CASO DOS BAIRROS TRADICIONAIS DE KANYAKUMARI, ÍNDIA

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ABSTRACT

The morphology of the built environment interacts with the surrounding thermal environment. Thermal interactions affect a neighborhood's energy demand and thermal comfort. The extreme temperatures owing to climate change demand intervention reciprocating in urban heating. Thus, this study analyzed the thermal interaction between morphology and the thermal environment. The study was conducted in the tropical city of Kanyakumari, located in India. The influence of aspect ratio, sky view factor, green cover ratio, and building cover ratio on the Universal Thermal Climate Index was studied. A quantitative analysis of the morphological variables was conducted to establish a relationship with the comfort variable. The aspect and green cover ratios positively correlated with the climate index. In contrast, the sky view factor and building cover ratio had a negative relation with the index. However, when vegetation was introduced in the streets, the interaction between the aspect ratio and the index was reversed, where an increase in aspect ratio reduced the comfort in the canyon by introducing vegetation.

Keywords
morphology, residential area, climate, tropical zones

RESUMEN

La morfología del entorno construido interactúa con el ambiente térmico circundante. Las interacciones térmicas afectan la demanda energética y el confort térmico de un vecindario. Las temperaturas extremas debido al cambio climático exigen una intervención para reciprocar la calefacción urbana. Por lo tanto, este estudio analizó la interacción térmica entre la morfología y el ambiente térmico. El estudio se llevó a cabo en la ciudad tropical de Kanyakumari, en la India. Se estudió la influencia de la relación de aspecto, el factor de vista del cielo, la relación de cubierta verde y la relación de cubierta edificada en el Índice Climático Térmico Universal. Se realizó un análisis cuantitativo de las variables morfológicas para establecer una relación con la variable de confort. Las relaciones de aspecto y cubierta verde se correlacionaron positivamente con el índice climático; por el contrario, el factor de vista del cielo y la relación de cubierta edificada tuvieron una relación negativa con el índice. Sin embargo, cuando se introdujo vegetación en las calles, la interacción entre la relación de aspecto y el índice se invirtió. Un aumento en la relación de aspecto redujo el confort en el cañón al introducir vegetación.

Palabras clave
morfología, zona residencial, clima, zonas tropicales

RESUMO

A morfologia do ambiente construído interage com o ambiente térmico circundante. As interações térmicas afetam a demanda energética e o conforto térmico de um bairro. As temperaturas extremas decorrentes das mudanças climáticas exigem intervenções que repercutem no aquecimento urbano. Assim, este estudo analisou a interação térmica entre a morfologia e o entorno térmico. O estudo foi realizado na cidade tropical de Kanyakumari, localizada na Índia. Foi estudada a influência da relação de aspecto, do fator de vista do céu, da relação de cobertura verde e da relação de cobertura dos edifícios no Índice Climático Térmico Universal. Realizou-se uma análise quantitativa das variáveis morfológicas para estabelecer uma relação com a variável de conforto. As proporções de aspecto e cobertura verde correlacionaram-se positivamente com o índice climático. Em contrapartida, o fator de vista do céu e a proporção de cobertura dos edifícios tiveram uma relação negativa com o índice. No entanto, com a introdução de vegetação nas ruas, a interação entre a proporção de aspecto e o índice foi invertida em áreas onde um aumento na relação de aspecto costumava reduzir o conforto no cânion.

Palavras-chave:
morfologia, área residencial, clima, zonas tropicais

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INTRODUCTION

Indian cities are undergoing significant and continuous development. Currently, the key concern in the design of cities is to mitigate urban heating (Pattacini, 2012) and respond to climate change. There are several aspects involved in this. The energy balance in the canopy layer determines the resultant thermal environment. The heat gain through solar radiation and anthropogenic factors in the absence of advection is equal to heat loss through convection, evaporation, and heat storage. The canyon geometry and thermal properties influence these thermal exchanges in the canopy layer (Oke, 1982). Thus, an optimum built geometry and surface configuration ensure climate-responsive neighborhoods (Oke et al., 1991). However, the urban configuration determines the mitigation strategy. Hence, the design strategy cannot be generalized (Golany, 1996).

Thermal comfort and reducing outdoor air temperature are essential for developing sustainable neighborhoods (Emmanuel & Fernando, 2007). The immediate morphology alters the microclimate of an open space and its interaction with the indoor environment. The built morphology and the thermal environment are interdependent. The Bureau of Energy Efficiency identified that the influence of extreme temperatures combined with economic growth increased energy demand to attain comfort (Bureau of Energy Efficiency, 2023). Hence, the optimum design of the neighborhood morphology aims to create a comfortable environment and reduce energy demand.

Earlier studies critically analyzed the indoor climate to reduce energy demand and improve comfort and air quality, while the current studies highlight outdoor settings for the same (Shafaghat et al., 2016). Hence, a holistic approach is essential to address indoor and outdoor environments as they have a reciprocal relationship.

In a thermal environment study, mean radiant temperature (MRT) needs to be analyzed in addition to air temperature. The analysis of the MRT will ensure comfort (Emmanuel & Fernando, 2007). Hence, a thermal comfort parameter that addresses the effect of solar radiation on perceived human comfort needs to be considered.

The tropics have been analyzed for their relationship between street geometry and microclimate. However, there are fewer studies on the coastal zones of the tropics. Similarly, the intercity microclimate variation has not been discussed (Shafaghat et al., 2016). Although studies address the tropical climate, urban design strategies cannot be generalized (Emmanuel & Fernando, 2007). Therefore, an *in-situ* measurement of the neighborhoods in the city will ensure a sustainable built environment.

The study of morphology for its thermal performance often addresses building, street, and landscape configurations simultaneously (Emmanuel & Johansson, 2006; Sun, 2011; Boukhabla et al., 2013; Tsoka et al., 2020). The positive effects of vegetation on the thermal environment are evident (Tsoka et al., 2017; Lassandro et al., 2019; Tsoka et al., 2020; Zhou et al., 2021). Hence, studies to optimize buildings and streets are critical for improved thermal conditions. In this study, the morphology selected reflected built environment configuration through aspect ratio, sky view factor, green coverage ratio, and building cover ratio. Even though the aspect ratio and sky view factor convey the degree of closure of the urban canyon, the study of the sky view factor was crucial as it can be altered easily (Zhu et al., 2022).

This study used traditional row house settlements in Kanyakumari as a case study to explore the relationship between morphological features and the thermal environment in a tropical setting. The thermal environment was studied using comfort variables at the street and neighborhood scales. The research identified the most effective design for a sustainable neighborhood through statistical analysis in a tropical context.

The analysis was conducted in Nagercoil, a city in Kanyakumari, India. It is located at 8.1° N latitude and 77.4° E longitude. The cultural and geographic features influenced the evolution of the built morphology of Kanyakumari. The city falls under a Tropical wet and dry (Aw) climate according to the Köppen-Geiger Classification and a warm and humid climate according to the National Building Code (NBC, 2016). The city experiences an annual average temperature of 27.2°C, a minimum of 23°C in February, and a maximum of 33.2°C in September. The adaptive thermal comfort was within the range in most months except April. (Figure 1a) The average annual relative humidity was 78.54%, with a minimum of 43% in February and a maximum of 99% in September. The humidity levels were mainly above the thermal band. (Figure 1b) The wind predominantly flows from west to east, reaching up to 5 on the Beaufort Scale. (Figure 1e) A slight wind movement below 1.5m/s can be observed from all directions. (Figure 1f) The city experiences clear skies between January and April. (Figure 1c) In April, heat stress was observed 97% of the time. (Figure 1d) The absence of dense cloud cover during April creates thermal stress. Hence, this study addressed the month with prolonged thermal stress (Betti et al., 2024).

METHODOLOGY

The study intended to establish a relationship between morphology and the thermal environment of Kanyakumari. The traditional neighborhoods of the city were selected for the study. These neighborhoods had row houses facing either north or south. Hence, the principal streets were along the east-west axis. The row houses and north-south orientation reduced heat gain inside the houses (Shankar

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Figure 1. Weather Profile of Kanyakumari. Source: Betti et al. (2024)

Table 1. Methodology. Source: Prepared by the authors.

Aim	Activity	Outcome	Details
Identify	Literature Review	Morphological Variables	Aspect Ratio (H/W)
			Sky View Factor (SVF)
			Green Cover Ratio (GCR)
			Building Cover Ratio (BCR)
		Thermal Environment Variables	Air Temperature 1.5 m
			Globe Temperature
			Relative Humidity
			Wind Movement 1.5 m
	Preliminary Study	Neighborhoods	Kottar (N-1)
			Vadeeswaram (N-2)
			Vadasery (N-3)
Select	Neighborhoods	Orientation	East-West Streets
		Aspect Ratio	Shallow (H/W < 1)
			Narrow (H/W > 1)
		GCR	GCR < 10
			GCR > 10
	Thermal Environment	Comfort Variable	Universal Thermal Climate Index (UTCI)
Process	Field Measurement	Air Temperature	Testo 440 Climate Measuring Instrument and 100 mm Ø Vane Probe
		Globe temperature	Heat Stress WBGT Meter
		Relative Humidity	Heat Stress WBGT Meter
		Wind Movement	Testo 440 Climate Measuring Instrument and 100 mm Ø Vane Probe
		Sky View Factor	Google Street View Application
Analyze	Statistics	Descriptive	Box Plots
			Scatter Plots

& Sundaram, 2023). This morphology exposed the streets to the intense solar radiation. Traditionally, these streets had trees, which were later removed to lay roads. This deteriorated the outdoor thermal environment. This character of the morphology is present only in Vadasery (N-3). Thus, comparing the thermal environment in these neighborhoods will ensure an optimum design strategy for the neighborhoods of Kanyakumari. The city experiences moderate air temperatures, high relative humidity, and wind movement. The weather data indicates that the conditions are ideal throughout the year. However, significant discomfort was also evident during April. The intense solar radiation causes heat gain and needs to be addressed.

A field investigation of three residential neighborhoods was conducted in April 2024 and was quantitatively analyzed. The variables for the study were derived from the literature review. The aspect ratio is the average height divided by the width of the street at a given point of measurement. The sky view factor is the portion of the visible sky to the total sky area from a specific point. These are three-dimensional variables that represent the exposure of the canyon to incoming radiation and wind movement. In two-dimensional variables, the green cover ratio is the fraction of landscaped area to the total area, while the building cover ratio is the ratio of built area to the total area. The green cover alters the thermal environment through evaporative cooling and shading. The built fraction provides shading, and the material property responds to the incoming radiation through stored heat and reflected radiation. The influence of aspect ratio, sky view factor, green cover ratio, and building cover ratio on the Universal Thermal Climate Index movement was analyzed. The field measurements taken at 1.5m and 3m were used to calculate the UTCI. The

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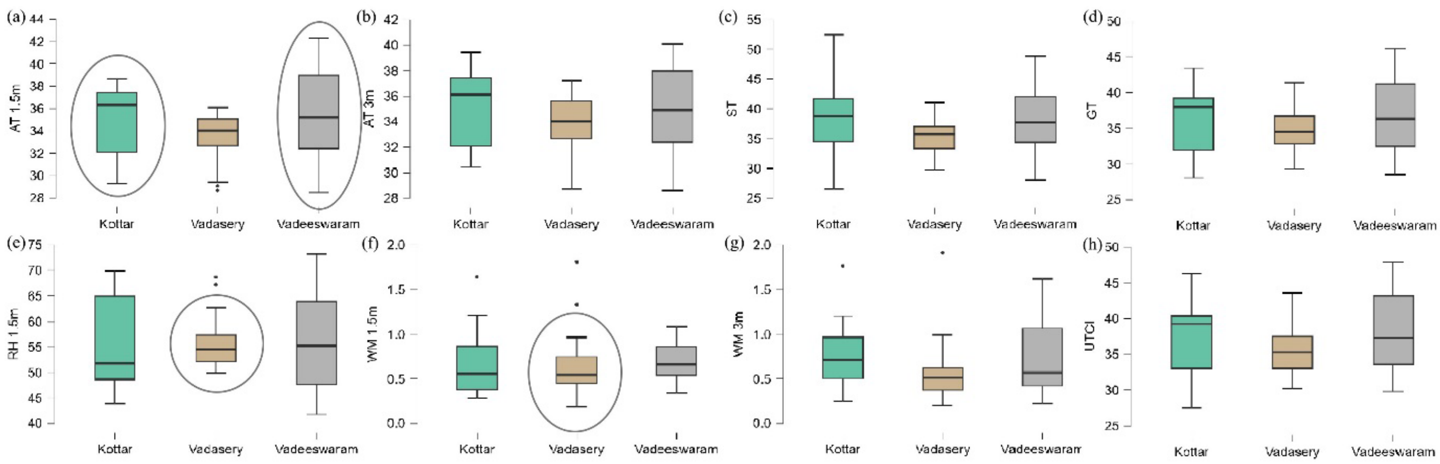

Figure 2. Microclimate Profile of the Neighborhoods. Source: Prepared by the authors.

mixed economic profile of the residential neighborhood ensures similar heat gains through devices and minimal vehicular movement. Hence, the impact of anthropogenic heat was not addressed. A previous study had found no significant difference between the aspect ratios of 1, 2, and 3 (G. Chen et al., 2020). Hence, streets were divided into aspect ratios of less than one and more than one for the analysis. The workflow of the study is described in Table 1.

NEIGHBORHOOD MORPHOLOGY

The neighborhoods are 20 km inland from the sea and surrounded by hills. The neighborhoods were selected based on their similarities in the orientation of streets. The selected neighborhoods were 1.5 km north of each other to ensure similar climatic conditions. The main streets of the neighborhood were aligned on the east-west axis. The intersections connecting them were in a north-south direction. Based on the documented morphological character, the aspect, and green coverage ratios were divided into categories. The streets were used to dry rice grains and yarn in N-1 before extensive development. The streets of N-2 are wide to accommodate processions during festivals. Hence, the size of the street allowed solar radiation and maximum footfall. The street character of N-3 was significantly different from N-1 and N-2 due to trees in the center of the streets. The buildings in the neighborhood were either two or three-story modern or traditional sloped-roof row houses. Hence, the height of the building ranged from 5m to 9m and had a maximum aspect ratio of three.

FIELD MEASUREMENT

April experiences a prolonged duration of heat stress. Hence, the field measurements were taken during this period. The data was recorded between 6 am and 6 pm every three hours. In total, 12 points were analyzed in the city. Neighborhoods 1, 2, and 3 had five, four, and three points, respectively. The measurements were taken at 1.5m to consider the pedestrian level comfort. The instrument was acclimatized for each point and recorded for 5 minutes. The radius of influence of 30 m, 40 m, and 50 m was analyzed in a preliminary analysis. The 50 m radius of influence was found to be more effective. The previous studies analyzed 25m, 50m, 56m, 75m, 100m, 125m, and 565m and found a 50 m radius of influence appropriate (Krüger & Givoni, 2007; Jusuf & Hien, 2012). The neighborhood was mapped for green coverage ratio (GCR), building cover ratio (BCR), and open space ratio (OSR). Since the open space ratio was similar in all the neighborhoods, only GCR and BCR were analyzed.

The air temperature and wind movement were measured through Testo 440 – Climate Measuring Instrument with a 100 mm wireless vane probe. The globe temperature and relative humidity were measured using the TM-188d – Heat Stress WBGT Meter. After processing the image collected through the Google Street View Application, the sky view factor was calculated from fish-eye images through RayMan Pro Version 3.1 (Shankar & Marwaha, 2023). The mean radiant temperature (MRT) was calculated using the formula derived for a 40mm black globe (Vanos et al., 2021; Ouyang et al., 2022). The air temperature, wind movement, relative humidity, and MRT were used to calculate UTCI from its official website.

RESULT AND ANALYSIS

A statistical analysis was conducted to understand the relationship between the morphological variables and the thermal environment. The thermal environment was analyzed through microclimate variables and a comfort variable. The microclimate variables addressed were air temperature, globe temperature, wind movement, and relative humidity. The universal thermal climate index was used to analyze comfort. The analysis was conducted in JASP (JASP Team, 2024).

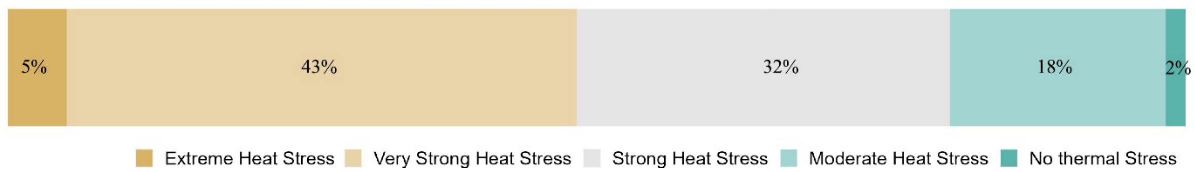

Figure 3. Distribution of UTCI category in the neighborhoods. Source: Prepared by the authors.

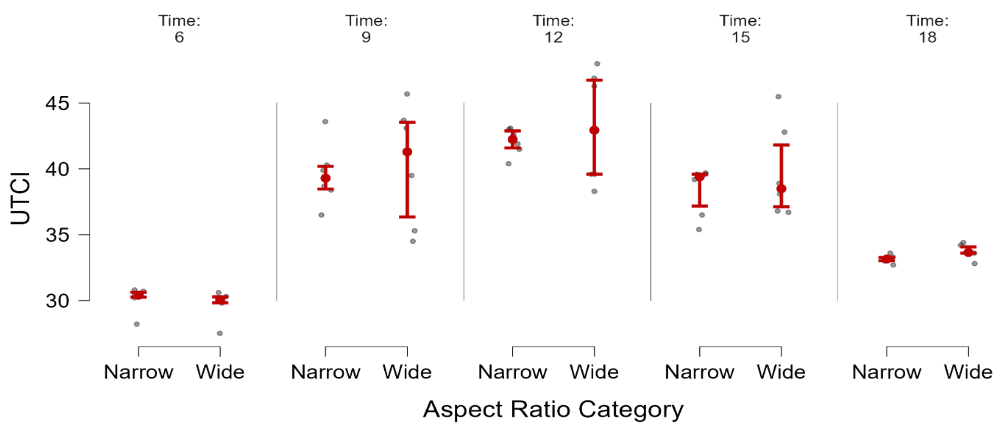

Figure 4. Impact of Aspect Ratio. Source: Prepared by the authors.

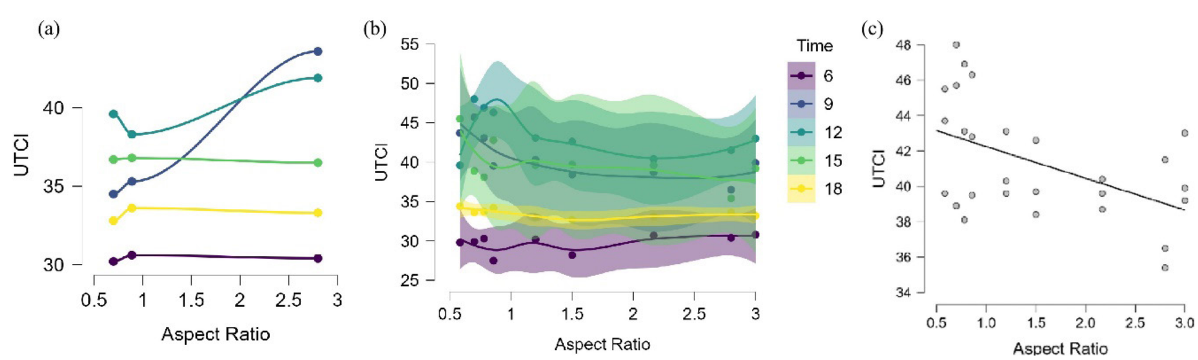

Figure 5. Time series data of Aspect Ratio (a) N-3 (b) N-1 and N-2 (c) Pearson's Correlation for N-1 and N-2. Source: Prepared by the authors.

THE NEIGHBORHOOD

All the neighborhoods showed a similar trend for temperature parameters, as observed in Figure 2. N-3 had a lower thermal range, while N-1 and N-2 experienced the lowest and highest temperatures (Figure 2a, b, c, and d). Hence, N-3 performed better than the other neighborhoods. Similarly, the relative humidity had a higher thermal range in N-1 and N-2, while it was consistently higher in N-3 (Figure 2e). The wind movement was comparatively lower in N-3 (Figure 2f). The mean UTCI suggested that the thermal comfort conditions were better in N-3, followed by N-2 and N-1 (Figure 2h). The UTCI categories were plotted according to their frequency in the neighborhoods in Figure 3. A significant difference from the weather data was evident. In contrast to the weather data, the neighborhoods experienced very strong heat stress of 43% instead of 28.6% (Figure 1), and the city did not experience extreme heat stress in the weather data. Hence, an *in-situ* measurement of the neighborhood will consider the prevalent thermal environment in the neighborhoods of Kanyakumari (Figure 3).

ASPECT RATIO

The two aspect ratio categories were analyzed for their effect on the thermal comfort variable. The wide canyons experienced a larger thermal range, while the narrow ones had a smaller one. The UTCI was higher for wide canyons than for narrow canyons. However, the 6 am data had lower UTCI for wide canyons than

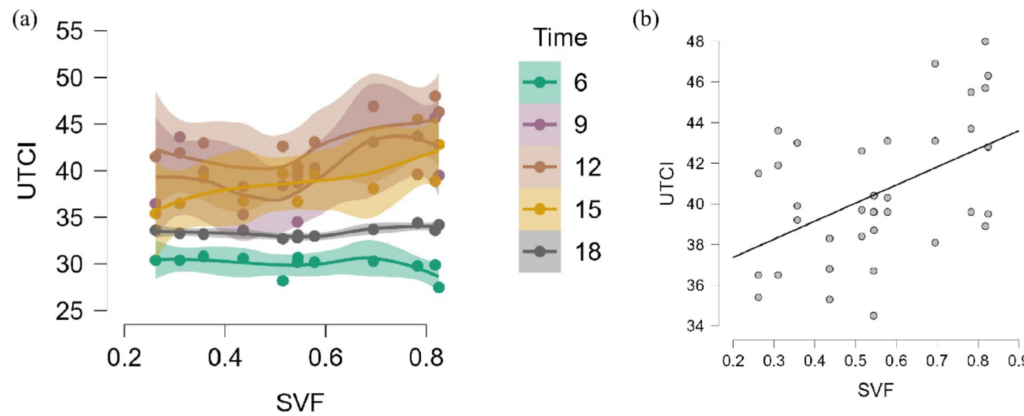

Figure 6. Time series data for all the neighborhoods and correlation plot. Source: Prepared by the authors.

for narrow canyons. The increased exposure in wide canyons enabled a better thermal environment at night. Hence, narrow canyons performed better than wide canyons during the daytime (Figure 4).

The continuous values of the aspect ratio were analyzed to derive the trends (Figure 5). Since the N-3 significantly differed in its thermal range and distribution, it was analyzed separately (Figure 5a). The scatter plots suggested a nonlinear relationship between UTCI and aspect ratio. The graph suggested a minimal change in the 6 am and 6 pm data concerning the aspect ratio (Figure 5b). In N3, the 9 am and 12 pm data highlighted the temperature increase with an increase in aspect ratio. Simultaneously, in N-1 and N-2, an increase in aspect ratio decreased temperature during 9 am, 12 pm, and 3 pm. The contrasting relationship of UTCI between neighborhoods was due to the influence of vegetation. A higher aspect ratio changes the temperature quickly due to increased exposure. However, the presence of vegetation in a narrow canyon captures heat. Hence, shallow canyons were ideal with vegetation, and narrow canyons were ideal without intensive vegetation in the street canyon.

The 6 am and 6 pm data did not show a significant difference. Hence, a correlation analysis was conducted for measurements at 9 am, 12 pm, and 3 pm. Karl Pearson's correlation was conducted as the UTCI had a p-value of 0.269, greater than 0.05 for N-1 and N-2. The Pearson's r was -0.497 with a p-value of 0.008. This suggests a negative relation of (0.497^2) 24.7%, and the null hypothesis can be rejected at a significance level of 1%. Hence, the aspect ratio should be higher for improved comfort in the streets during the daytime. However, the significant effect of shading from the trees played the most crucial role in reducing UTCI. Thus, improved comfort can be achieved through building structure or vegetation shading (Figure 5c).

SKY VIEW FACTOR

The relation between SVF and UTCI was analyzed for all the neighborhoods. A slight increase in UTCI can be observed between 9 am and 3 pm. Figure 6a shows a reduction in UTCI between 0.4 and 0.6 at 9 am and 12 pm. Also, there was no significant change in the 6 am and 6 pm data. Hence, the morning and evening data were omitted for further analysis (Figure 6a). The UTCI was normally distributed with a p-value of 0.089. Pearson's Correlation, a parametric test, was conducted since the p-value was greater than 0.05. The correlation analysis suggested a Pearson's r of 0.489 with a p-value of 0.002. Hence, there is a ($0.489^2 = 0.239$) 23.9% positive relationship with a 1% significance level. The daytime UTCI will increase with an increase in the sky view factor (Figure 6b). Thus, the sky view factor of more than 0.6 is detrimental to the daytime thermal environment.

GREEN COVER RATIO

The green coverage ratio was analyzed based on two categories. The GCR greater than 10% has a gradual increase in UTCI. However, the increase was instantaneous when the GCR was less than 10%. The maximum temperature was experienced at noon when the GCR was less than 10%. The nighttime temperature was slightly higher when GCR was greater than 10% (Figure 7). The thermal range was higher in higher green coverage due to differential heating in the neighborhood. A higher green coverage ratio positively affected the daytime thermal environment. The maximum green coverage studied in this analysis was only 20%. Hence, a higher green coverage ratio needs to be analyzed.

The relationship between green coverage and UTCI was analyzed over time. The 6 am and 6 pm data showed no significant trend (Figure 8a). However, the data between 9 am and 3 pm showed a decrease in UTCI with an increase in GCR (Figure 8b). The 9 am and 12 pm data followed

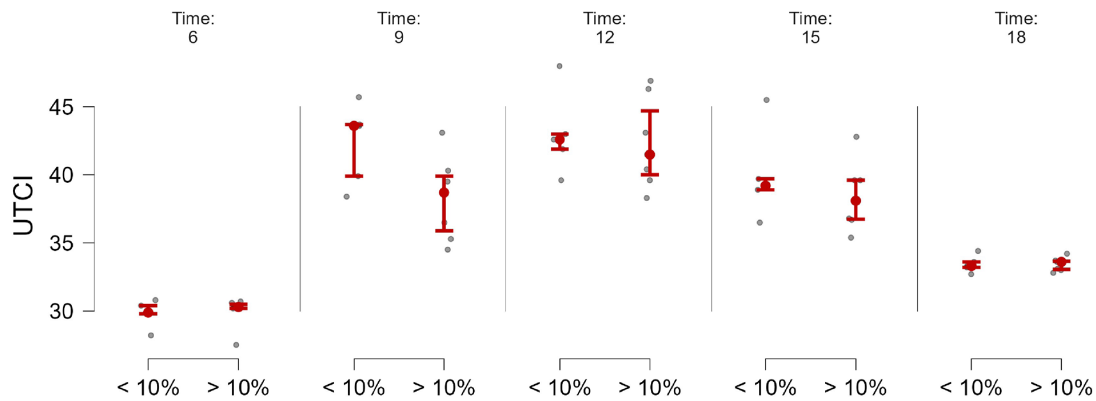

Figure 7. Impact of Green Coverage Ratio. Source: Prepared by the authors.

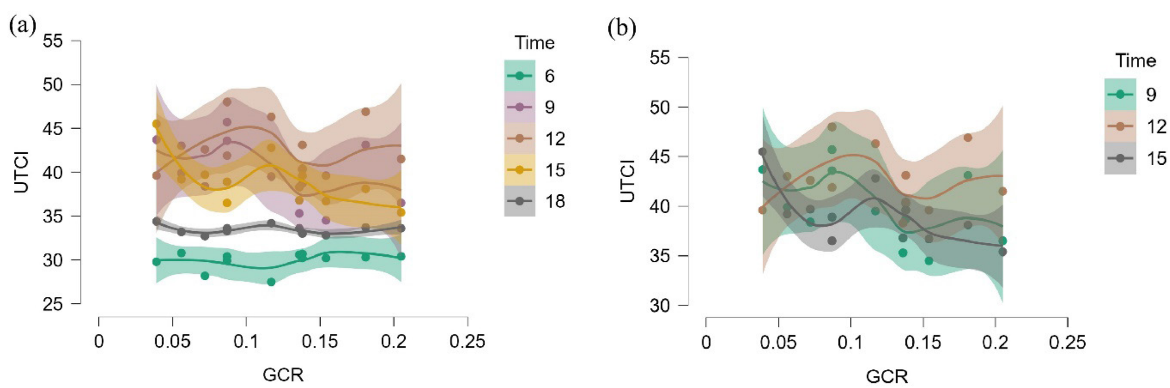

Figure 8. Time series data of the neighborhood (a) 6 am to 6 pm, (b) 9 am to 3 pm. Source: Prepared by the authors.

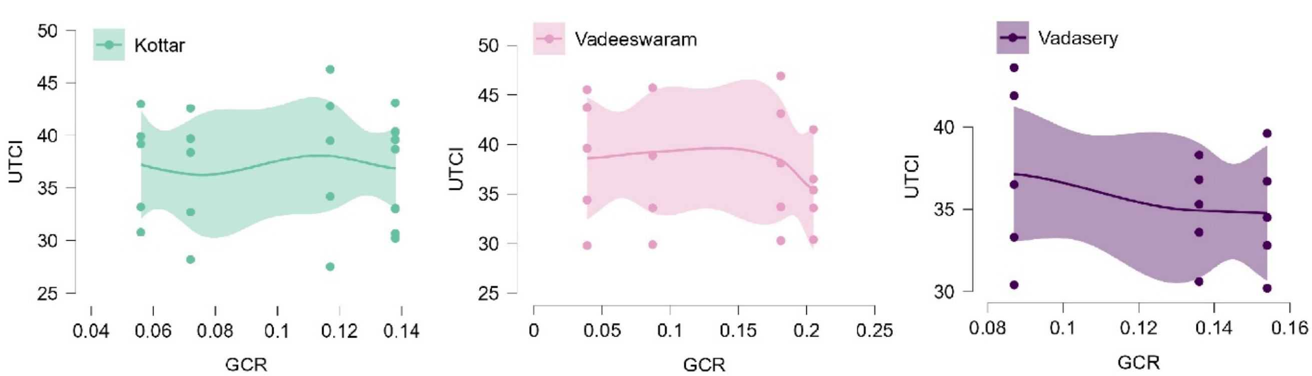

Figure 9. UTCI in the three neighborhoods N-1 - Kottar, N-2 - Vadeeswaram and N-3 – Vadasery. Source: Prepared by the authors.

similar maximums and minimums. While at 3 pm, the reduction was delayed with an increase in GCR. This suggests heat retention in areas with higher vegetation. The decrease in temperature is most prominent in N-3 (Figure 9). Hence, the vegetation in the street canyon led to a reduction in UTCI and significantly improved the thermal environment due to shading. However, a correlation between GCR and UTCI was not established.

BUILDING COVER RATIO

The relation between BCR and UTCI was analyzed. The analysis did not include the 6 am and 6 pm data, as no significant trend existed (Figure 10a). The increase in UTCI with an increase in BCR was established in Figure 10(b). The UTCI was normally distributed. Hence, a Pearson's r correlation was conducted on the data collected between 9 am and 3 pm. The value of Pearson's r was 0.422, with

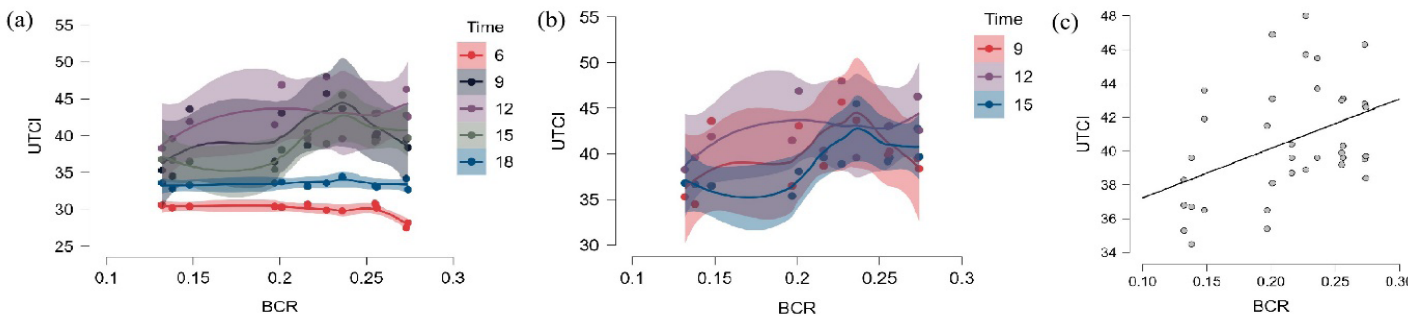

Figure 10. Time series data and correlation between BCR and UTCI. Source: Prepared by the authors.

a p-value of 0.010. Thus, BCR and UTCI have a positive relation of 17.8% and can reject the null hypothesis at a 5 % significance level. Thus, an increased fraction of the built environment will deteriorate the daytime thermal environment. Even though BCR, GCR, and OSR are three segments of a whole. The BCR established a significant correlation with the UTCI rather than the GCR (Figure 10c).

CONCLUSION

The neighborhood geometry was analyzed to address the summer heat stress in Kanyakumari. The influence of aspect ratio, sky view factor, green cover ratio, and building cover ratio on the Universal Thermal Climate Index was established. An increase in aspect ratio increases comfort during daytime, as observed in a similar study conducted in tropical cities (De & Mukherjee, 2018; Sharmin et al., 2019; Jamei et al., 2020). This case was valid in the absence of vegetation. However, vegetation in the neighborhood had an inverse effect on thermal comfort. An increase in aspect ratio decreased the thermal comfort when the street canyon had vegetation. This aligns with the study conducted in the coastal area of Sri Lanka (Emmanuel & Johansson, 2006). Moreover, a reduction in wind movement was observed when vegetation was introduced. Hence, a study suggested vegetation should not hinder wind movement to provide shade (S. Chen et al., 2020). The sky view factor had a positive relationship with the comfort variable. An increase in SVF led to an increase in daytime temperature variables. This aligns with the study conducted in similar climatic conditions (Sharmin et al., 2019; Yu et al., 2020). The ameliorating effect of vegetation was established as the shading effect of vegetation played a significant role in attaining comfort, similar to other studies (Johansson et al., 2004; Sun, 2011). An increase in building coverage reduces thermal comfort. Hence, a similar study recommended sparsely spaced tall buildings (De & Mukherjee, 2018).

This study attempted to understand the thermal interaction between 2D and 3D morphology and the surrounding environment in Kanyakumari. The study intended to reduce heat stress experienced by a coastal city in a tropical climate. Finally, shading was found to be a significant contributor to attaining thermal comfort. A higher aspect ratio and GCR, as well as lower SVF and BCR, were found to be ideal for developing a sustainable neighborhood. Additionally, the impact is reversed when vegetation is introduced into the morphology. Hence, lower aspect ratios are recommended when trees are introduced in the street canyon. In this study, the effect of orientation was not analyzed. Also, the influence of anthropogenic heat was avoided. Hence, future studies should address the impact of orientation and anthropogenic heat.

AUTHOR CONTRIBUTION CRediT

Conceptualization, M.S.; Data Curation, M.S.; Formal Analysis, M.S.; Funding Acquisition; Research, M.S.; Methodology, M.S. and A.M.S.; Project Management, A.M.S.; Resources, M.S.; Software. M.S.; Supervision, A.M.S.; Validation, M.S.; Visualization, M.S.; Writing-original draft, M.S.; Writing-review and editing; Writing-revision and editing, A.M.S.

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ASSESSING OUTDOOR THERMAL COMFORT IN HIGH-DENSITY URBAN KAMPUNGS IN TAMANSARI, BANDUNG: A MICROCLIMATE SIMULATION STUDY

EVALUACIÓN DEL CONFORT TÉRMICO EXTERIOR EN KAMPUNGS URBANOS DE ALTA DENSIDAD EN TAMANSARI, BANDUNG: UN ESTUDIO DE SIMULACIÓN DEL MICROCLIMA

AVALIAÇÃO DO CONFORTO TÉRMICO AO AR LIVRE EM KAMPUNGS URBANOS DE ALTA DENSIDADE EM TAMANSARI, BANDUNG: UM ESTUDO DE SIMULAÇÃO DO MICROCLIMA

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ABSTRACT

Urban kampungs, characterized by dense, organically developed settlements, present unique challenges in outdoor thermal comfort. This study investigates how key physical variables—building arrangement, surface materials, and vegetation—impact the microclimate of outdoor spaces in Tamansari, Bandung, using ENVI-met 4 simulations. The findings reveal that material reflectivity significantly influences air temperature, with lower-albedo paving proving more effective in reducing heat accumulation. Compact building arrangements with a high height-to-width ratio provide essential shading, mitigating heat stress, while strategically placed vegetation enhances shading and wind flow, contributing to improved thermal comfort. These insights offer valuable guidelines for architects and urban planners designing climate-responsive, high-density urban environments. The study underscores the importance of integrating passive cooling strategies to improve outdoor livability in urban kampungs, especially in tropical climates.

Keywords
urban kampung, outdoor thermal comfort, performance simulation, ENVI-met, high-density settlement

RESUMEN

Los asentamientos urbanos, caracterizados por asentamientos densos y desarrollados orgánicamente, presentan desafíos únicos para lograr el confort térmico al aire libre. Este estudio investiga cómo las variables físicas clave (disposición de los edificios, materiales de la superficie y vegetación) afectan el microclima de los espacios al aire libre en Tamansari, Bandung, utilizando simulaciones ENVI-met 4. Los hallazgos revelan que la reflectividad del material influye significativamente en la temperatura del aire, y que los pavimentos con un albedo más bajo resultan más efectivos para reducir la acumulación de calor. Las disposiciones de edificios compactos con una alta relación altura-ancho brindan un sombreado esencial, mitigando el estrés térmico, mientras que la vegetación ubicada estratégicamente mejora tanto el sombreado como el flujo del viento, lo que contribuye a mejorar el confort térmico. Estos conocimientos ofrecen pautas valiosas para los arquitectos y planificadores urbanos que buscan diseñar entornos urbanos de alta densidad que respondan al clima. El estudio resalta la importancia de integrar estrategias de refrigeración pasiva para mejorar la habitabilidad al aire libre en los kampungs urbanos, particularmente en climas tropicales.

Palabras clave
asentamiento urbano, confort térmico al aire libre, simulación de rendimiento, ENVI-met, asentamiento de alta densidad

RESUMO

Os assentamentos urbanos, caracterizados por assentamentos densos e desenvolvidos organicamente, apresentam desafios únicos em termos de conforto térmico ao ar livre. Este estudo investiga como variáveis físicas importantes — disposição dos edifícios, materiais de superfície e vegetação — afetam o microclima dos espaços ao ar livre em Tamansari, Bandung, utilizando simulações ENVI-met 4. Os resultados revelam que a refletividade dos materiais influencia significativamente a temperatura do ar, com pavimentos de baixo albedo se mostrando mais eficazes na redução do acúmulo de calor. O arranjo compacto dos edifícios, com uma alta relação altura/largura, proporciona sombreamento essencial, mitigando o estresse térmico, enquanto a vegetação estrategicamente posicionada aumenta o sombreamento e o fluxo de vento, contribuindo para melhorar o conforto térmico. Essas informações oferecem diretrizes valiosas para arquitetos e urbanistas que projetam ambientes urbanos de alta densidade e que respondem às mudanças climáticas. O estudo ressalta a importância de integrar estratégias de resfriamento passivo para melhorar a habitabilidade ao ar livre em kampungs urbanos, especialmente em climas tropicais.

Palavras-chave:
assentamentos urbano, conforto térmico ao ar livre, simulação de desempenho, ENVI-met, assentamento de alta densidade

INTRODUCTION

Architects and city planners, to face the population's concerns regarding the environment and climate change, are now considering the urban micro-climate in their planning constraints, especially the intervention of outdoor spaces. In urban areas, particularly in Urban Kampungs, outdoor spaces are essential for sustaining habitats because they accommodate pedestrians, cyclists, and varied outdoor activities to contribute to urban livability (Johansson & Emmanuel, 2006). Studies have demonstrated that urban morphology, including street orientation and building configuration, directly impacts outdoor thermal comfort by regulating solar radiation exposure and wind circulation (Taleghani et al., 2014).

Urban kampungs are settlements that existed long before formal urban planning emerged. Developed informally, they are characterized by traditional features and irregular structures, while small building coverage, dense massing arrangement, narrow alleys, and organic development are features of urban Kampung houses. The concept of kampungs arose because of family growth in an area with limited land and economic issues (Asriana et al., 2024; Hamidah et al., 2017; Rochmania & Sukmawati, 2024). They are common in most developed Southeast Asian cities, such as Jakarta, Bandung, Bangkok, and Manila. Initial observations in the case studied here, the Tamansari Urban Kampung, Bandung, show many social activities within closely spaced houses, with children playing in the street and small squares around the houses. In a setting of tight spaces, outdoor typology, narrow streets, and small squares, intimate outdoor activity between inhabitants is escalated. This sense of community is a valuable social aspect of urban kampung settlements, contributing to social resilience in the city. Hence, improving outdoor communal spaces would support social cohesion and elevate the overall habitability of the urban kampung.

The time inhabitants spend in outdoor spaces often reflects their subjective satisfaction with the thermal comfort level. People's perception of comfort is not solely driven by physical measurements such as temperature and humidity, but also by physiological and cultural factors (Nikolopoulou & Steemers, 2003). For instance, in urban kampung settlements, the acceptance of varying thermal conditions might be higher due to the social acceptance of outdoor living. So, this study explores how shaded areas, natural ventilation, and green elements can significantly enhance the inhabitants' perceived thermal comfort and encourage more outdoor activity even in warm climates.

People expect different thermal comfort experiences in indoor and outdoor spaces. Their expectations vary depending on exposure circumstances, such as sun and shade variants, wind speed and direction, changes in humidity rate, direct and indirect radiation, etc. (Givoni et al., 2003; Wang & Su, 2025). The external environment significantly affects how people live, and it is determined by natural conditions, anthropogenic factors, the density of urban construction, the size of vegetation areas, etc. (Klemm, 2007). Enhancing outdoor thermal comfort can also impact health and well-being, promote physical activities, and increase social interactions (Abaas, 2020; van den Bosch & Ode Sang, 2017).

Researchers have extensively studied thermal comfort conditions in urban environments. Liu found that in the last 23 years, there have been 632 articles in the Web of Science and Scopus using a similar keyword (Liu et al., 2023; Mandić et al., 2024). However, limited attention has been given to informal, high-density settlements characterized by urban kampungs. This study seeks to address this gap by simulating outdoor thermal comfort in urban kampungs and defining the role of their unique physical conditions. By modeling the site with an understanding of existing building arrangements, surface material, and vegetation, this study aims to provide insights into optimizing outdoor spaces in high-density settlements. The findings could offer valuable guidelines for urban planners to create better thermal comfort and well-being in urban kampungs.

MICROCLIMATE THERMAL COMFORT

This section outlines the approach to improving outdoor thermal comfort conditions in urban environments. The physical parameters include environmental factors such as the mean radiant temperature (MRT), air temperature, wind speed, and relative humidity. Recent studies emphasize that, in high-density urban settlements, MRT plays a critical role in determining thermal sensation compared to air temperature alone. In compact environments like urban kampungs, narrow streets, dense building masses, and limited vegetation amplify solar radiation, increasing MRT and causing greater heat stress even with moderate air temperatures. Moreover, research by Gallardo et al. (2016) highlights that even small increases in natural ventilation can significantly enhance perceived thermal comfort in warm, humid climates. Wind speeds of merely 0.3-1.0 m/s also improve comfort perception when combined with shading or surface cooling strategies. Research has proven that physical intervention affects urban microclimates and that these changes in the urban environment result in thermal comfort. To improve thermal comfort, inhabitants can adjust physical factors like building arrangement, materials, vegetation, and water features (Cheng et al., 2022; Liao et al., 2024; Pamungkas et al., 2024; Rodriguez et al., 2025; Uno et al., 2018; Zhang et al., 2025). The following section explains how this factor decreases inhabitants' heat stress in microclimates.

BUILDING ARRANGEMENT

In blocks of buildings, alley surfaces receive solar radiation, which influences outdoor thermal atmospheres and

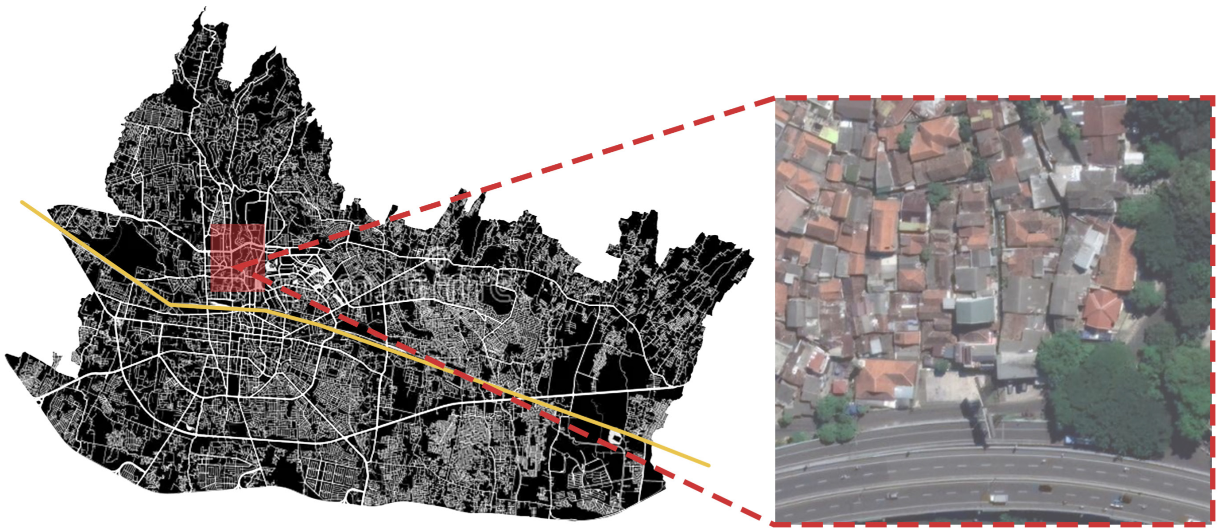

Figure 1. Assessment location, Kampung Tamansari, Bandung. Sources: Google Earth, modified by the Authors

affects an alley's thermal sensitivities. However, there are significant differences between human thermal comfort sensation values in sunny and shaded areas due to the solar radiation (Aleksandrowicz & Pearlmutter, 2023; Kim et al., 2024; Murakami, 2006).

Shashua-Bar and Hoffman (2000) introduced the "spacing ratio" (buildings' distance parallel to street/building length parallel to street orientation) to quantify the separated form. This follows the basic street form pattern and morphological indicators. Studies have addressed the solar access index of street canyons, such as in the urban kampung's negative space, using H/W ratios in variable values with E-W and N-S street orientation (Arnfield, 1990). These fundamental indicators were used to set up the case study with H/ W of 0.5, 1, 2, 4, and E-W, N-S, NE-SW, and NW-SE orientations (Ali-Toudert & Mayer, 2006).

Wind-induced pressure distributions are another aspect of building arrangement. These depend on many factors in the urban environment, such as the condition of the approach flow, the wind direction, the urban structure's geometry, and the urban surroundings (Montazeri & Blocken, 2013; Setaih et al., 2013).

Surface material

Using less absorptive (high albedo) materials is a practical, promising technique to reduce the thermal environment's effect on pedestrian comfort. High albedo surfaces reflect a greater portion of incoming solar radiation, thereby reducing the amount absorbed and stored as heat in urban environments. It is characterized by the ability of environmental surfaces to absorb incoming solar radiation in urban environments (Akbari et al., 1992; Baniassadi et al., 2018; Fintikakis et al., 2011). On the other hand, white and lighter-color surfaces can enhance thermal comfort by reducing ambient temperature. Research evidence has indicated that increasing the solar reflectance of materials by 0.25 significantly reduces the material's temperature by 10°C, as it keeps the structural surfaces cooler under the sun, thus reducing heat convection from the material to the ambient air (Akbari et al., 2001; Setaih et al., 2013; Synnefa et al., 2011). While the principle remains valid in tropical regions like Bandung, empirical studies suggest that temperature reductions due to albedo improvements may be slightly moderated due to consistently high baseline humidity and diffuse radiation effects (Benrazavi et al., 2016; Liu et al., 2023).

Vegetation

One of the most common and effective methods of improving outdoor pedestrian thermal comfort in urban spaces is planting vegetation and trees in available open spaces. Such an intervention can lessen the sun's heat gain, providing cooling through both shading and evapotranspiration (Dimoudi & Nikolopoulou, 2003). Empirical studies have demonstrated the strong role of vegetation in modifying urban microclimates. For instance, Picot (2004) observed that urban parks in hot climates reduce local air temperatures by up to 2- 3 °C compared to adjacent built-up areas. Similarly, Mahmoud (2011) reported that shaded areas under tree canopies exhibited a lower mean radiant temperature (MRT) than unshaded spaces.

The great advantage of tree cover is the cooling effect from the joint impact of evapotranspiration (ET) and canopy shading (Kim & Lee, 2024; Kim et al., 2024; Shashua-Bar & Hoffman, 2000). Beyond its aesthetic role and pleasant natural perception, increasing greenery in urban areas represents a significant mitigation technique as it helps reduce heat stress, blocks out noise, improves air quality, and protects people from the wind, making it an essential component of climate-resilient urban design

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Figure 2. Current Situation in Kampung Tamansari. This shows typical building height and street width. The settlement (top) inside has a high H/W ratio, and the perimeter (bottom) has a low H/W ratio. Sources: Photographs taken by the Authors.

(Fintikakis et al., 2011; Liu et al., 2023). Recent simulation studies reveal that vegetation cooling's effectiveness is highly dependent on corridor geometry. In canyons with higher H/W ratios, trees' shading impact becomes more pronounced, enhancing reductions in both air temperature and MRT. In their simulation, vegetation is more effective for corridors with a W-E orientation than other orientations (Liu et al., 2023; Suryantara et al., 2019).

METHODOLOGY

The case study was conducted in Tamansari (Figure 1), an urban kampung located in Bandung, Indonesia (6°53›50.5»S 107°36›31.2» E). Bandung covers a total area of 16.729,65 hectares and has a population of 2,579,837 people in 2023, making it one of the most densely populated cities in Indonesia with a density of 15,051 people/km^2. Tamansari exemplifies the morphological characteristics of urban kampungs in Southeast Asia, where outdoor spaces undeniably express diverse social interactions (Figure 2).

The effect of outdoor features on thermal comfort is analyzed through microclimate simulation using ENVI-met 4 software. It is important to note that this study did not use a calibrated model. No field-measured data were incorporated for calibration or validation purposes. Instead, the simulation model uses constant meteorological conditions set manually based on local climatology data.

The selected simulation domain is 60 m (x) x 60 m (y) x 15 m (z) with a spatial resolution of 1m per grid. Default environmental parameters are used, but because the study location is not available in the software, the longitude and latitude of the location are set manually. Due to the location, some location-dependent physical parameters such as temperature, humidity, and wind speed are set based on data from BMKG Indonesia (Badan Meteorologi, Klimatologi dan Geofisika) or the Indonesian Agency for Meteorology, Climatology and Geophysics. The environmental parameters used were air temperature (23°C-33°C, average 27°C), relative humidity (47-89%, average 48%), and wind speed was set at 1 m/s from east to west. The simulation was run for 18 hours, from 4:00 until 22:00. Because the location is in the southern hemisphere, the day chosen for the calculation is the summer solstice for the southern hemisphere, which is on December 21st, the hottest day of the year.

The base model used existing concrete paving with an albedo of 0.25, representing standard grey surfaces under real conditions. These values were applied across ground surfaces, including streets, pavement, and communal spaces. Vegetation was modeled as three-dimensional volumetric objects, as in its real-life condition, accounting for leaf area density (LAD), tree height, and crown shape. ENVI-met simulates vegetation as dynamic microclimate agents that influence solar shading, evapotranspiration, and wind flow. As Bruse & Fleer (1998) suggested, these parameters allow the model to simulate the vegetation's effect on temperature and airflow more realistically. The existing vegetation on-site, mostly medium-sized trees with broad canopies, was integrated into the simulation, and additional greening scenarios were explored to assess their impact on outdoor thermal conditions.

The simulation aimed to isolate and compare the effects of building configuration (H/W ratios and orientation), surface material (albedo variation), and vegetation patterns on outdoor microclimate conditions. The simulation evaluates diffuse, direct, and reflected shortwave (SW) radiation, wind speed, and the mean radiant temperature (MRT). These parameters are crucial for understanding thermal comfort. Diffuse SW Radiation contributes to the radiant heat load even in shaded conditions. Direct SW

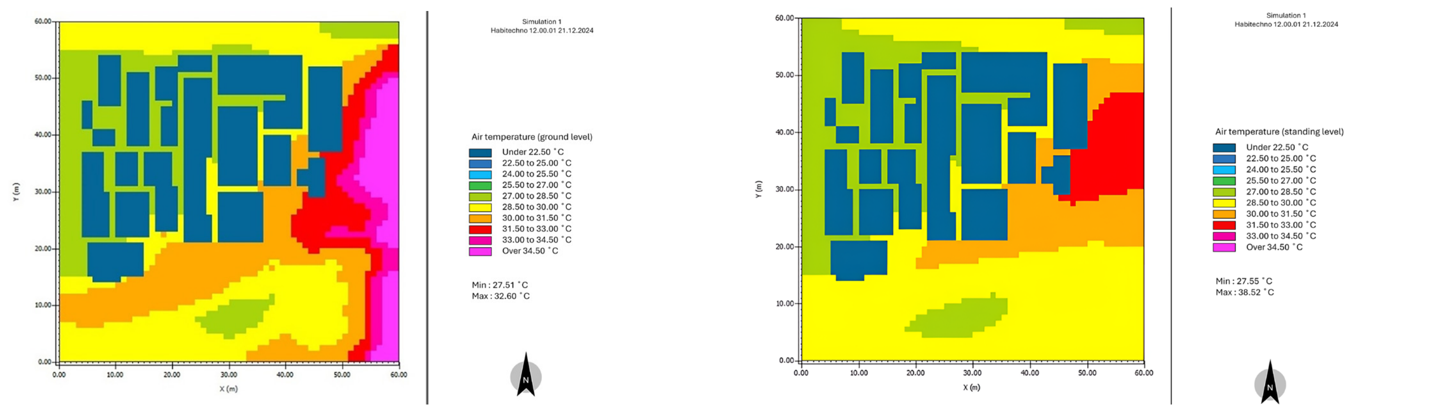

Figure 3. (A) Reflected Radiation at Ground Level; (B) Reflected Radiation at a Standing Level. Sources: Prepared by the Authors.

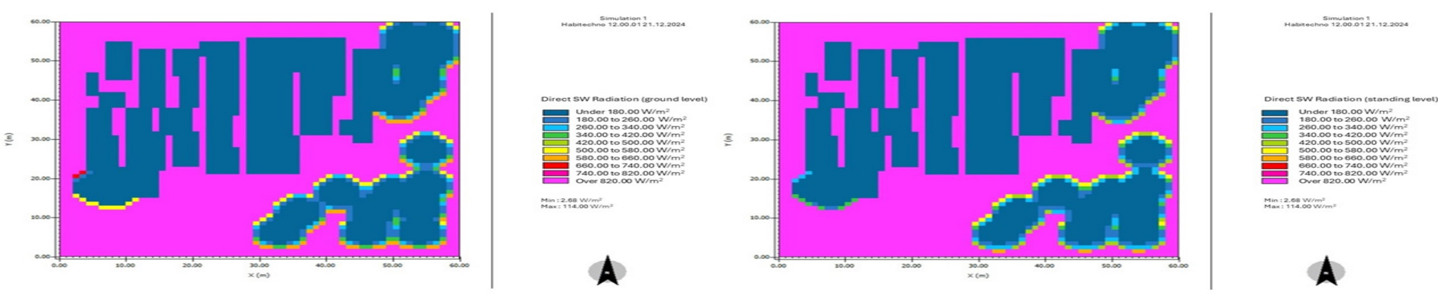

Figure 4. (A) Direct SW Radiation at Ground Level. (B) Direct SW Radiation at a Standing Level. Sources: Preparation by the Authors.

radiation can significantly increase surface temperatures. Reflective SW radiation measures the portion of solar radiation reflected from the urban surface. Wind speed influences convective cooling and air circulation. The results provided insights into temperature distribution, mean radiant temperature (MRT), and wind speed, which are crucial contributors to perceived outdoor thermal comfort. MRT represents the combined effect of all radiation sources on human thermal perception.

The simulation compared temperature variations at both ground (0.5 m) and standing level (1.5m). Ground level provides insights into the thermal environment by seating children and accumulating ground-surface heat. Standing level represents the average height of an adult pedestrian and critical thermal exposure during typical outdoor activities. Evaluating both ensures a comprehensive understanding of the key factors for outdoor thermal comfort and leads to more precise and context-sensitive urban design recommendations.

RESULTS AND DISCUSSION

TEMPERATURE DISTRIBUTION AND SURFACE MATERIALS

Air temperature analysis reveals a significant difference between ground level and standing level. Figure 3 shows that the temperature near the ground is consistently higher than 1.5 meters above ground level. This variation is primarily attributed to surface materials' reflectivity (albedo). In this simulation, the surface covering material used for the corridor is concrete with high albedo, as in the real-life scenario. High-albedo materials increase heat accumulation in urban areas, exacerbating thermal stress (Synnefa et al., 2007).

Further examination of solar radiation (Figure 3 and Figure 4) indicates that direct and diffuse radiation do not significantly differ between the two heights. There are differences between radiation values in areas with a <1 H/W ratio at a standing and a ground level, as shown in the highlighted rectangular area (Figure 3). Reflected shortwave (SW) radiation (Figure 5) shows a noticeable ground-level increase. Since there is no specific standard number for this radiation, this study examines the values at different height levels. This result indicates that the dependence between the floor surface and the H/W ratio contributes to elevated ambient temperatures.

Effects on Building Arrangement

An E-W street orientation gains 30-36 °C at ground level and 33-39°C at standing level on >1 H/W ratio, and a N-S street orientation has a 42- 48°C MRT range at ground

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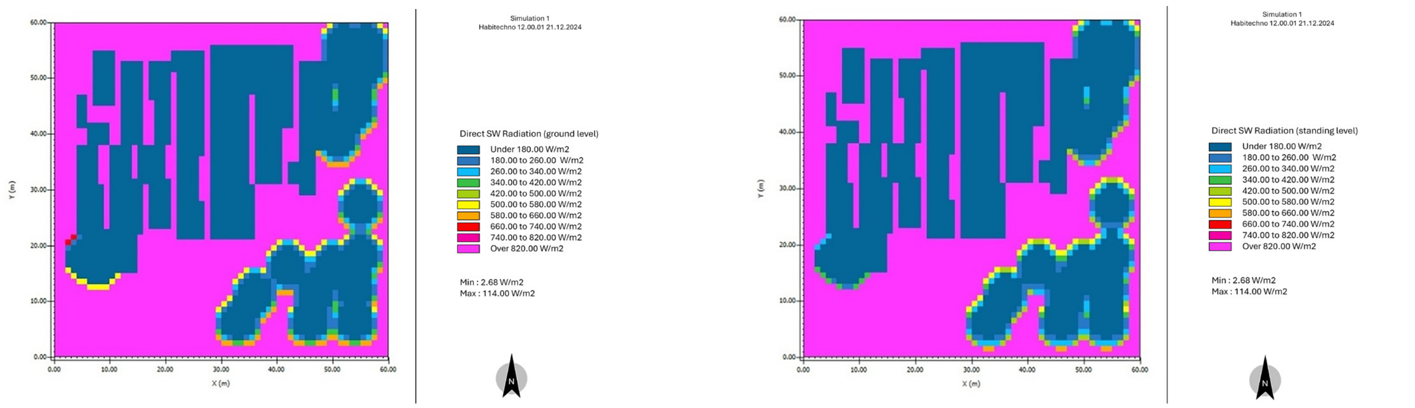

Figure 5. (A) Reflected SW Radiation at Ground Level. (B) Reflected SW Radiation at a Standing Level. Sources: Preparation by the Authors.

Table 1. Values of different H/W ratios and MRT ranges. Sources: Preparation by the Authors.

H/W Ratio	Street orientation	MRT range ground level (˚C)	MRT range standing level (˚C)
0.83	E-W	48-51	51-54
1.66	E-W	33-36	36-39
2.5	E-W	30-33	33-36
5	E-W	30-33	33-39
1.25	N-S	45-48	51-54
2.5	N-S	45-48	51-54
5	N-S	42-45	51-54

level and 51-54˚C at standing level (Table 1). Normal MRT should be less than 40˚C (Nikolopoulou & Steemers, 2003; Pamungkas et al., 2024), which makes E-W street orientation more comfortable than N-W. This result differs from other previous studies where E-W street orientation creates a more uncomfortable thermal condition than N-E.

This result shows that building arrangement and H/W ratio are critical in modifying thermal conditions through shading. The simulation results confirm that the streets' height-to-width (H/W) ratio influences shading efficiency. In this case study, the sun's path is slightly above the equator, so the sunlight falling on the building mass north of the road casts shadows on the E-W street. Moreover, N-S streets with an H/W ratio of>1 provide more shading, effectively reducing MRT on the ground and standing level (Figure 5). Building arrangements also significantly influence shading efficiency. Previous studies indicate that an H/W ratio >1 provides effective shading, minimizing direct solar radiation exposure (Taleghani et al., 2014; Ali-Toudert & Mayer, 2006).

Furthermore, street orientation affects solar access on the street corridor. As a previous study suggests (Ali-Toudert & Mayer, 2006), East-West orientations prove more effective in providing shade and enhancing thermal comfort. This orientation creates more expansive shaded areas throughout the day, reducing heat exposure to pedestrian paths and public spaces. Studies in tropical cities, such as those conducted by Johansson and Emmanuel (2006), confirm that suitable urban layouts can significantly mitigate heat stress, particularly when integrated with vegetation and built-form shading.

Vegetation and Wind Flow

This simulation shows differences in wind speed at ground and standing level in the settlement's perimeter and interior outdoor areas. The perimeter has a wide main road, an H/W ratio <1, and contains a group of trembesi trees, while the interior outdoor has an H/W ratio >1. In areas with an H/W ratio >1, wind speed remains stable at 0.15-0.45 m/s, whereas in areas with an H/W ratio <1, wind speed varies between 0.3-1.2 m/s at both ground level and standing level (Figure 6).

Vegetation contributes to both shading and wind flow regulation. This simulation reveals that wind speed is generally higher at the standing level than at the ground

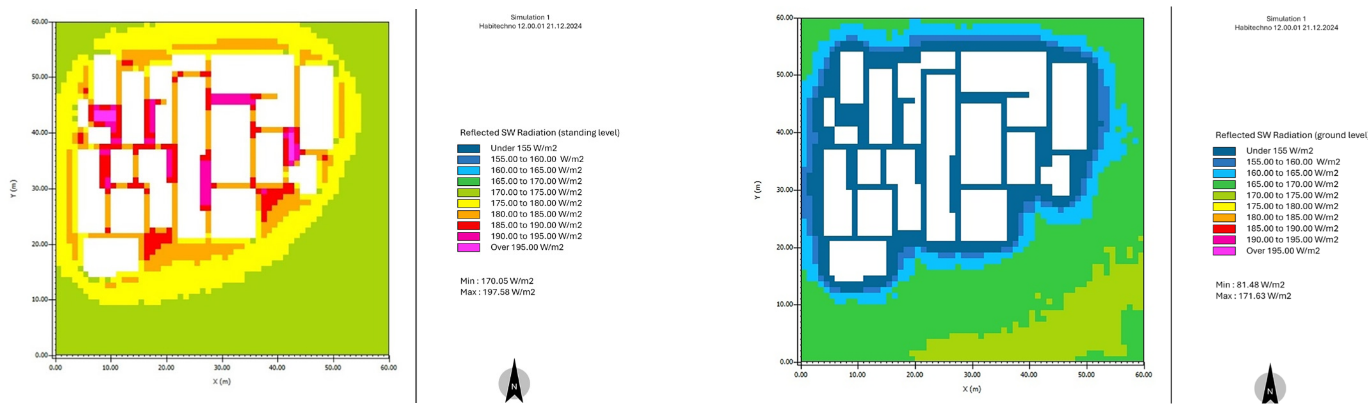

Figure 6. (A) MRT at Ground Level. (B) MRT at a Standing Level. Sources: Preparation by the Authors.

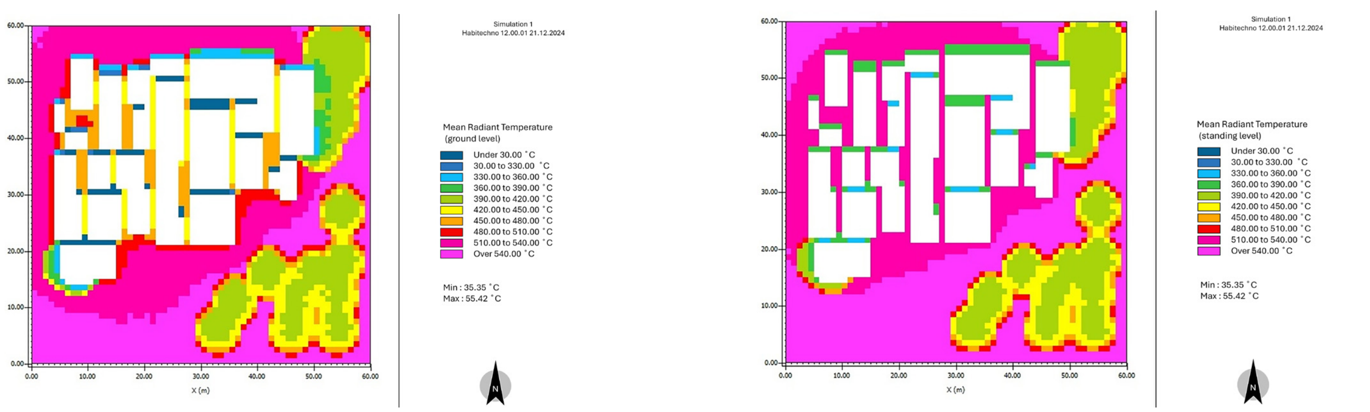

Figure 7. (A) Wind Speed at Standing Level. (B) Wind Speed at Standing Level. Sources: Preparation by the Authors.

level at the settlement's perimeter (Figure 7), indicating disruption caused by surface friction. This also indicates that air movement is quite comfortable with <2.5 m/s for the inhabitants for frequent outdoor sitting activities. On the other hand, this study shows that vegetation does not play an active role in high H/W ratio areas and organic regional morphology, in contrast to several previous studies (Liu et al., 2023; Rodriguez et al., 2025; Suryantara et al., 2019).

However, open spaces with vegetation demonstrate increased wind speed, suggesting that strategically placed greenery can enhance natural ventilation while simultaneously reducing thermal stress. In this case, the vegetation in the eastern area is a trembesi tree (*Samanea saman*) with a big trunk and a wide canopy. So, the air at ground and standing level is ventilated well across its area. Other researchers have also demonstrated that strategically placed vegetation can reduce urban temperatures by up to 5 °C, significantly enhancing microclimatic conditions (Dimoudi & Nikolopoulou, 2003; Shashua-Bar & Hoffman, 2000).

Additionally, tree shading provides several cooling effects through solar radiation buffers and evapotranspiration, reinforcing vegetation's role in improving microclimatic conditions. These findings align with previous studies emphasizing the importance of integrating vegetation into settlements for thermal comfort optimization. Moreover, Bowler et al. (2010) highlighted that vegetation can contribute to long-term cooling effects, reducing the intensity of urban heat islands. Recent studies have shown that combining tree canopies with permeable ground surfaces can amplify cooling effects (Morakinyo et al., 2017), reinforcing the importance of integrating urban greening strategies. A strategy that can be a viable option for narrow alleys is a vertical garden and potted plants. Furthermore, trees contribute to airflow regulation by increasing wind speed in open spaces, further promoting cooling effects, as demonstrated in studies across dense urban settlements in Asia (Ng et al., 2011).

Implications for urban planning

The results highlight the importance of holistic urban design strategies integrating building arrangement, material selection, and vegetation to create thermally comfortable outdoor environments. The strategic placement of vegetation, particularly in open spaces along the W-E corridor axis, is essential. Studies confirm that shading reduces direct radiation on surfaces while keeping wind corridors unobstructed (Shashua-Bar & Hoffman, 2000). As seen in Figure 6, the MRT on the W-E corridor is higher than the N-S corridor at similar altitude coordinates. The placement, including rooftop gardens and terrace vegetation on the second or third floors, can promote evapotranspiration and improve thermal comfort at higher levels, especially in an H/W ratio >1 (Morakinyo et al., 2017; Perini & Magliocco, 2014). This strategy also becomes even more crucial for a W-E H/W ratio <1 corridor, since it controls wind speed. Vertical gardens, such as green walls and facade planting, also help regulate building temperatures while improving air quality.

Light-colored pavements and facades can reflect more sunlight and absorb less heat, making them suitable for open areas (Synnefa et al., 2007; Santamouris, 2013). However, excessive reflectivity may trap heat within confined spaces in narrow alleys with closely packed buildings, leading to unintended warming effects. Future studies should explore combinations of optimal existing high-albedo and permeable materials to ensure balanced heat mitigation.

This study demonstrates that albedo floor surfaces in outdoor areas can elevate pedestrians' heat stress in urban kampungs with narrow spaces flanked by tight two—to three-story buildings. The increased reflectivity leads to higher radiant heat exposure, which offsets the benefits of reduced air temperatures. As a result, pedestrians may experience heightened thermal discomfort despite cooler ambient conditions. This study highlights the importance of considering broader climatic interaction when applying such materials for paving, instead of concrete.

Compact settlement design in high-density areas requires careful planning to integrate ventilation corridors and adjust the composition of buildings' H/W ratios and street orientations. Gaps between buildings along the north-south axis enhance airflow, while vegetation buffers on the east-west side are thermal regulators. These buffers reduce radiation exposure and filter pollutants effectively.

Semi-open spaces and shaded communal areas within dense settlements can enhance social and environmental resilience by reducing heat stress and promoting public well-being. These strategies are practical guidelines for urban planners and architects designing high-density kampung settlements in tropical climates.

Improving thermal comfort in narrow alleys within high-density settlements requires a multifaceted approach that considers spatial constraints, private spatial needs, and climatic conditions. Urban planners need to engage with local communities and authorities to implement designs and policies for this area with organic development. Regional planning requires a community-driven approach that can synergize the implementation of ideas and policies in public areas, the domain of planner design, and the implementation of ideas on building surfaces, which are the domain of private design. In implementing the policy in private areas, urban planners should encourage the integration of sustainable building materials essential for long-term thermal comfort improvements.

CONCLUSIONS

This study examines the influence of surface materials, building arrangement, and vegetation on outdoor thermal comfort in urban kampungs. Each factor plays a crucial role in modifying the microclimate of outdoor spaces, with significant implications for urban design and planning. Addressing these factors holistically can foster healthier and more livable high-density urban environments.

The study reveals that high-albedo surface materials tend to elevate air temperatures due to their reflective properties, particularly ground surfaces. Lower albedo paving materials are preferred to mitigate heat accumulation. Building arrangements with a high height-to-width (H/W) ratio provide effective shading, minimizing direct solar radiation and reducing mean radiant temperature (MRT). An east-west building orientation is more effective in creating shaded outdoor areas. Vegetation improves thermal comfort by providing shade and ET, which helps dissipate heat. This study reveals that it has a lower impact on increasing wind flow on >1 H/W ratio corridors and organic structures than <1, since building mass reduces wind speed. To maximize its benefits, vegetation should be strategically placed around open spaces to optimize airflow.

This research enriches the understanding of outdoor thermal comfort in high-density urban kampungs, which can be a foundation in urban planners' decision-making. The findings serve as a valuable reference for urban planners, architects, and policymakers aiming to design sustainable, thermally comfortable urban kampungs or high-density settlements. However, effective implementation will require collaboration with local communities, as private building surfaces largely determine outdoor thermal conditions.

Overall, the study significantly contributes to the discourse on outdoor thermal comfort in dense urban kampungs. It emphasizes the necessity of addressing microclimatic variables through a holistic design approach. Future research should incorporate thermal comfort validation, simulate the effect of designer adjustments, conduct long-term monitoring, and explore additional environmental factors such as humidity control and water features. Comparative studies across multiple urban kampungs could further enhance the applicability of these findings.

AUTHOR CONTRIBUTION CRediT

Conceptualization, R.P., S., D.K; Data Curation, R.P., S., D.K; Formal Analysis, R.P., S.; Funding Acquisition, R.P., S., D.K.; Research, Acronym; Methodology, R.P., S.; Project Management, D.K; Resources, R.P., S., D.K; Software. S.; Supervision, D.S; Validation, R.P., S.; Visualization, R.P., S.; Writing - original draft, R.P.; Writing - review and editing, R.P., S.; Writing - revision and editing, R.P., S.

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WIDESPREAD APPLICATION OF REHABILITATION STRATEGIES FOR WALLS OF PUBLIC HEALTHCARE CENTERS IN TUCUMÁN, ARGENTINA

ESTRATEGIAS DE REHABILITACIÓN DE APLICACIÓN GENERALIZADA EN MUROS DE CAPS EN TUCUMÁN, ARGENTINA

ESTRATÉGIAS DE REABILITAÇÃO DE APLICAÇÃO GENERALIZADA EM PAREDES DE CENTROS DE ATENÇÃO PRIMÁRIA À SAÚDE EM TUCUMÁN, ARGENTINA

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RESUMEN

Este trabajo aborda las deficiencias térmico-energéticas presentes en la envolvente vertical de los Centros de Atención Primaria de Salud (CAPS) en San Miguel de Tucumán, Argentina donde estudios previos revelan un desempeño inadecuado de sus muros, generándose una elevada demanda energética. Con el objetivo de proponer estrategias de rehabilitación masiva aplicables a los diversos tipos de soluciones constructivas existentes, se evalúan diferentes soluciones de aislamiento térmico que consideran sus prestaciones térmicas, costo económico y ciclo de vida. Mediante un análisis multicriterio con cálculo de ponderación, se seleccionaron las propuestas más convenientes. El análisis de la mejora en diez casos representativos evidencia un ahorro promedio de 21,32 %. en calefacción y 15,41 % en refrigeración. Se concluye que la implementación de las estrategias seleccionadas presenta un potencial significativo para optimizar el comportamiento térmico y reducir la demanda energética en los CAPS de la región.

Palabras clave
centros de salud, aislación térmica, muros, rehabilitación

ABSTRACT

This work addresses the thermal-energy deficiencies in the vertical envelope of Primary Health Care (PHC) Centers in San Miguel de Tucumán, where previous studies reveal inadequate performance of their walls, resulting in a high energy demand. Different thermal insulation solutions are evaluated based on their thermal performance, economic cost, and life cycle to propose widespread rehabilitation strategies for the diverse types of existing construction solutions. The most convenient proposals were selected using a multi-criteria analysis with a weighting calculation. The analysis of the improvement in ten representative cases shows an average saving of 21.32% in heating and 15.41% in cooling. It is concluded that implementing the selected strategies has a significant potential to optimize thermal behavior and reduce energy demand in the region's PHC Centers.

Keywords
health centers, thermal insulation, walls, rehabilitation

RESUMO

Este trabalho aborda as deficiências térmico-energéticas presentes na envolvente vertical dos Centros de Atenção Primária à Saúde (CAPS) em San Miguel de Tucumán, Argentina, onde estudos prévios revelaram um desempenho inadequado das paredes, gerando uma elevada demanda energética. Com o objetivo de propor estratégias de reabilitação em larga escala aplicáveis aos diversos tipos de soluções construtivas existentes, são avaliadas diferentes soluções de isolamento térmico que consideram suas performances térmicas, custo econômico e ciclo de vida. Por meio de uma análise multicritério com cálculo de ponderação, foram selecionadas as propostas mais convenientes. A análise da melhoria em dez casos representativos evidencia uma economia média de 21,32% em aquecimento e 15,41% em refrigeração. Conclui-se que a implementação das estratégias selecionadas apresenta um potencial significativo para otimizar o comportamento térmico e reduzir a demanda energética nos CAPS da região.

Palavras-chave:
centros de saúde, isolamento térmico, paredes, reabilitação

INTRODUCTION

There is a growing consensus on the importance of climate change and the role of anthropogenic greenhouse gas emissions (Recalde et al., 2018; Mora-Barrantes et al., 2021). Global energy consumption is recognized as a central cause (Gómez Cerdeiro, 2021; Mercado Burciaga, 2023). The building sector, recognized as a significant contributor to this crisis (Flores, 2021; Ortega-Díaz et al., 2023), currently accounts for approximately 40% of CO_2 emissions and one-third of the world's energy consumption (Muñoz-Rojas et al., 2023; Abdou et al., 2021). Air conditioning is a determining factor (Kuchen & Kozak, 2020; Galindo-Borbón et al., 2024) due to the increasing demand for thermal comfort (Daioglou et al., 2022; Andersen et al., 2019). The building envelope is responsible for a substantial part of the energy losses (Ascione et al., 2019; Bacelis et al., 2024), and offers considerable potential for consumption optimization and reduction (Wang et al., 2019; Costantini-Romero & Francisca, 2022). In this context, any action aimed at reducing energy demand through the rehabilitation of the envelope's materiality becomes relevant (Ré & Filippín, 2021). In Argentina, the building sector is responsible for nearly 37% of the final energy consumption, led by the residential sector, followed by the commercial and public sector, where the Health subsector is located, which accounts for 8.35% of this (Ministry of Economy, 2023). Although this subsector has a lower share of final energy consumption than other sectors, it is characterized as a public service of social interest (Urteneche et al., 2022).

The city of San Miguel de Tucumán (SMT), located in northwestern Argentina, has a subtropical climate characterized by a dry season, dry winters, and rainy summers, with annual rainfall exceeding 1000 mm and temperatures exceeding 40 °C (González & Ceballos, 2021; Giovino et al., 2022). There are 32 PHCs (Public Healthcare Centers) that constitute the health infrastructure for the local community. Previous studies conducted in these PHCs (Fernández & Garzón, 2023; Fernández & Garzón, 2024) have shown a significant energy inefficiency associated with thermal conditioning and deficiencies in the hygrothermal behavior of their vertical envelopes. This situation directly affects the comfort of patients and staff, generates high operating costs, and increases energy demand on the local grid. Therefore, improving the thermal performance of these buildings is relevant not only from a comfort and efficiency perspective, but also contributes to regional environmental sustainability.

This work aims to generate systematic rehabilitation strategies for the exterior vertical enclosures (EVEs) of Primary Health Care (PHC) centers in SMT, designed for their widespread application in the existing building stock. In this context, the term *systematic* refers to an evaluation and selection methodology based on defined and replicable criteria. At the same time, *mass application* focuses on its replicability potential in multiple buildings with similar typologies. The innovation of this research is based on the proposal of an original methodology for evaluating and selecting these strategies. This methodology is based on a weighting system that considers the economic cost, thermal performance, and life cycle analysis (LCA).

METHODOLOGY

This study proposes an analysis of rehabilitation strategies for the vertical envelope of the PHCs located in SMT. Initially, the thermal properties of the vertical envelope are analyzed, followed by the definition of proposals and their constructive feasibility for the context. Then, each proposal is evaluated from three perspectives: economic cost, thermal properties, and LCA.

In the thermal analysis, the thermal resistance of each rehabilitation proposal is calculated according to the procedure established in the IRAM 11601 (2002) standard. For this, equation 1 is considered, where the thermal resistance of a flat component, formed by several homogeneous layers (R_t), is equal to the sum of the resistances of each of those layers (R1, R2, ..., Rn) in m²W/K. In turn, equation 2 is used to determine the resistance of the different layers (R), where R is equal to the ratio between the thickness of the layer (e) in meters and the thermal conductivity of the material (λ) expressed in W/mK.

$$R_t = R_1 + R_2 + ... + R_n + R_{c1} + R_{cn} \quad (1)$$

$$R = e/\lambda \quad (2)$$

To evaluate the LCA, the Design Assistance Tool for a More Sustainable Building (HADES) is used. HADES is an open-source software developed by the Industrial Construction Institute of Catalonia (ITeC), designed for the environmental analysis of materials and construction elements. It is based on the principles and methodological framework established in the ISO 14040 (2006) and ISO 14044 (2006) standards. The choice of HADES is based on its accessibility, intuitive interface, and extensive database of common construction materials in the Spanish and Latin American context, which facilitates the modeling of the rehabilitation proposals considered in this study. The indicators considered and evaluated in this case are embodied energy (MJ/m²), which indicates the non-renewable energy

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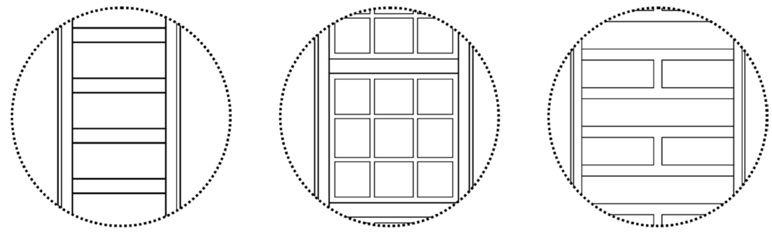

Figure 1. Wall construction solutions, thermal transmittance coefficients, and hygrothermal comfort levels. Source: Preparation by the Authors.

consumed during the materials' life cycle, and CO_2 equivalent emissions (kCO_2eq/m^2), which quantify the associated greenhouse gas emissions.

For the economic analysis, the direct costs of materials and labor necessary to implement each rehabilitation proposal were considered. Unit prices were established based on SMT's local market, averaging different points of sale in the city for the materials. Labor costs were based on up-to-date values from the UOCRA (Construction Workers Union of the Argentine Republic), corresponding to November 2024. The cost per square meter of each proposal was calculated in isolation, excluding specific completion details that may vary depending on the particular case. The values were expressed in US dollars.

Based on these analyses, the most relevant strategy was selected using our own numerical weighting methodology, which was designed to objectively determine the most effective one. To each of the mentioned criteria, the same percentage weight was awarded. In turn, within each criterion, a score from 1 to 10 was assigned to the different proposals, where 1 represents the worst performance and 10, the best. The assignment of scores was based on ranges of values defined for each indicator. The total score obtained for each proposal was calculated by adding the score obtained in each criterion. The proposal with the highest total score, which represents the best balance between the evaluated criteria, was considered the optimal option for rehabilitation.

Finally, the global seasonal thermal behavior of 10 existing PHCs in SMT was evaluated, selected using a non-probabilistic convenience sampling (Scharager & Reyes, 2001) to represent the diversity of construction typologies identified in the building stock. The selection criteria include the representativeness of the existing vertical envelope types, as well as variations in location and orientation. This selection was made to allow for a greater depth of analysis of the thermal behavior of a manageable number of cases. For each of these 10 PHCs, its existing vertical envelope is defined in the CIDEE-EA calculator (Elsinger et al., 2021), from the constructive details revealed *in situ*. Subsequently, the application of the selected rehabilitation proposal to the vertical envelope of each of the 10 PHCs was modeled, with the thermal transmittance values updated according to the properties of the rehabilitation solution. The annual heating and cooling thermal loads, as defined by IRAM 11604 and IRAM 11659-1 standards, were analyzed. The original case was compared with the rehabilitated case, and the percentage impact of the improvement in the overall thermal behavior was analyzed for each of the 10 representative PHCs.

RESULTS

CHARACTERIZATION OF PHCS' WALLS

The EVEs of all the PHCs in SMT are made from ceramic brick masonry. Three constructive solutions are distinguished: M1, solid 0.15 m ceramic brick masonry plastered on both sides with earthquake-resistant chaining; M2, hollow 0.20 m ceramic brick masonry plastered on both sides; and M3, solid 0.30 m ceramic brick masonry plastered on both sides. The most typical case is the M2, which is the constructive solution for 37.04% of the PHCs. It is followed by M3, with 33.3%, then the M1 wall with 18.52%. Finally, 11.11% of the buildings combine the M2 with M3, which are buildings that underwent later extensions (Fernández & Garzón, 2021).

The thermal transmittance levels for each case are presented below (Figure 1), along with their verification against the hygrothermal comfort levels recommended by IRAM (A: ecological, B: recommended, and C: minimum). It is observed that in no case is the recommended level met, and only the M2 type wall complies with the minimum level.

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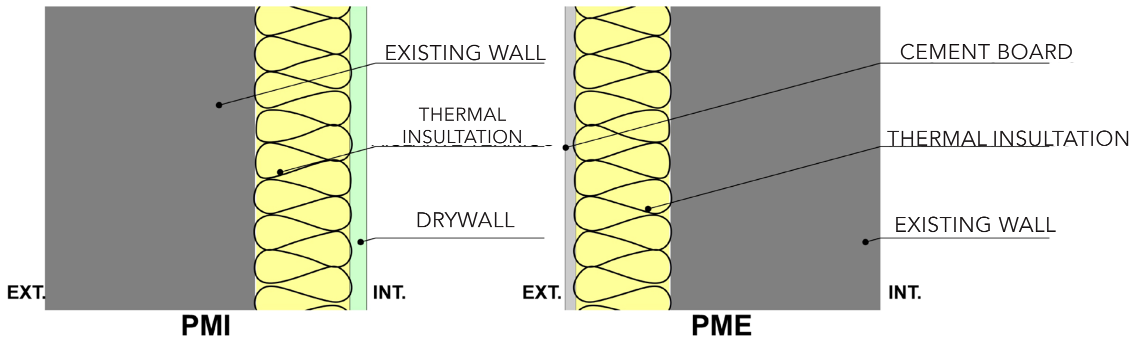

Figure 2. Outline of proposals for the rehabilitation of interior (PMI) and exterior (PME) EVE. Source: Preparation by the Authors.

Table 1. Main technical characteristics of insulation found in the local market. Source: Preparation by the Authors.

Characteristics	Expanded polystyrene (EPS)	Glass wool (GW)	Rock wool (RW)
Origin	Synthetic	Mineral	Mineral
Structure	Closed cells	Fibrous	Fibrous
Fire behavior	Self-extinguishing	Incombustible	Incombustible
Water vapor permeability	Low	High	High
Density	Low 16 to 19 kg/m3	Medium 30 to 70 kg/m3	Medium-high 35 to 160 kg/m3
Mechanical resistance	Low	Medium	Medium-high
Price	Medium	Medium	High

Table 2. Definition and assignment of nomenclatures in the six rehabilitation proposals. Source: Preparation by the Authors.

Proposal number	Location of the insulation	Type of insulation	Proposal name
1	Exterior	EPS	PME_1
2	Exterior	GW	PME_2
3	Exterior	RW	PME_3
4	Interior	EPS	PMI_1
5	Interior	GW	PMI_2
6	Interior	RW	PMI_3

PRESENTATION OF PROPOSALS

The rehabilitation strategies applicable to the walls are presented below. In all cases, they consist of incorporating an intermediate thermal insulation and a surface finishing material. For this, the incorporation of the insulation on the inner (PMI) and outer (PME) faces is proposed (Figure 2). The types of insulation are selected for their permanent availability in the SMT market, as well as for being materials that the local workforce can apply. It is essential to note that for the proposed system to be effective, it must be implemented appropriately. These are expanded polystyrene in sheets, glass wool with aluminum, and rock wool with aluminum. In Table 1, the main characteristics of the selected insulating materials are presented.

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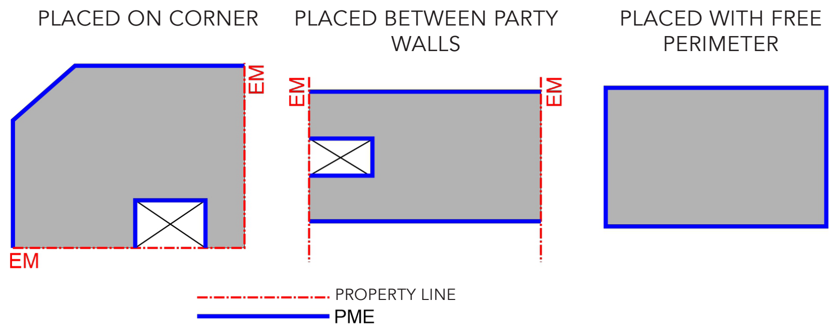

Figure 3. Layout of the PME application depending on the type of site. Source: Preparation by the Authors.

Table 3. Comparative analysis of the main characteristics of each of the proposals made. Source: Preparation by the Authors.

Proposal nomenclature	Thermal resistance [m2W/K]	Embodied energy [MJ/m2]	CO2 equivalent [$kCO_2eq/m2$]	Economic cost in [U$S/m2]
PME_1	1.93	30,660	3491	60.59
PME_2	1.74	26,621	2185	58.94
PME_3	2.16	21,884	1773	78.52
PMI_1	1.95	30,419	3450	32.36
PMI_2	1.77	26,381	2144	30.71
PMI_3	2.18	21,644	1733	50.30

It is proposed to incorporate insulation through galvanized sheet profiles available on the market, which are of standard sizes, along with drywall for the interior and fiber cement for the exterior. The measurement adopted for the profile and insulation is 70 mm thick. As a result of these combinations, three types of insulation with two placement possibilities yield six wall rehabilitation proposals. The acronyms PME are assigned for exterior wall proposals and PMI for interior ones; in turn, number one is assigned for those with expanded polystyrene, number two for glass wool, and number three for rock wool. The nomenclature assigned for each proposal considered is shown in Table 2.

CONSTRUCTIVE FEASIBILITY

The geometric configuration and location of each building condition the implementation of the PMEs. Three types were detected: between party walls (42.3%), corner supported by two party walls (42.3%), and free perimeter (15.38%). Although these solutions offer the advantage of being able to be implemented without interrupting the health center's activities, their application is limited in cases where the building is attached to walls. In these situations, intervention on a global scale is only viable within the walls that adjoin the public road or with internal patios (Figure 3). This is because the application of this system requires a sufficient workspace for the placement of the constructive elements and the subsequent finishing. In the case of buildings located in free perimeters, the constructive feasibility is total, allowing for the intervention on all exterior walls.

On the other hand, the PMIs, although they require the temporary interruption of PHC activities, have the advantage of being applicable in all indoor spaces without restrictions. By being executed inside the building, the need to consider external factors, such as weather protection, is eliminated, which simplifies logistics and reduces the execution costs and risks of future pathologies. To minimize the impact on public attention, it is recommended to carry out the work in stages, where each environment is intervened upon independently.

DETAILED ANALYSIS OF THE PROPOSALS

The main characteristics of the proposals made are presented below (Table 3). Initially, the thermal insulation is analyzed. To do this, on the one hand, the thermal resistance of each solution is studied in isolation. Secondly, the LCA of each proposal is studied using the HADES tool, considering the indicators mentioned in the methodology. Finally, the

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Table 4. Comparison of total score between thermal insulation, economic cost, and environmental impact for wall rehabilitation proposals. Source: Preparation by the Authors.

Proposal nomenclature	Thermal insulation	LCA	Economic cost	TOTAL
PME_1	8.85	7.06	5.07	20.98
PME_2	7.98	8.13	5.21	21.32
PME_3	9.91	9.89	3.91	23.71
PMI_1	8.94	7.12	9.49	25.55
PMI_2	8.12	8.20	10.00	26.32
PMI_3	10.00	10.00	6.11	26.11

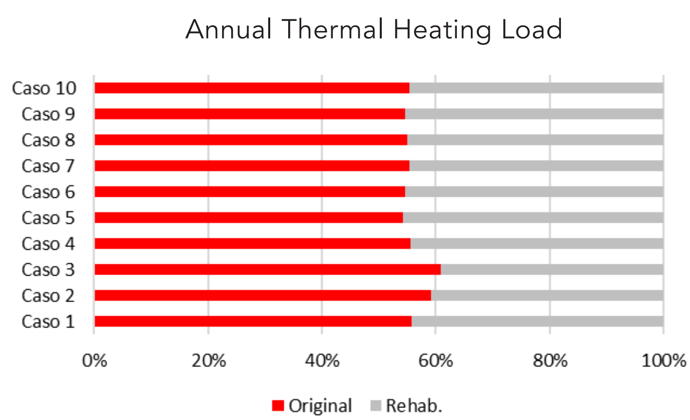

Figure 4. Annual thermal heating load, expressed in percentage for 10 existing PHCs in SMT in its original version and with the EVE rehabilitation proposal. Source: Preparation by the Authors.

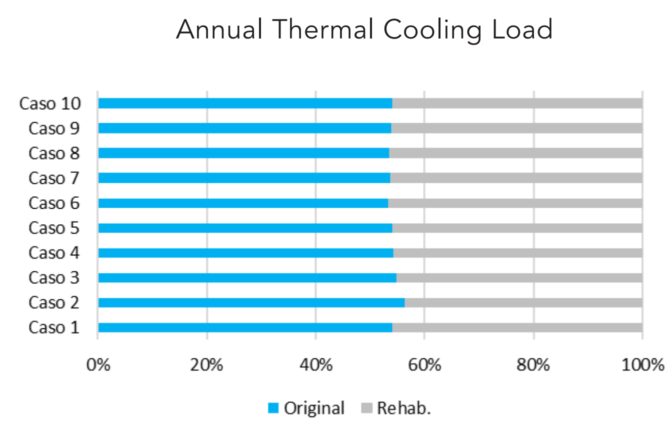

Figure 5. Thermal cooling load, expressed as a percentage for 10 existing PHCs in SMT in its original version and with the EVE rehabilitation proposal. Source: Preparation by the Authors.

unit economic cost is evaluated in US$/m² for each of them. In Table 3, these properties are expressed for each of the proposals made.

WEIGHTING AND SELECTION OF THE PROPOSAL

To select the most appropriate proposal in terms of cost-benefit ratio, a score is assigned to each proposal based on its performance in each considered criterion, and these scores are then added together. This score ranges from 1 to 10; the highest score is awarded to the proposal that performs best in each specific criterion. For example, in economic cost, a score of 10 is given to the one with the lowest price. The rest of the proposals will be evaluated proportionally, that is, the closer a proposal comes to the best performance in a factor, the higher its score will be. This assignment of scores is based on a simple rule of three, which allows an objective quantification of the performance of each proposal compared to the others.

The proposal with the highest score for walls is the PMI_2 (Table 4). In this comparative analysis, it is seen that the variation between proposals in terms of thermal insulation is 20%. In contrast, the economic cost variation is more significant, approaching 50%, and the environmental impact variation is 30%. Moreover, the interior proposals have a better cost-benefit ratio, as they are more cost-effective and sustainable than the exterior ones.

APPLICATION OF THE PROPOSAL TO EXISTING CASES

Finally, the thermal behavior of the selected rehabilitation proposal applied to ten existing PHC cases in the city of SMT is analyzed globally. The variants considered are the annual heating thermal load (kWh) and the cooling thermal load (W). The graphs shown below (Figure 4 and Figure 5) present a comparative analysis of both variants, for each case in its original version and with the proposed wall rehabilitation.

In both variants, a significant improvement in the overall thermal performance is observed across the

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different cases. For the annual heating thermal load, the improvement ranges from 17 to 30%, with an average value of 21.32%. In the case of the cooling thermal load, this ranges from 13 to 22%, with an average of 15.41%.

DISCUSSION

The evaluation of the thermal behavior of the EVE existing in the PHCs reveals, in general, high thermal transmittance values (K). Values of up to 2.84 W/m²K are recorded, which significantly exceed the value recommended by the IRAM standard of 1.10 W/m²K for warm areas. These high values have a direct impact on user thermal comfort, as they make it difficult to maintain a stable and comfortable indoor temperature. Additionally, it has a significant impact on the energy consumption of buildings, increasing the demand for HVAC systems to compensate for heat losses or gains through the envelope, which in turn translates into higher operating costs and a larger carbon footprint.

In this work, it is concluded that the most suitable proposal for the rehabilitation of walls in PHCs in SMT is PMI_2 (application of glass wool as an insulating material on the inner face). An additional factor that reinforces the desirability of the internal proposals is their feasibility of application in all the cases of PHCs analyzed, as detailed in the Feasibility section. This characteristic of universal applicability, added to its favorable performance in the evaluated criteria, makes it an optimal constructive intervention for generalized rehabilitation.

The analysis of the rehabilitation solutions evaluates each proposal in isolation. Although this allows an objective comparison in terms of thermal properties, cost, and sustainability, the specific constructive implications for each PHC are not considered in detail. The actual application of these solutions could lead to a greater use of materials, and consequently, an increase in environmental impact and total economic cost of the intervention.

Regarding the risks and uncertainties associated with the proposed solutions, it is essential to acknowledge that the long-term durability of insulating materials, particularly in indoor applications, may be influenced by factors such as humidity and temperature fluctuations. Inadequate maintenance could compromise the rehabilitation's efficiency over time. Therefore, it is essential to have specific installation and maintenance protocols to guarantee the effectiveness and durability of the implemented solutions.

CONCLUSIONS

This study addresses the problem of energy deficiency in SMT's PHCs and proposes rehabilitation strategies for its widespread application in the vertical envelope. The main result shows that incorporating thermal insulation on the inner faces of the walls is the most appropriate rehabilitation strategy from an economic, sustainability, and feasibility perspective. Likewise, glass wool is identified as the most suitable product on the local market due to its cost-thermal performance ratio and environmental impact. The implementation of this strategy demonstrates a significant improvement in the overall thermal energy behavior of the analyzed PHCs, with an average reduction of 15% in the cooling thermal load and 20% in the heating thermal load.

The rehabilitation of vertical envelopes in PHCs yields multiple benefits. The reduction of energy consumption and improvement of thermal comfort contribute to the sustainability of health services by minimizing their environmental footprint and optimizing the quality of life for both users and healthcare personnel. These results are aligned with the growing need to implement energy efficiency measures in the building sector, specifically in its envelope, as pointed out by several authors cited in this work (Ascione et al., 2019; Bacelis et al., 2024; Wang et al., 2019; Costantini-Romero & Francisca, 2022; Ré & Filippín, 2021).

This research contributes a methodology for evaluating envelope rehabilitation strategies based on the application of IRAM standards, as well as technical, economic, and environmental criteria. Its replicability potential allows addressing energy efficiency challenges in various types of buildings, public and private. In this sense, the results and the methodology offer valuable information for the formulation of public policies. These should focus on the sustainability of the health infrastructure at both the local and national levels by promoting the adoption of energy rehabilitation solutions that consider technical and life-cycle criteria. For future lines of research, it is suggested to explore the implementation on a larger scale, the impact of user behavior, and the integration of active HVAC systems for comprehensive energy optimization. Finally, it is concluded that the energy rehabilitation of the envelope in PHCs is a concrete and practical step towards the sustainability of public health infrastructure.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, A.F., B.S.G.; Data curation, A.F., B.S.G.; Formal analysis, A.F., B.S.G.; Acquisition of financing, not applicable; Research, A.F.; Methodology; A.F., B.S.G.; Project management, B.S.G.; Resources, A.F., B.S.G..; Software. A.F., B.S.G.; Supervision, B.S.G.; Validation, A.F., B.S.G.; Visualization, A.F., B.S.G.; Writing - original draft, A.F., B.S.G.; Writing - revision and editing, A.F., B.S.G.

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SOLAR PROTECTION IN MEDITERRANEAN BUILDINGS, MADRID, SPAIN: DESIGNING WITH ALGORITHMS AND ARTIFICIAL INTELLIGENCE

PROTECCIÓN SOLAR EN EDIFICACIONES MEDITERRÁNEAS, MADRID, ESPAÑA: DISEÑO CON ALGORITMOS E INTELIGENCIA ARTIFICIAL

PROTEÇÃO SOLAR EM EDIFICAÇÕES MEDITERRÂNEAS, MADRI, ESPANHA: PROJETO COM ALGORITMOS E INTELIGÊNCIA ARTIFICIAL

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RESUMEN

Este artículo analiza la integración de tecnologías digitales y algoritmos paramétricos en el diseño de sistemas de protección solar para edificaciones en contextos mediterráneos, como Madrid, España. Se utilizó un modelo base representativo de un edificio de escala media, se evaluaron cuatro configuraciones de protección solar mediante simulaciones avanzadas que incorporaron datos climáticos locales y trayectorias solares anuales. Las estrategias exploradas incluyen parasoles horizontales, inclinados, un diseño biomimético Voronoi y un modelo compuesto que combina estos enfoques. Los hallazgos destacan cómo la inteligencia artificial y los algoritmos computacionales permiten optimizar el rendimiento energético y el confort térmico, al tiempo que redefinen las posibilidades estéticas y sostenibles en la arquitectura contemporánea. Este enfoque propone un marco innovador para enfrentar los desafíos climáticos, que evidencia el potencial de las herramientas digitales en la transformación del diseño arquitectónico hacia un paradigma más resiliente y adaptativo.

Palabras clave
diseño paramétrico, inteligencia artificial, sostenibilidad arquitectónica, protección solar

ABSTRACT

This article examines the integration of digital technologies and parametric algorithms when designing solar protection systems for buildings in Mediterranean contexts, such as Madrid. Four solar protection configurations were evaluated through advanced simulations using a base model representative of a medium-scale building, incorporating local climatic data and annual solar trajectories. The strategies examined include horizontal louvers, inclined shading devices, a biomimetic Voronoi design, and a composite model that combines these approaches. The findings highlight how artificial intelligence and computational algorithms optimize energy performance and thermal comfort while redefining aesthetic and sustainable possibilities in contemporary architecture. This approach proposes an innovative framework to address climate challenges, showcasing the potential of digital tools to transform architectural design into a more resilient and adaptive paradigm.

Keywords
parametric design, artificial intelligence, architectural sustainability, solar protection

RESUMO

Este artigo analisa a integração de tecnologias digitais e algoritmos paramétricos no projeto de sistemas de proteção solar para edificações em contextos mediterrâneos, como o de Madri, na Espanha. Utilizou-se um modelo básico representativo de um edifício de escala média e avaliaram-se quatro configurações de proteção solar por meio de simulações avançadas que incorporaram dados climáticos locais e trajetórias solares anuais. As estratégias exploradas incluem toldos horizontais, inclinados, um design biomimético Voronoi e um modelo composto que combina estas abordagens. As conclusões destacam como a inteligência artificial e os algoritmos computacionais permitem otimizar o desempenho energético e o conforto térmico, ao mesmo tempo que redefinem as possibilidades estéticas e sustentáveis na arquitetura contemporânea. Esta abordagem propõe um quadro inovador para enfrentar os desafios climáticos, evidenciando o potencial das ferramentas digitais na transformação do projeto arquitetônico rumo a um paradigma mais resiliente e adaptativo.

Palavras-chave:
design paramétrico, inteligência artificial, sustentabilidade arquitetônica, proteção solar

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INTRODUCTION

In the current context of accelerated urbanization and environmental challenges, contemporary architecture is emerging as a key discipline to face the effects of climate change. In Mediterranean regions, such as Madrid, solar radiation poses a significant challenge, particularly during the warm months, when the temperature of building interiors substantially increases. This phenomenon intensifies the use of air conditioning systems, which increases energy consumption and carbon emissions. This underlines the need for more sustainable architectural solutions (García Molina et al., 2024).

In these conditions, conventional solar protection strategies, although effective in past contexts, are insufficient in the face of current climate and energy demands. Therefore, it is essential to explore innovative approaches that integrate advanced technologies, such as parametric algorithms, artificial intelligence, and adaptive geometries, to design more precise and effective architectural solutions. These tools allow the development of optimized configurations that respond dynamically to varying weather conditions, thereby reducing thermal gain and improving interior comfort (Sickle-Torres et al., 2024; Kolokotsa et al., 2022; Rodríguez-de-Ita & Sosa-Compeán, 2024).

Advances in digital technologies, computational algorithms, and artificial intelligence have profoundly transformed contemporary architecture, allowing unprecedented energy and aesthetic optimizations. The integration of these tools not only improves energy efficiency but also drives innovative design that pushes the boundaries of traditional approaches. Studies such as Tipán-Renjifo and Tipán-Suárez (2022) highlight how Voronoi patterns, generated using computational algorithms, allow the exploration of complex morphologies that respond directly to climatic and functional conditions. These patterns optimize energy performance and enrich the built environment (Chen, 2021). Additionally, this approach facilitates the prediction and dynamic adjustment of solar incidence, resulting in a significant reduction in total radiation compared to a model without protection (Jalali et al., 2022). Wieser et al. (2024) underline that these technologies enable adaptive customizations that respond to seasonal climatic variations and thermal comfort needs. In particular, this approach optimizes energy efficiency and improves indoor comfort in climates such as Madrid.

Parametric systems not only enable solutions of great formal complexity but also facilitate their production using technologies such as laser cutting or 3D printing. Betman et al. (2023) note that these methods reduce waste, costs, and lead times while increasing the accuracy of designs based on Voronoi patterns. However, these innovations face obstacles, including high initial investment, dependence on specialized software, and the need for advanced technical skills, which may restrict their adoption in resource-constrained environments (Gamal et al., 2024).

From a sustainability perspective, these systems not only significantly reduce the energy consumption associated with air conditioning but also contribute to mitigating buildings' environmental impact, aligning with global carbon emission reduction objectives (Ramos-Sanz, 2019; Aghimien et al., 2022). Aesthetically, the advanced algorithms offer a customization that turns each project into a unique work, while promoting a harmonious integration with the environment. Tipán-Renjifo and Tipán-Suárez (2022) highlight how these solutions reconfigure the dialogue between the building and its context, elevating the architectural experience.

However, Wieser et al. (2024) state that dynamic systems, such as tilted individual sunshades, require maintenance planning to ensure their longevity. This includes redundancies and clear protocols to prevent technical failures. Despite these limitations, the integration of digital technologies, artificial intelligence, and advanced algorithms in architecture redefines contemporary design. Responding to complex challenges, it offers adaptive, sustainable, and creative solutions for the future (Atef et al., 2024). As noted by Betman et al. (2023), these tools not only optimize energy efficiency but also inspire a new generation of innovative architectural proposals.

This article focuses on evaluating advanced solar protection strategies applied to a representative building model in the Mediterranean climate. Four configurations are compared through detailed simulations: a base model without protection, a system with horizontal sunshades, another with angularly adjusted individual sunshades, and a solution based on Voronoi geometric patterns. These configurations are analyzed in terms of their ability to mitigate solar radiation and optimize the buildings' energy performance (Amraoui et al., 2021). The work seeks to demonstrate how digital technologies and approaches inspired by natural systems can overcome the limitations of traditional models by promoting a more sustainable and adaptive architecture (Bertagna et al., 2023). This approach not only addresses the challenges associated with climate change but also establishes a new paradigm in architectural design by integrating functionality, technological innovation, and sustainability in Mediterranean and Ibero-American climates.

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Figure 1. View of the residential building located at Plaza España 6, Getafe (Madrid), along with its location within the urban environment and the volumetric scheme of the site. Source: Google Maps (2025).

METHODOLOGY

This study uses a parametric and computational approach to evaluate solar protection strategies in a Mediterranean climate context, using a real building in Getafe (Madrid, Spain) as a reference case. The methodology is structured in four stages: characterization of the climate and the building, modeling and simulation of solar radiation, design of protection strategies, and a comparative analysis of energy performance.

The first step was to characterize Getafe's Mediterranean climate using global irradiance, temperature, and Köppen climate classification data (Csa: Mediterranean with hot summer). With more than 2,800 hours of sunshine per year and average summer temperatures exceeding 30°C, solar protection is a top priority. The selected building is a medium-scale, multifamily residential building located at Plaza España 6, Getafe (coordinates: 40.309300, -3.724501). It is a rectangular prism measuring 30 m × 50 m × 50 m, with an envelope surface area of 9,500 m² and a total volume of 75,000 m³. Its compact shape allows minimizing the surface exposed to heat exchange, facilitating the analysis (Figure 1).

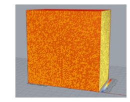
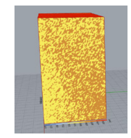
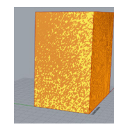
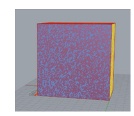
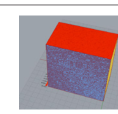
In a second stage, the base building was digitally modeled without solar protection, establishing a reference scenario. From solar simulations carried out with Ladybug in Grasshopper, the annual radiation distribution was obtained for each of the five exposed faces: north, south, east, west, and roof. The values were calculated precisely according to the specific solar trajectories of Madrid, and the direct radiation was considered as diffuse. This analysis revealed that the southern and upper faces receive more than 60% of the annual radiation, which justifies their prioritization in the design of strategies. The information is summarized in Table 1, which includes the average radiation per surface, and in Figure 2, Figure 3, and Figure 4, which visualize the differences in exposure.

Three solar protection strategies were designed: (1) horizontal sunshades with 1.50 m deep sheets and constant vertical separation; (2) individual tilted sunshades, arranged according to predominant solar angles and adapted by modules; and (3) a biomimetic Voronoi envelope, generated with parametric algorithms that vary the size of the perforations depending on the orientation and solar exposure. Each strategy was applied to the same base model, and three variants were generated, which were then subjected to simulation under identical climatic conditions.

The simulations evaluated the incident radiation per m² on each face of the building. The data was processed with GPT4All, a local AI model with no external connection, to ensure reproducibility and traceability. To optimize the geometric parameters of each strategy, genetic algorithms were used using Galapagos, and custom scripts in GhPython were used to adjust the configurations to the specific conditions of Getafe.

Finally, a fourth variant was designed: a composite model that combines the best solutions detected in each orientation. This includes tilted sunshades on the east, west, and south facades, as well as a Voronoi lattice on the north face and the roof, thereby achieving optimized coverage. The performance of each strategy was compared in terms of total accumulated radiation, percentage reduction compared to the base model, and thermal distribution by orientation. All the information was systematized

Table 1. Analysis of the base prism by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)	Layout
Sur	2500	2.981	00.0	
Este	1500	1.360	00.0	
Oeste	1500	1.398	00.0	
Norte	2500	0.976	00.0	
Superior	1500	2.299	00.0	

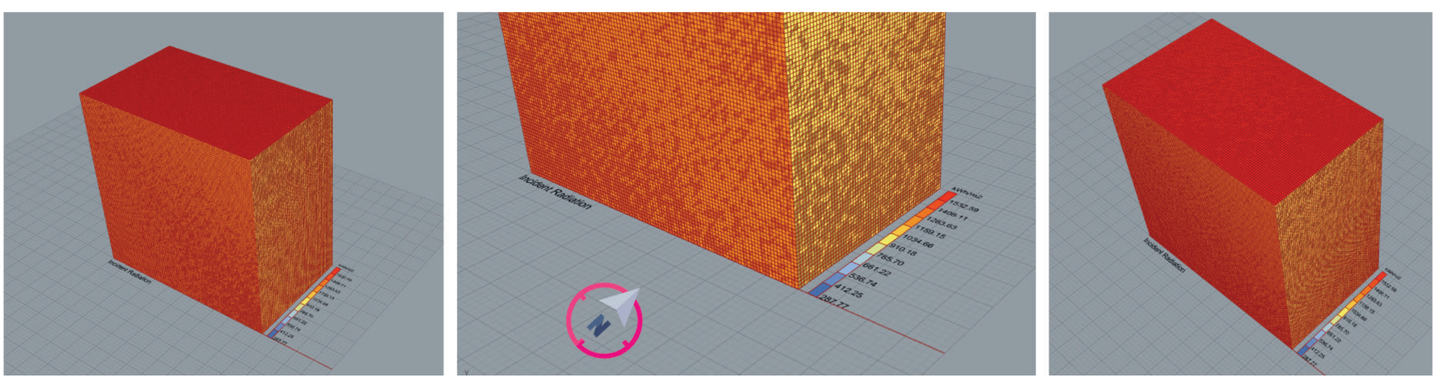


Figure 2. Digital simulation of the base prism with visualization of the solar radiation values on the surfaces. Source: Preparation by the Authors.

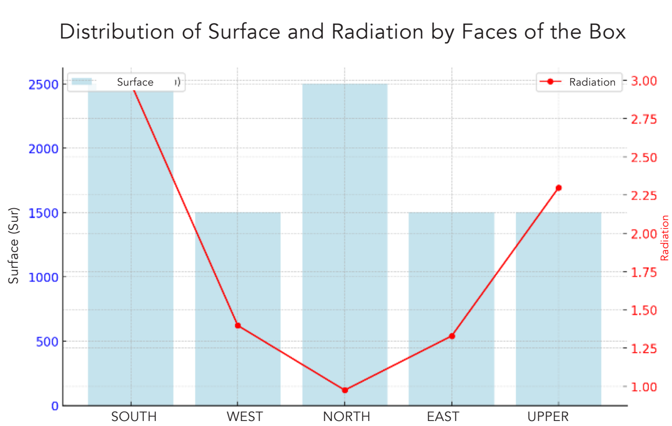


Figure 3. Distribution of surface and radiation on the faces of the base prism, showing the relationship between area and received radiation. Source: Preparation by the Authors.

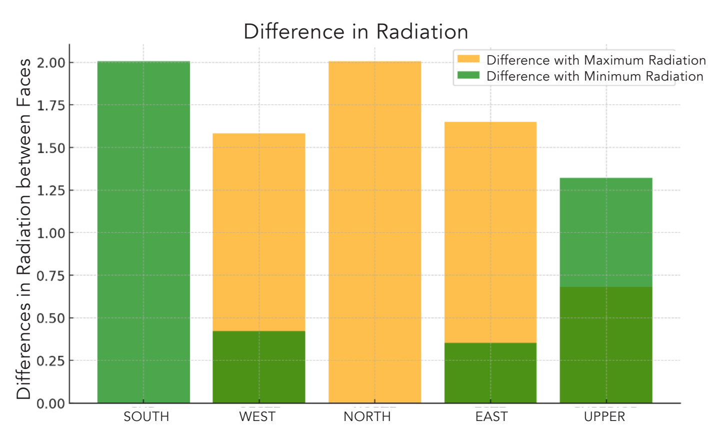


Figure 4. Variations in radiation per face of the base prism, with a comparison of maximum and minimum values observed to highlight the differences in exposure in the analyzed model. Source: Preparation by the Authors.

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in comparative tables and illustrated by graphics and visual simulations, which allowed understanding the performance of each configuration from a technical and project perspective.

DISTRIBUTION OF SOLAR RADIATION BY FACE

Before evaluating the solar protection strategies, the distribution of the incident radiation on each of the base model's surfaces was analyzed without shading elements. This stage allowed identifying which facades concentrated the most exposure, establishing the criteria for geometric intervention. The model accumulates an annual total of 9,415 kWh/m^2, with the southern and upper faces receiving more than 60% of that energy (Figure 2, Figure 3, and Figure 4). Table 1 summarizes the radiation values per face and its surface, which shows the differences according to orientation:

This information served as a comparative basis for evaluating the performance of each strategy in reducing incident solar radiation.

DESIGN OF SOLAR PROTECTION STRATEGIES

According to Urias-Barrera (2024), three solar protection strategies were analyzed and designed to minimize incident solar radiation, optimize energy efficiency, and enhance thermal comfort, compared to the base model. Each strategy was based on principles of geometric optimization and solar behavior and was evaluated using advanced computational tools.

1. Box with horizontal sunshades. Rectangular horizontal sheets, 1.50 meters deep and 0.25 meters thick, were used, evenly distributed on the facades with a constant vertical separation of 0.75 meters. These dimensions were determined to ensure adequate shading at the times of greatest solar incidence, especially in summer. The choice of the horizontal model responds to its proven ability to effectively block direct radiation from high solar angles, typical in Mediterranean latitudes, while preserving an adequate entry of daylight in the less warm months.
2. Box with individual tilted sunshades. This strategy integrates individual elements in the form of square slats inclined at a variable angle between 0° and -90 °, designed according to the prevailing solar angles throughout the year in Madrid. Each sunshade has specific dimensions of 1.50 meters in length, 1.50 meters in horizontal width, and 0.05 meters in thickness. Although, for practical purposes of the initial calculation, a wide modular surface of 5 meters by 5 meters was established, it is important to clarify that, in reality, each visible module internally comprises groups of individual smaller sunshades. This allows efficiently managing the large dimensions seen in the image, making the proposal technically viable, logical, and feasible from a constructive, functional, and architectural perspective. The tilted configuration thus addresses the need for a more dynamic and effective protection against daily and seasonal solar variations, significantly improving the thermal adaptation capacity without negatively affecting the internal daylighting or the building's aesthetic coherence.
3. Box with Voronoi pattern. This model incorporates a biomimetic structure with latticework generated by Voronoi parametric algorithms. The perforations have variable dimensions, ranging from 0.50 to 4.50 meters in diameter, arranged according to a parametric gradient adjusted to maximize protection against both direct and diffuse solar radiation, while maintaining a balance between visual transparency and the shadow generated. The choice of the Voronoi design is justified by its proven ability to effectively disperse incident solar radiation, reduce thermal accumulation, and offer a visually distinctive and functional architectural solution that aligns with sustainable and adaptive principles (Asghar et al., 2020; Trujillo Díaz, 2016).

SIMULATIONS AND COMPUTATIONAL TOOLS

To evaluate each strategy, advanced computational simulation tools were used that combined geometric and climatic models with optimization algorithms and artificial intelligence (Al-Shukri & Al-Majidi, 2020). In this process, Rhinoceros and its native Grasshopper plug-in were used, which integrate different optimization algorithms, such as Ladybug, Galapagos, and algorithms developed in the GhPython Script. The simulations were conducted under the same climatic conditions, using specific data from the Madrid context as a reference.

1. Climate modeling and solar trajectories: Detailed data on global and diffuse solar radiation were included, with annual and seasonal average values. Additionally, daily solar trajectories were modeled throughout the year, taking into account the characteristic inclination of the Mediterranean latitudes. For this, Ladybug, a tool integrated into Grasshopper, was used, which allowed a detailed analysis of the solar parameters and their impact on the building.
2. Energy evaluation: The incident radiation levels per square meter on each surface of the prism were calculated. These calculations were visualized through energy density maps, which allowed a detailed comparison between the strategies. The data were processed using GPT4All, an open-source artificial intelligence model that runs locally on a personal computer, without requiring an internet

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Table 2. Analysis of the model with horizontal sunshades by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)
South	2500	1.608	46.0
East	1500	0.682	48.7
West	1500	0.717	48.7
North	2500	0.499	48.8
Upper	1500	2.298	0.0

connection or dependence on external services such as ChatGPT or similar commercial platforms, thereby ensuring an autonomous and reproducible analysis.

3. Optimization using advanced algorithms: Genetic algorithms were implemented with Galapagos to optimize the configuration of solar protections, by iteratively selecting the most effective arrangements to reduce solar radiation (Díaz Valdés, 2021). Machine learning methods, supported by GPT4All, complemented the analysis by predicting solar incidence patterns and shadows to more accurately simulate the thermal behavior of facades. Similarly, scripts were developed in GhPython to customize and adjust the optimization parameters based on the specific climatic data of Madrid.

The selection of these three configurations arises from the need to explore different geometric and functional responses to the climatic challenge posed by solar radiation in Mediterranean climates. The horizontal model was chosen for its constructive simplicity and effectiveness against the sun in a high position. The tilted one was chosen for its adaptive flexibility and better performance against variable solar angles. The Voronoi model was chosen for its innovative character and ability to integrate aesthetic and functional criteria through the use of advanced parametric algorithms.

ANALYSIS PARAMETERS

The models were evaluated considering the following aspects:

- Total and diffuse solar radiation: Average annual values were calculated, seasonally segmented.
- Percentage reduction of radiation: Comparison of effectiveness compared to the base model.
- Energy distribution: Identification of critical areas with higher thermal gain.
- Impact on thermal comfort and energy efficiency: Estimation of the reduction in energy consumption associated with air conditioning.

This comprehensive approach made it possible to evaluate the effectiveness of each strategy, considering both its energy performance and architectural implications. In addition, it laid the foundations for developing sustainable and adaptive solutions, aligned with the Mediterranean climatic conditions.

RESULTS OF THE ANALYSIS

SOLAR PROTECTION STRATEGIES

The comparative analysis of solar protection strategies was conducted using a representative base model with an orientation parallel to the cardinal points. The building has a south facade that is completely exposed to direct radiation, while the north facade remains in shadow for most of the year. The east and west facades receive solar incidence mainly during the mornings and afternoons, respectively, and the horizontal roof is exposed throughout the day. This orientation was kept constant in all simulations to ensure the consistency of the results.

Three configurations were evaluated: Horizontal sunshades, individual tilted sunshades, and Voronoi latticework, as well as a hybrid strategy that combined the most efficient solutions of each model. The results obtained for each proposal are described below.

The first strategy, based on horizontal sunshades, achieved a 68% reduction in accumulated radiation compared to the unprotected model, resulting in a total of 3.04 kWh/m². The south face experienced a significant reduction (46%), although the roof remained unprotected, maintaining its exposure levels. The efficiency was moderate on the east and west facades, with values close to 48%, thanks to the constant shading of the slats. However, the lack of upper coverage limited the overall effectiveness of the system, especially in environments such as Madrid, where zenith radiation is high during the summer.

Horizontal sunshades (Figure 5) are effective on vertical faces (south, east, west, and north), as they reduce radiation evenly (Table 2). However, the upper face is still exposed to the maximum radiation, which limits the overall efficiency of the model. The uniformity in the reductions of the east and west faces suggests a design with constant separation, which can be improved

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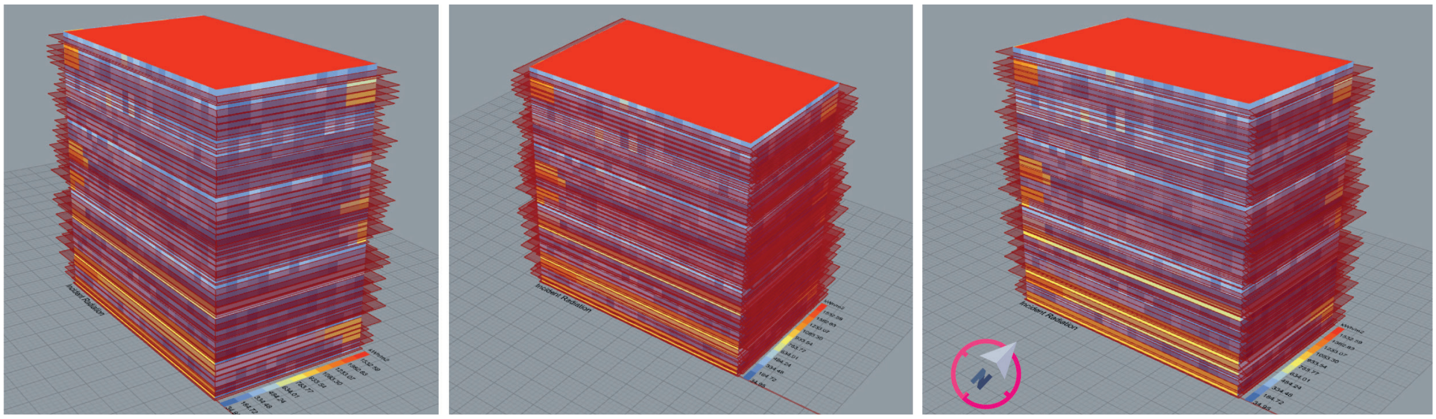

Figure 5. Differences in radiation per face of the base prism with sunshades, highlighting the variations in exposure compared to the extreme values. Source: Preparation by the Authors.

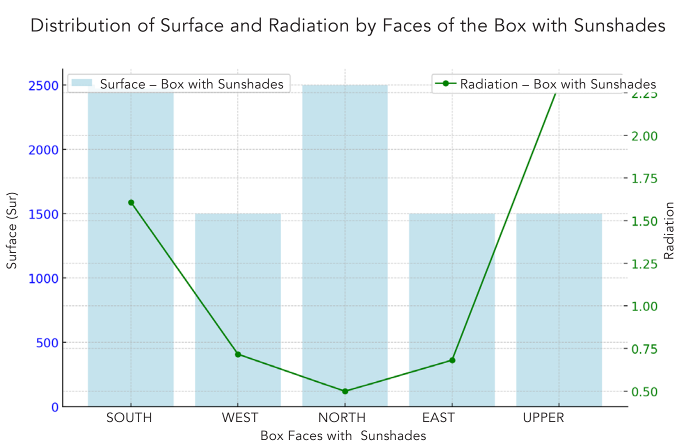

Figure 6. Surface and radiation distribution per face of the box with sunshades, which highlights the relationship between exposed area and received radiation. Source: Preparation by the Authors.

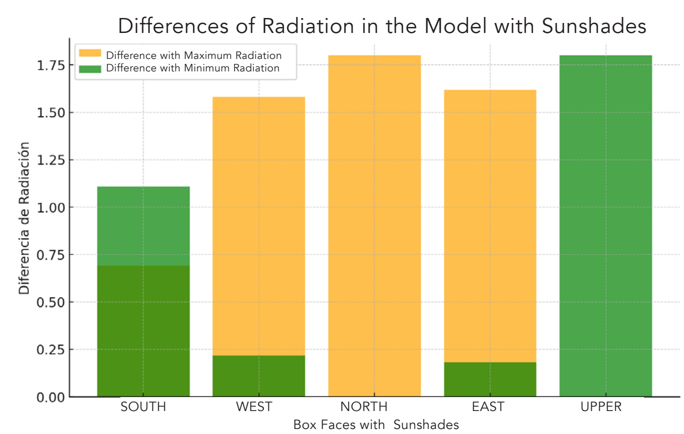

Figure 7. Differences in radiation in the model with sunshades, when comparing each face with the maximum and minimum values of the set. Source: Preparation by the Authors.

Table 3. Analysis of the model individual tilted sunshades by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)
South	2500	0.471	84.2
East	1500	0.293	77.9
West	1500	0.301	78.5
North	2500	0.328	66.4
Upper	1500	0.830	63.9

by adjustments in density or length according to solar variations. These results underscore the importance of comprehensive protection that covers all exposed faces to optimize thermal and energy performance in Mediterranean climates (Figure 6 and Figure 7).

In the second strategy, individual tilted sunshades, substantial improvements were observed. The radiation was reduced by 71.8% compared to the base model, accumulating only 2.65 kWh/m². This strategy was especially effective on the south facade, where it achieved a reduction of 84.2%, and on the roof, with a decrease of 63.9%. The tilted design allowed a better adaptation to the daily and seasonal solar trajectory by generating dynamic shadow zones without compromising interior daylighting. The reductions were uniform on all sides, confirming the superior performance of this strategy compared to traditional solutions (Table 3).

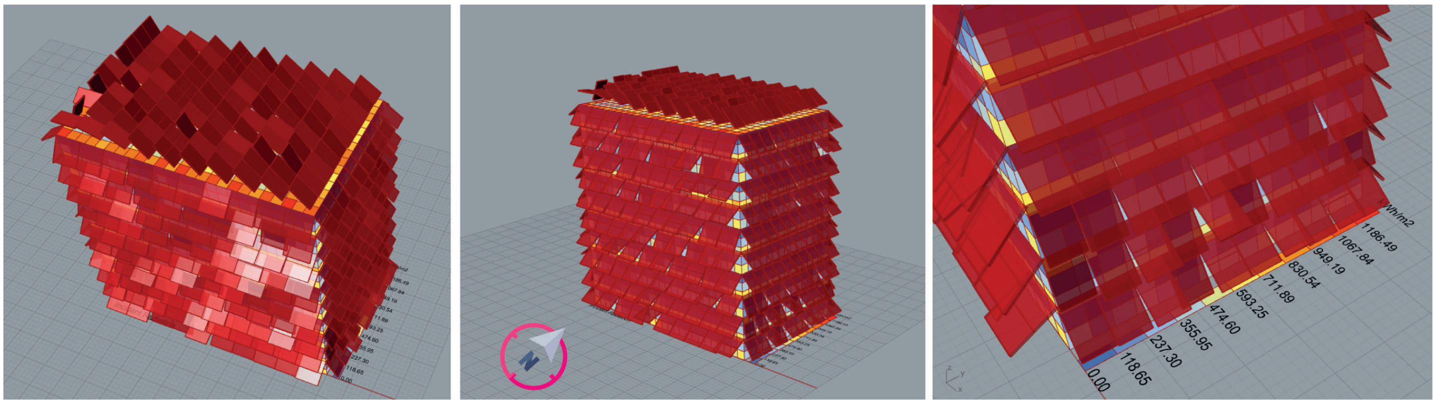

Figure 8. Differences in radiation per face of the base prism with tilted sunshades, each one being compared with the extreme values, highlight the variations in exposure. Source: Preparation by the Authors.

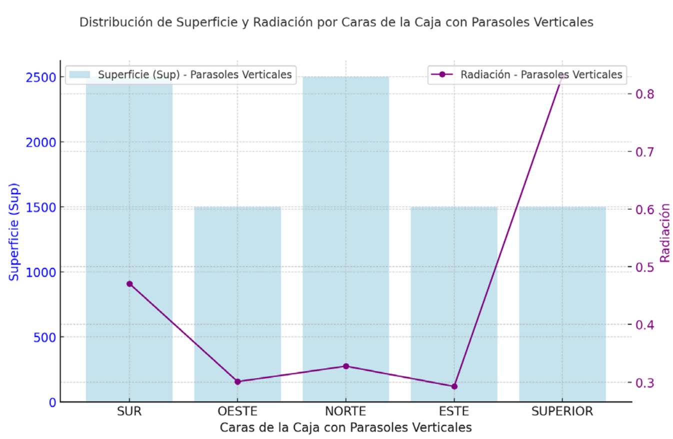

Figure 9. Surface and radiation distribution by prism face with tilted sunshades highlights the interaction between design and solar exposure. Source: Preparation by the Authors.

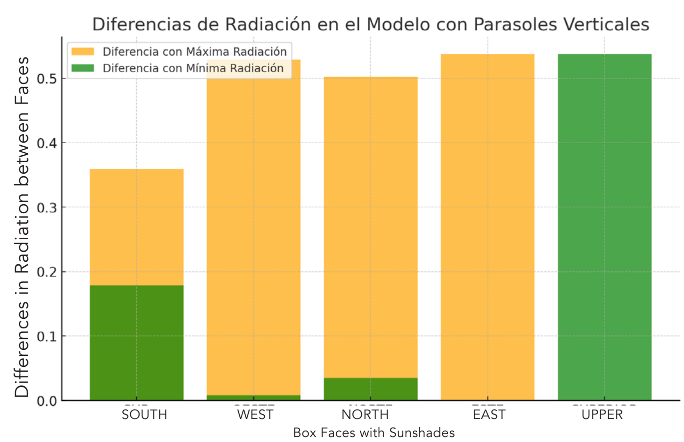

Figure 10. Radiation differences in the model with tilted sunshades, when comparing each face with the maximum and minimum values. Source: Preparation by the Authors.

Table 4. Analysis of the model with Voronoi sunshades by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)
South	2500	0.706	76.3
East	1500	0.324	75.6
West	1500	0.329	76.4
North	2500	0.249	74.4
Upper	1500	0.249	89.1

On the south face, the reduction is especially noticeable, which reflects its effectiveness for the predominant orientation in Madrid during the summer (Figure 8). In addition, the decrease in the radiation of the upper face is significant, a result that is not observed with horizontal sunshades. This is due to the shading generated by the vertical elements that cast shadow from the side faces, which demonstrates a more strategic design, adapted to the local climatic context (Figure 9 and Figure 10).

The third configuration evaluated was an envelope based on Voronoi geometric patterns, designed using parametric algorithms with holes of varying sizes. This solution achieved the highest individual efficiency, resulting in a 76.7% reduction in radiation (2.20 kWh/m²). The upper face benefited the most, with a reduction of 89.1%, while the vertical faces reached values between 74% and 76%. The irregular and three-dimensional geometry enabled the effective

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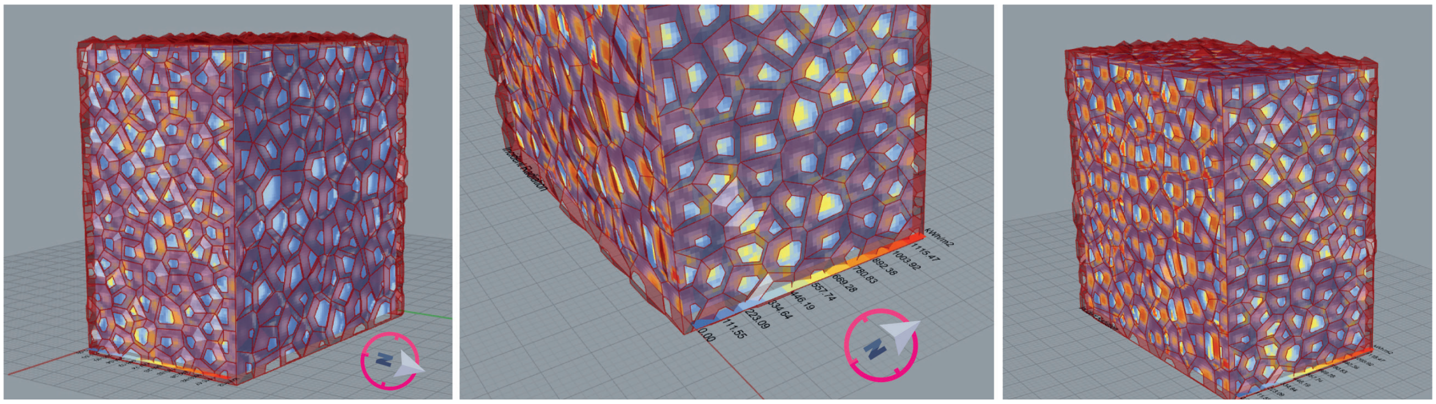

Figure 11. Differences in radiation per face of the base prism with Voronoi sunshades, when comparing each one with the maximum and minimum values observed. Source: Preparation by the Authors.

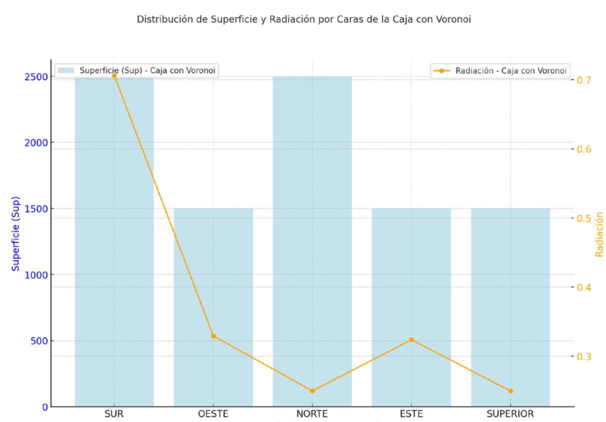

Figure 12. Surface and radiation distribution per face of the prism with Voronoi protection, which highlights the relationship between exposure and geometric design. Source: Preparation by the Authors.

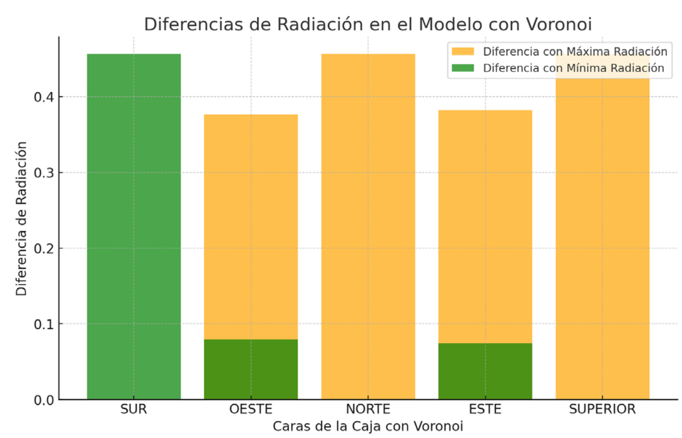

Figure 13. Radiation differences in the Voronoi model, when comparing each face with the maximum and minimum values. Source: Preparation by the Authors.

dispersion of radiation by combining solar control, formal identity, and bioinspired structural criteria (Table 4). However, its constructive complexity could pose a barrier in standard residential contexts, an aspect discussed later (Figure 11).

The Voronoi design not only significantly reduces radiation on all sides but also optimizes the thermal comfort and energy efficiency of the internal volume. Its uniform performance and the outstanding reduction on the upper face make it the most innovative and effective solution, adapted to the climatic conditions of the Mediterranean context (Figure 12 and Figure 13).

Finally, a composite model was developed by integrating the most effective systems by orientation: tilted sunshades on the south, east, and west facades, and a Voronoi system on the north face and the roof (Figure 14). This hybrid model achieved a total reduction of 81.9% (1.62 kWh/m^2), the lowest of all the configurations analyzed. The south face, traditionally the most critical, was reduced to 0.35 kWh/m^2, while the roof decreased to 0.18 kWh/m^2. The east and west faces were maintained at values around 0.23, achieving a balanced distribution and uniform protection in all orientations (Figure 15 and Figure 16). This solution demonstrated a high thermal and formal efficiency, with a level of optimization adaptable to different climatic contexts of the Mediterranean arc. The following table (Table 5) summarizes the annual average radiation values per face and the percentage reduction compared to the unprotected model:

The results confirm that the composite model surpasses the individual solutions by combining the best of each, adapting its response to the building's geometry and solar incidence according to orientation. This flexibility makes it an optimal alternative for buildings with multiple exposed facades in hot climates (Table 6).

Figure 17 and Figure 18 illustrate the radiation patterns by face and the morphology of each strategy, facilitating the visual interpretation of the results and evidencing the formal impact of each proposal. The

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Table 5. Comparison of the results of the different models of sunshades. Source: Preparation by the Authors.

Face	Without Sunshades kWh/m2	Horizontal kWh/m2	Vertical kWh/m2	Voronoi kWh/m2	Composite kWh/m2	Best Solution
South	2.98	1.61	0.47	0.71	0.35	Compositive
East	1.33	0.68	0.29	0.32	0.23	Compositive
West	1.40	0.72	0.30	0.33	0.23	Compositive
North	0.98	0.50	0.33	0.25	0.23	Compositive
Upper	2.30	2.30	0.83	0.25	0.18	Compositive

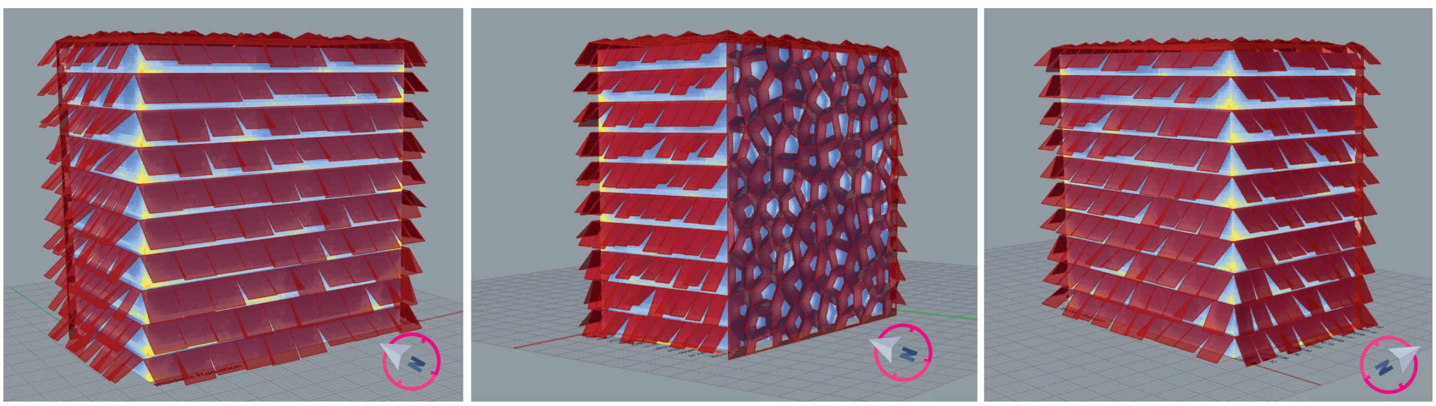

Figure 14. Composite model that integrates tilted sunshades on the south, east, and west facades, due to their high exposure to direct solar radiation, and a geometric system based on Voronoi diagrams on the north and Upper surfaces, optimizing both solar control and the overall energy efficiency of the building. Source: Preparation by the Authors.

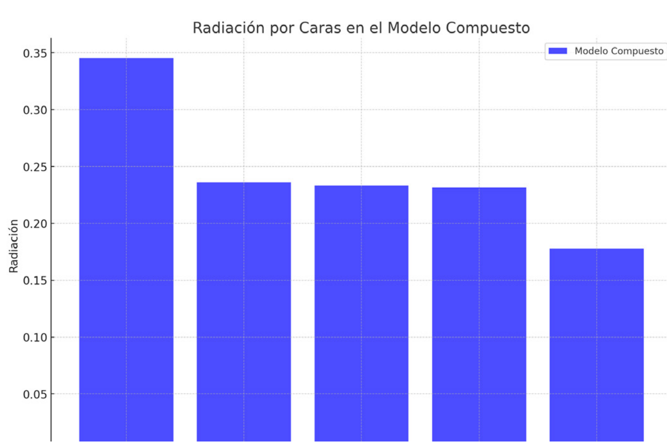

Figure 15. Radiation per face in the Composite Model, which highlights a significant reduction in all orientations. The SOUTH face, although it is the most exposed, reduces its radiation to 0.345 units. The EAST and WEST faces maintain a balanced level around 0.23 units, while the NORTH face shows a low exposure with 0.233 units. The UPPER face registers the least radiation, with only 0.178 units, evidencing the effectiveness of the composite design. Source: Preparation by the Authors.

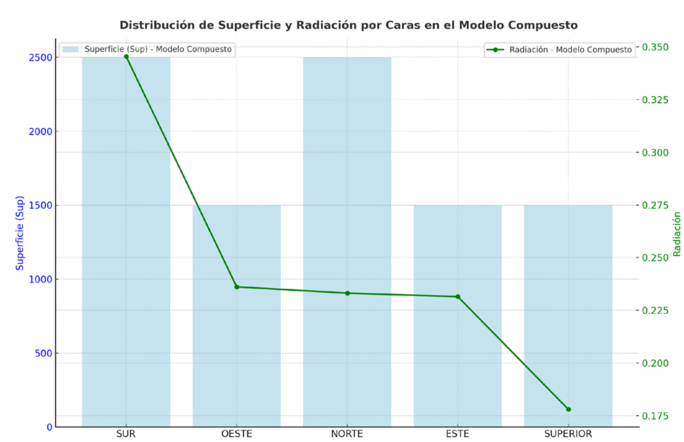

Figure 16. Distribution of the surface by face and the radiation values in the composite model, highlighting the radiation variations according to the orientation and exposure of each face. Source: Preparation by the Authors.

Table 6. Comparison of the results of the different models of sunshades. Source: Preparation by the Authors.

Model	Total Radiation (kWh/m2)	Reduction (%)
Without Sunshades	8.98	—
With Horizontal Sunshades	5.81	35.4%
With Vertical Sunshades	2.65	70.5%
With Voronoi	2.20	75.5%
Composite Model	1.62	81.9%

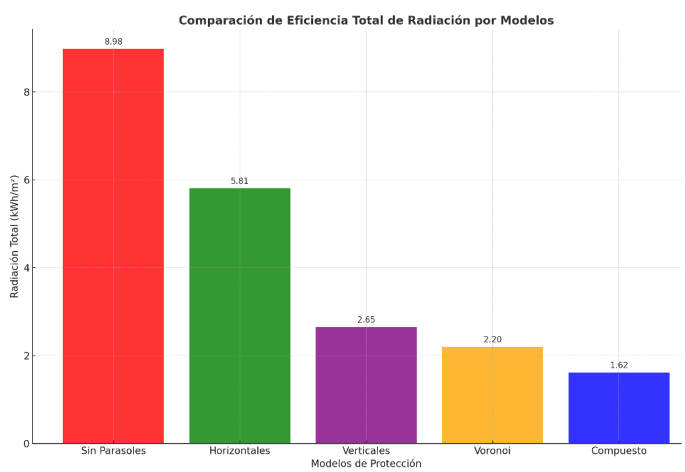

Figure 17. Graphical comparison of the total radiation in the different models evaluated. The graph highlights the model without sunshades as the one with the highest exposure, while the composite model is positioned as the most efficient solution, with the lowest accumulated radiation. Source: Preparation by the Authors.

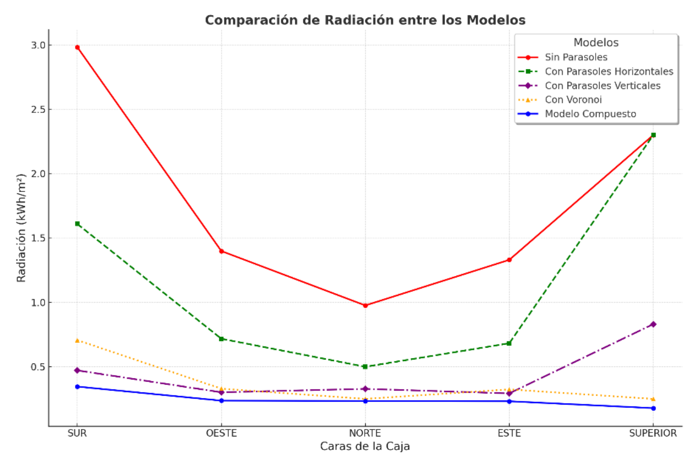

Figure 18. Comparative graph representing the radiation on the different faces of the box for the five models. Source: Preparation by the Authors.

reader is recommended to observe, in particular, the progression between the Voronoi strategy and the composite model, where an effective synthesis is achieved between thermal performance, architectural aesthetics, and technical feasibility.

CONSTRUCTIVE FEASIBILITY AND MATERIALITY OF THE PROPOSED STRATEGIES

Beyond the computer analysis, considering the constructive feasibility of the proposed strategies is essential. In particular, the composite model can be developed using currently available digital manufacturing technologies, without requiring complex or exclusive systems. The tilted sunshades are compatible with modular solutions made of anodized aluminum or low-thickness galvanized steel, with standard anchors for the ventilated facade or auxiliary structure. Thermoformed recyclable plastic panels, suitable for high-solar-exposure environments, could also be used. As for the Voronoi envelope, its materialization is feasible through CNC cutting on sheet metal, 3D printing on technical polymers, or GFRP-type composite panels, depending on the desired degree of rigidity, curvature, and translucency. These techniques allow for the control of the thickness, pattern, and assembly of each module, which facilitates prefabrication and on-site assembly.

In institutional or cultural projects, these strategies can be implemented with total geometric fidelity. In residential programs, it is feasible to adopt simplified versions that maintain the principle of adaptive solar control without incurring cost overruns. The key lies in adjusting the degree of complexity to the program and the budget, maintaining the optimized morphological logic that underlies each solution.

Recent studies have already documented the structural and morphological applications of the Voronoi pattern in architecture, demonstrating its adaptability and efficiency in both mechanical and formal terms. In particular, Agudelo Londoño et al. (2015) highlighted its properties in load distribution and shock absorption, while Sora Yanquén (2007) and Flores Jurado et al. (2020) analyzed its potential

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in generating optimized three-dimensional surfaces through parametric design. More recently, Habib et al. (2024) and Bormashenko et al. (2021) have explored new classifications and entropy measures in Voronoi systems, applied to the design of adaptive envelopes and the coding of natural patterns. These investigations confirm that Voronoi morphology not only has aesthetic or theoretical value but also offers a viable framework for developing materializable, sustainable, and structurally coherent architectural solutions.

CONCLUSIONS

This study demonstrates that integrating advanced geometric strategies with computer simulation tools enables significant optimization of solar protection in buildings with a Mediterranean climate. Through a rigorous and quantitative analysis, different configurations that responded to real conditions of the urban and climatic environment of Getafe, within the Community of Madrid, were compared.

The results show that the composite model, which combines tilted sunshades on the most exposed facades with a Voronoi latticework on the surfaces that receive diffuse or overhead radiation, achieves the most significant reduction in accumulated radiation, with an improvement of 81.9% compared to the unprotected model. This solution is presented as a balanced and replicable proposal, capable of adapting to various orientations and sunlight conditions without compromising the aesthetic or energy performance of the entire structure.

Unlike horizontal systems, which, although easy to implement, do not effectively protect the roof, and pure Voronoi envelopes, whose complexity can limit their use in conventional residential projects, the hybrid model offers a pragmatic and adaptable alternative. The tilted elements, being arranged according to specific solar angles, maximize the shadow cast on the facades during critical hours without impeding daylighting. On the other hand, the Voronoi pattern, applied exclusively to the roof and north facade, allows for localized geometric optimization with strong expressive and technical potential.

As previously stated, these strategies can be developed using modular construction systems and accessible digital technologies, by adjusting their degree of complexity depending on the architectural program. This technical flexibility opens up new possibilities for its implementation in both institutional contexts and medium-scale residential programs, allowing high-performance solutions with controlled costs and maintenance.

In terms of design, the study confirms the need to abandon generic or standardized approaches in solar protection and move towards solutions that integrate design and simulation from the initial stages. The use of algorithms and climate analysis allows not only improved energy efficiency but also enriched architectural expressiveness without sacrificing functionality. The shape ceases to be an arbitrary aesthetic result and becomes a direct consequence of the interaction between geometry, climate, and program.

Although the post-occupational monitoring phase is not addressed in this article, it is acknowledged that the next step will be to evaluate the actual implementation of these systems in pilot works, which identify thermal behavior under everyday use conditions. Likewise, it is considered pertinent to study its application in non-residential buildings, such as schools, libraries, or cultural centers, where functional flexibility and formal expressiveness allow a freer integration of advanced solar control technologies.

Ultimately, this research not only examines the impact of parametric and bioinspired methods on architecture but also underscores their role in transforming contemporary design culture by fostering a more integrated and systemic approach to design. Far from being limited to a reactive response, architecture must assume a proactive role where the models developed are not definitive solutions, but catalysts for critical speculation that intertwines aesthetics, technique, and ethics, redefining the relationship with space, time, and the environment.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, M.A.F.N.; Data Curation, M.A.F.N.; Formal analysis, M.A.F.N.; Acquisition of funding, M.A.F.N.; Research, M.A.F.N.; Methodology, M.A.F.N.; Project management, M.A.F.N.; Resources, M.A.F.N.; Software. M.A.F.N.; Supervision, M.A.F.N.; Validation, M.A.F.N.; Visualization, M.A.F.N.; Writing - original draft, M.A.F.N.; Writing - revision and editing, M.A.F.N.

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SOLAR PHOTOVOLTAIC ENERGY IN FAMILY DWELLINGS: A BIBLIOMETRIC STUDY OF ISSUES EXPLORED, TRENDS, AND CHALLENGES

ENERGÍA SOLAR FOTOVOLTAICA EN VIVIENDAS FAMILIARES: ESTUDIO BIBLIOMÉTRICO DE TEMAS EXPLORADOS, TENDENCIAS Y RETOS

ENERGIA SOLAR FOTOVOLTAICA EM RESIDÊNCIAS FAMILIARES: ESTUDO BIBLIOMÉTRICO DE TEMAS EXPLORADOS, TENDÊNCIAS E DESAFIOS

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RESUMEN

Este estudio analiza la evolución científica sobre energía solar fotovoltaica en viviendas familiares mediante un análisis bibliométrico basado en Scopus y herramientas como Bibliometrix y VOSviewer. Se examinaron 414 documentos publicados entre los años 2000 y 2024, se aplicó un enfoque cuantitativo y técnicas de visualización de redes. Los hallazgos evidencian un crecimiento sostenido desde el año 2008 y un auge desde 2016, impulsado por el interés global en energías renovables. Las principales contribuciones provienen de áreas como energía, ingeniería y ciencias ambientales, consolidándose "Applied Energy" y "Energies" como revistas clave. Conceptos como "solar energy" y "energy efficiency" dominan el campo, destacándose temas motores como almacenamiento de energía e integración de redes inteligentes, y emergentes como simulaciones energéticas. Se recomienda ampliar las fuentes de datos y explorar enfoques comparativos para mejorar la comprensión de los factores que afectan la adopción de esta tecnología.

Palabras clave
energía solar, tecnología fotovoltaica, viviendas familiares, sostenibilidad

ABSTRACT

This study analyzes the scientific evolution of solar photovoltaic energy in family dwellings using a bibliometric analysis based on Scopus and tools such as Bibliometrix and VOSviewer. 414 papers published between 2000 and 2024 were reviewed, employing a quantitative approach and network visualization techniques. The findings indicate sustained growth since 2008 and a notable surge since 2016, driven by global interest in renewable energies. The main contributions come from energy, engineering, and environmental sciences, with "Applied Energy" and "Energies" consolidated as key journals. Concepts such as "solar energy" and "energy efficiency" dominate the field, with topics like energy storage and smart grid integration standing out, as well as emerging areas like energy simulations. It is recommended that data sources be expanded and comparative approaches be explored to improve the understanding of the factors influencing the adoption of this technology.

Keywords
solar energy, photovoltaic technology, family housing, sustainability

RESUMO

Este estudo analisa a evolução científica da energia solar fotovoltaica em residências familiares por meio de uma análise bibliométrica baseada no Scopus e ferramentas como Bibliometrix e VOSviewer. Foram examinados 414 documentos publicados entre os anos 2000 e 2024, aplicando-se uma abordagem quantitativa e técnicas de visualização de redes. Os resultados evidenciam um crescimento sustentado desde 2008 e um auge desde 2016, impulsionado pelo interesse global em energias renováveis. As principais contribuições provêm de áreas como energia, engenharia e ciências ambientais, com a consolidação de "Applied Energy" e "Energies" como revistas-chave. Conceitos como "energia solar" e "eficiência energética" dominam o campo, com destaque para temas catalisadores como o armazenamento de energia e a integração de redes inteligentes, e temas emergentes como as simulações energéticas. Recomenda-se ampliar as fontes de dados e explorar abordagens comparativas para melhorar a compreensão dos fatores que afetam a adoção desta tecnologia.

Palavras-chave:
energia solar, tecnologia fotovoltaica, residências familiares, sustentabilidade

INTRODUCTION

Solar photovoltaic energy has emerged as a primary solution to address the growing demand for clean and sustainable energy worldwide. In a context marked by the transition to decarbonized economies, photovoltaic technologies have shown enormous potential to reduce greenhouse gas emissions and mitigate the effects of climate change. In particular, applications in family homes have become relevant due to their ability to promote energy self-sufficiency, optimize electricity consumption, and contribute to the economic well-being of households (Maghrabie et al., 2021; Cillari et al., 2021; Nykyri et al., 2022; Vahabi Khah et al., 2023). However, these initiatives face significant challenges related to technological limitations, high initial investment costs, and regulatory barriers that hinder mass adoption (Liu et al., 2021b; Herrando et al., 2023; Shabbir et al., 2022).

At a global level, climate and energy policies have played a crucial role in promoting solar photovoltaic energy projects in dwellings. The implementation of strategies such as energy communities and distributed generation in European Union countries has promoted the integration of photovoltaic systems in residential environments, which has achieved promising results in terms of efficiency and sustainability (Gallego-Castillo et al., 2021; D'Agostino et al., 2022; Gamaleldine & Corvacho, 2022; García-Gáfaro et al., 2022). Nevertheless, regional inequalities in terms of infrastructure and access to renewable technologies underscore the need to design approaches tailored to the local specificities and socio-economic capacities of each region (Nematchoua et al., 2021; Hu et al., 2021; Cerezo-Narváez et al., 2021; Xue et al., 2021).

The research question is posed in this context: What are the patterns and trends of the scientific approach to photovoltaic solar energy in family homes over time? This question seeks to elucidate not only the evolution of scientific production, but also the priority areas of research, the predominant methodological approaches and the factors that drive or limit progress in this field; and specifically: 1): How many studies have been published over the years?, 2) Who are the most active authors in the area?, 3) What are the most important journals related to the topic?, 4) Which areas of knowledge have been researched, 5) What is the semantic development of the phenomenon under study?, 6) What are the driving topics, perspectives, niches, and emerging themes of the phenomenon under study?, 7) What are the historical roots of the central concept or construct of the topic under study? The current literature presents a wide variety of perspectives that address aspects such as efficient energy management, storage technologies, and interactions between users and photovoltaic systems (Liu et al., 2021b; Alqahtani & Balta-Ozkan, 2021; Mascherbauer et al., 2022; Padovani et al., 2021).

In this sense, the main objective of the study is to know the patterns and trends of the scientific approach over time and also to evaluate the impact of academic sources, determine the main authors, identify the areas of knowledge from which they have been investigated, explore the most pertinent topics, evaluate methodological approaches, identify potential areas for future research, and establish the origin of the main construct of the topic to be investigated. This study is justified by the need to understand how research in solar photovoltaics for family homes has evolved, which identifies patterns, trends, and areas of opportunity for future explorations. By providing a comprehensive bibliometric analysis, it is hoped that this contribution will enhance knowledge in this field, offering valuable tools for researchers, policymakers, and professionals seeking to accelerate the transition to sustainable renewable energies.

Several studies have highlighted the impact of complementary technologies on improving the performance of photovoltaic systems. For example, Liu et al. (2021a), Bakthavatchalam et al. (2022), and Heinz and Rieberer (2021) underline the importance of energy storage using batteries and the use of hydrogen vehicles to guarantee a continuous energy supply in residential communities. Similarly, Maghrabie et al. (2021), Forrousso et al. (2024), Sadeghibakhtiar et al. (2024), and Sohani et al. (2023) highlight the innovative applications of photovoltaic systems integrated in buildings, which not only improve energy efficiency but also reduce operating costs and promote long-term sustainability. These investigations underscore the need for a multidisciplinary approach that integrates technological, economic, and social perspectives.

On the other hand, studies such as those of Gallego-Castillo et al. (2021) and Masip et al. (2023) mention that the success of solar photovoltaics in housing depends on striking an appropriate balance between political regulations and social acceptance. The establishment of autonomous energy communities and the exchange of energy between users have been key proposals to promote collaboration and reduce implementation costs. In addition, recent research highlights the need to consider future climate changes and their impact on the viability of photovoltaic systems, which reinforces the relevance of long-term strategic planning (Nematchoua et al., 2021; Neves et al., 2021).

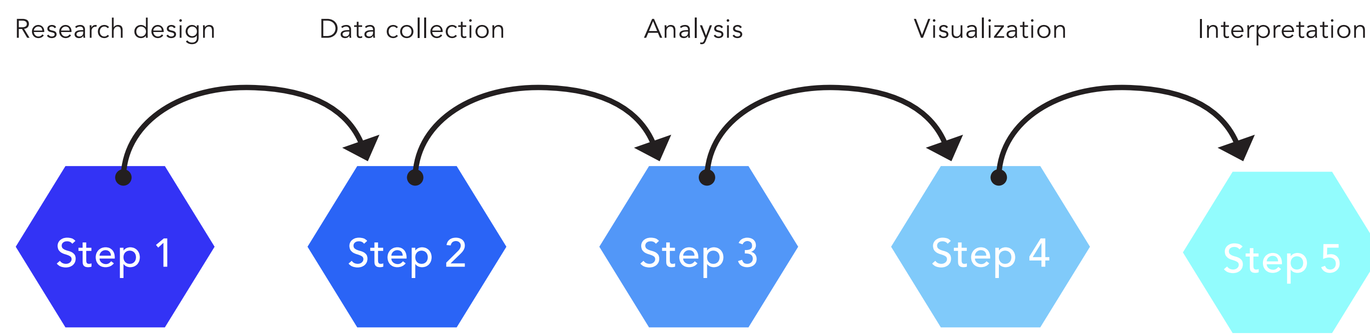

Figure 1. Steps of the proposed methodological model. Source: Prepared by the authors.

METHODOLOGY

This quantitative research is a bibliometric analysis, the same that has been used in different fields of study among researchers (Aria & Cuccurullo, 2017). The methodological model proposed by Zupic and Čater (2014) was used, which consists of five steps: i) research design; ii) collection of bibliometric data; iii) analysis; iv) visualization, and v) interpretation (Figure 1).

RESEARCH DESIGN

This research, examining photovoltaic solar energy in family homes, analyzed a series of academic articles collected up to 2024. The research design is a non-experimental longitudinal study, incorporating studies conducted since 2000. For this reason, this study offers significant perspectives that can help make well-informed decisions about solar photovoltaics and family homes in a complex and constantly evolving landscape.

COLLECTION OF BIBLIOMETRIC DATA

In this bibliometric analysis, the internationally recognized Scopus database was used, which contains approximately 28 million abstracts (Burnham, 2006), making it the most comprehensive database available. At the same time, the search parameters were determined from the information contained in the title, the abstract and the keywords of the publications, introducing several search terms related to the topic of study, such as "photovoltaic solar energy;" "solar panels;" "photovoltaic systems;" "solar power generation;" "photovoltaic technology;" "distributed solar energy"; and "family homes;" "residential homes;" "single family homes;" "family residences;" "domestic homes;" or "residential buildings". The words selected were chosen to improve accuracy, relevance, and clarity, while catering to a broad range of audiences and perspectives. They facilitate obtaining more relevant results and allow exploring various facets of solar photovoltaic energy in family homes. The initial search yielded a total of 4,656 documents spanning from 2000 to November 2024. It is worth noting that the search strategy was limited to open-access resources, as it sought to provide access to research articles.

Filters were then applied to improve the results. For this, the search was carried out in the titles for the key terms: TITLE-ABS-KEY ("Photovoltaic solar energy" OR "Solar Panels" OR "Photovoltaic systems" OR "Solar power generation" OR "Photovoltaic technology" OR "Distributed Solar Energy") AND TITLE-ABS-KEY ("Family homes" OR "Residential homes" OR "Single family homes" OR "Family residences" OR "Domestic homes" OR " Residential buildings"), which resulted in a total of 414 records relevant to this research. Additionally, the necessary bibliometric data were obtained from the Scopus platform in CSV file format, which includes all available information, such as the number of citations, authors, year of publication, journal titles, and other relevant details. This data was used in the study to obtain relevant conclusions and results.

RESULTS

This section presents the results of the bibliometric analysis regarding the research questions posed, related to photovoltaic solar energy in family homes (Table 1).

Throughout the analyzed period, from 2000 to 2024, a total of 414 documents were published, according to the provided data. This number reflects the continuous effort in generating knowledge related to the subject of study. In addition, the average annual growth rate of 18.84% indicates a consistent increase in scientific production, suggesting a growing interest in the academic community to explore and address related thematic areas. The information reflects a solid research activity with a collaborative approach,

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Table 1. General information. Source: Metadata was used, analyzing the indicators in Bibliometrix to 2024

Description	Results
MAIN INFORMATION ABOUT THE DATA	
Period	2000:2024
Sources (Journals, Books, etc.)	151
Documents	414
Annual growth rate %	18.84
Average age of the document	3.57
Average number of citations per document	18.19
References	16240
CONTENTS OF THE DOCUMENT	
Keywords plus (ID)	2588
Author's keywords (DE)	1302
AUTHORS	
Authors	1444
Authors of single-author documents	20
COLLABORATION BETWEEN AUTHORS	
Documents by a single author	21
Co-authors by document	3.86
International co-authorships %	27.29

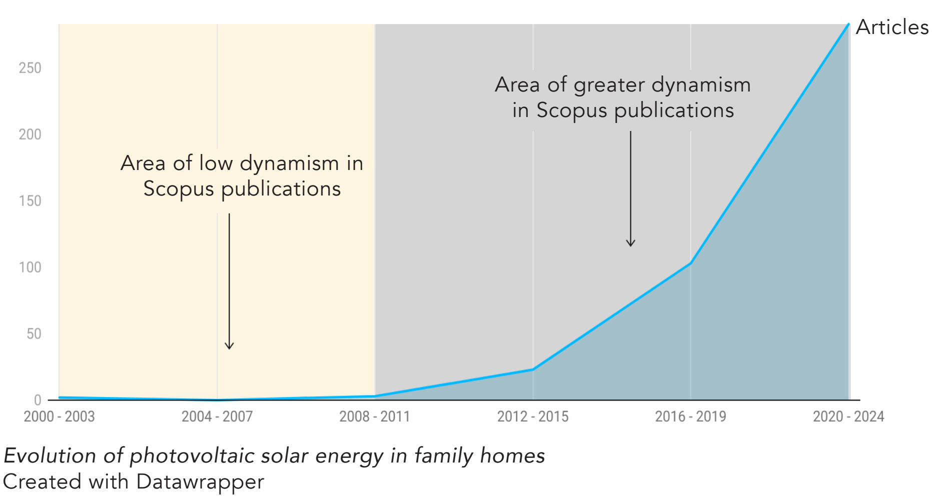

Figure 2. Changes over time in the number of publications. Source: Prepared by the authors.

as evidenced by the average of 3.86 co-authors per document and a notable proportion of international co-authors, which accounts for 27.29%. This shows a trend towards greater integration and global cooperation in the studies published during the analyzed period.

The evolution of publications related to photovoltaic solar energy in family homes shows an interesting pattern over time (Figure 2). Between 2000 and 2007, a period of low dynamism was observed, characterized by slow growth in the number of published articles. This period reflects a limited initial interest or the early stage of research in this field. From 2008 to 2015, a more sustained increase is observed, marking a transition to an area of greater dynamism. However, it is between 2016 and 2024 that an accelerated growth is experienced, reaching a significant peak in publications. This increase suggests a growing global

Lotka's Law. A large proportion of authors contribute one article, and only a minimal proportion contribute more than two articles
Created with Datawrapper

Figure 3. Observance of Lotka's Law Source: Prepared using metadata obtained from Scopus, indicators analyzed in Bibliometrix, and presented through Datawrapper.

Table 2. Performances of the top 10 authors in the collection. Source: Prepared using metadata obtained from Scopus, the indicators were processed in Bibliometrix.

Author	h-index	m-index	Total citations	Publications	First publication
ABDALLAH R	4	1.00	92	4	2021
ALBATAYNEH A	4	1.00	94	6	2021
ASIF M	4	0.40	164	4	2015
JUAIDI A	4	1.00	92	4	2021
MANZANO-AGUGLIARO F	4	1.00	92	4	2021
ABANDA FH	3	0.33	82	3	2016
CHRISTOFORIDIS GC	3	0.38	105	3	2017
DONG J	3	0.27	25	3	2014
ENONGENE KE	3	0.33	82	3	2016
KURUGANTI T	3	0.43	24	3	2018

Top 10 authors, measured by h and m index, since the first year of publication

interest in the topic, likely driven by heightened environmental awareness, sustainability policies, and technological advancements in solar photovoltaics. In this sense, the graph also highlights that this field of study has gained popularity in recent years, with an exponential increase in academic production between 2020 and 2024, which reflects its relevance as a critical issue within the debates on renewable energy and sustainability.

Figure 3 and Table 2 reinforce the analysis based on Lotka's Law, which states that most authors contribute with a single article, while a small percentage make multiple contributions. In this case, the distribution shows that 1,333 authors (92.31%) have published only one article, which confirms that the research effort in this field is concentrated on specific contributions. This could be due to the emerging or interdisciplinary nature of the topic, which has attracted researchers from different areas who make a single publication related to this field. Also, a significantly smaller number of authors, 78 (5.4%), have published two articles, while only 24 authors (1.66%) have contributed with three publications. This decreasing pattern continues, with only seven authors publishing four articles, and marginal figures for those who have published five or six articles, each representing 0.07% of the researchers.

This behavior suggests that, although the field of study has a broad scope in terms of participation, few researchers specialize in depth and make recurring contributions. Such a distribution not only reflects the

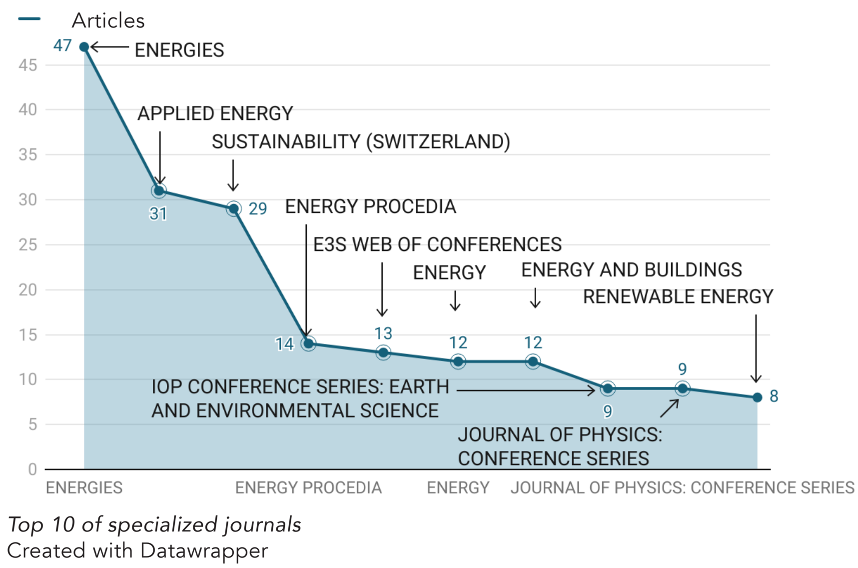

Figure 4. Observance of Bradford's Law concerning the productivity of journal publications. Source: Prepared by the Authors, using metadata obtained from Scopus, indicators analyzed in Bibliometrix, and presented through Datawrapper.

dynamic nature of the topic but also its capacity to engage researchers from diverse contexts. However, the low number of authors with multiple publications could indicate a need to consolidate research communities more dedicated to the topic, which could further enhance the accumulated knowledge and innovations in this field.

The analysis of the productivity of the top 10 authors in the field of solar photovoltaic energy for family homes, based on the h and m indices, as well as total citations and publications, evidences significant contributions within a relatively recent timeframe. Most of these authors started publishing between 2014 and 2021, reflecting that this field of study is relatively new and has gained traction in recent years. Among the authors, Albatayneh A. stands out as the most prolific, with six publications and 94 total citations, achieving an h-index of 4 and an m-index of 1.00, indicating a consistent and sustained impact since 2021. Other authors, such as Abdallah R., Juaidi A., and Manzano-Aguilaro F., also exhibit similar performance, with an h-index of 4 and an m-index of 1.00, accompanied by four publications each, all published since 2021. This group of authors represents a recent and concentrated contribution in terms of academic impact.

On the other hand, authors such as Asif M. and Dong J. have a more extensive career, having begun publishing in 2015 and 2014, respectively. Asif M. stands out with 164 citations in total, the highest number among the authors analyzed, suggesting that his publications have had a significant impact on the field. Nonetheless, his m-index of 0.40 indicates a more moderate pace of citation, considering the elapsed time. Furthermore, authors like Abanda FH and Enongene KE, with an h-index of 3 and an m-index of 0.33, have made a notable contribution with three publications each since 2016, accumulating 82 citations. Meanwhile, Dong J. and Kuruganti T. have a more limited impact in terms of total citations (25 and 24, respectively), suggesting that their influence in the field could be more specific or still in development. In general, the data reflect an expanding field, with significant contributions coming from authors who, for the most part, have begun to publish in recent years. This suggests a trend toward the growth and consolidation of knowledge about solar photovoltaic energy in family homes, driven by a group of key researchers who lead academic production.

Figure 4 illustrates the application of Bradford's Law to the productivity of journals related to solar photovoltaic energy in family homes, with a focus on journals in Zone 1, which are considered core sources. According to this law, a small number of journals concentrate the majority of publications in a specific subject area, as evident in the graph. In this case, Energies is positioned as the primary source, with 47 published articles, making it the core line of scientific dissemination in this field. Its predominance reflects its high specialization and relevance for researchers working in this area. Other journals, such as Applied Energy and Sustainability (Switzerland), are also part of this core, with 31 and 29 articles, respectively.

However, although their contribution is less than that of Energies, these journals are still essential sources, representing reliable and high-impact publishing platforms for studies related to the subject. As one moves towards the following journals on the list, such as Energy Procedia (14 articles) and E3S Web of Conferences (13 articles), productivity decreases,

Table 3. Productivity of the top 10 journals, linked to the collection. Source: Preparation by the Authors. The table was created using metadata obtained from Scopus, and the indicators were processed in Bibliometrix.

Fuente	Índice h	Índice m	Total citas	Publicaciones	Año inicio publicaciones
APPLIED ENERGY	23	2.30	1817	31	2015
ENERGIES	13	1.08	537	47	2013
SUSTAINABILITY (SWITZERLAND)	13	1.30	498	29	2015
ENERGY PROCEDIA	9	0.90	212	14	2015
ENERGY	8	0.50	281	12	2009
ENERGY AND BUILDINGS	8	0.80	270	12	2015
RENEWABLE AND SUSTAINABLE ENERGY REVIEWS	7	0.88	289	7	2017
RENEWABLE ENERGY	7	0.70	425	8	2015
ENERGY REPORTS	5	0.56	263	7	2016
IEEE ACCESS	5	0.71	159	7	2018

Top 10 most important journals, measured by the h and m index, since they started publication

which follows the pattern expected by Bradford's Law. These journals, although relevant, do not reach the same density of publications as the first three, but they continue to be significant within the core zone. In conclusion, the observation of Bradford's Law in this collection reaffirms that a small number of journals concentrate the majority of relevant publications. This suggests that researchers tend to prefer these core sources to maximize the visibility and impact of their work, consolidating their role as key players in the dissemination of knowledge in the field of solar photovoltaic energy.

The analysis of the productivity of the top 10 journals linked to the collection (Table 3) shows an evident heterogeneity in terms of impact and volume of publications. Applied Energy is positioned as the most influential journal, with an h-index of 23—the highest on the list—reflecting its ability to accumulate a large number of citations (1,817 in total) from 31 publications since 2015. Its m-index of 2.30 indicates a constant impact over time. On the other hand, Energies stands out for its volume, with 47 publications, the most significant number among the journals analyzed. Although it has an h-index of 13 and a total of 537 citations, this suggests a more moderate impact compared to its number of articles. Its m-index of 1.08 reflects a significant but less consistent contribution in terms of citations per year since 2013. Journals such as Sustainability (Switzerland) and Energy Procedia have h-indices of 13 and 9, respectively, with a start of publications in 2015. Although Sustainability (Switzerland) has more publications (29 vs. 14) and a higher relative impact (m-index of 1.30 vs. 0.90), both journals have proven to be important for the field.

The case of Energy is notable for being the oldest journal on the list, which started its publications in 2009. With an h-index of 8 and a total of 281 appointments, its productivity is consistent, although its m-index of 0.50 reflects a lower rate of impact accumulation. On the other hand, Renewable and Sustainable Energy Reviews and Renewable Energy have h-indices of 7. Nevertheless, the former accumulates fewer publications (7 versus 8) and a slightly lower total of citations (289 versus 425). This could indicate a more targeted specialization of the articles published in these journals. Finally, journals such as Energy Reports and IEEE Access, with h-indices of 5 each, represent sources of lower volume and age (since 2016 and 2018, respectively). However, their inclusion on this list reflects their emerging relevance to the topic. Together, these journals represent a mix of consolidated and emerging platforms that, collectively, contribute to the development and dissemination of knowledge in solar photovoltaic energy for family homes. The variability in their h and m indices, as well as the number of citations, reflects differences in scope, specialization, and impact within the field.

Figure 5 illustrates the distribution of research on photovoltaic solar energy in family homes across various areas of knowledge, reflecting its multidisciplinary nature. The most significant focus comes from the Energy area, which accounts for 28.4% of the analyzed documents. This data is consistent with the nature of the topic, since solar photovoltaic energy is a technology directly related to the energy sector, both in terms of generation and efficiency. The second highest represented area is Engineering, with 23.5% of the studies. This approach emphasizes the importance of

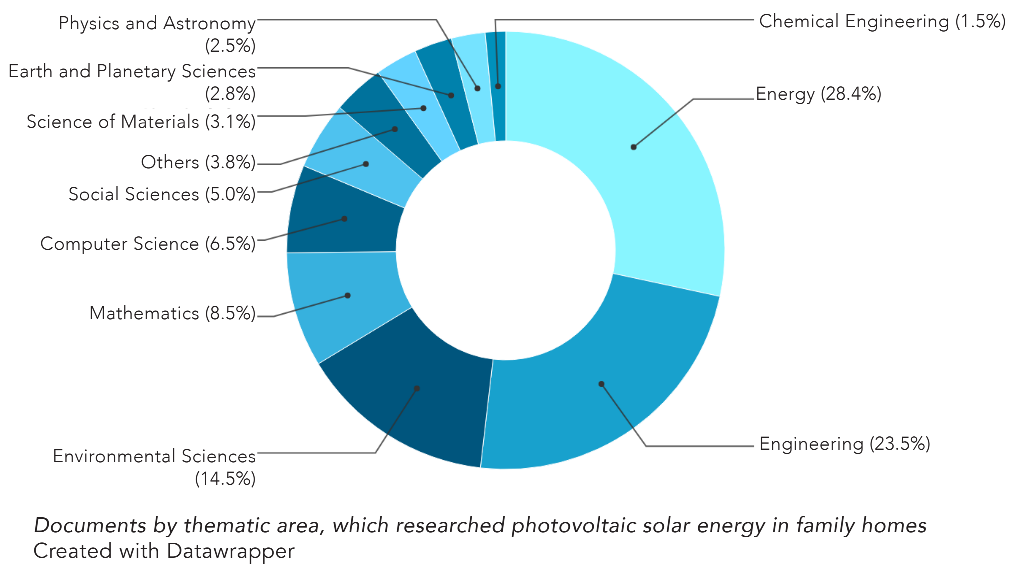

Figure 5. Areas of knowledge that scientifically investigate photovoltaic solar energy in family homes. Source: Prepared by the Authors using metadata obtained from Scopus and presented through Datawrapper.

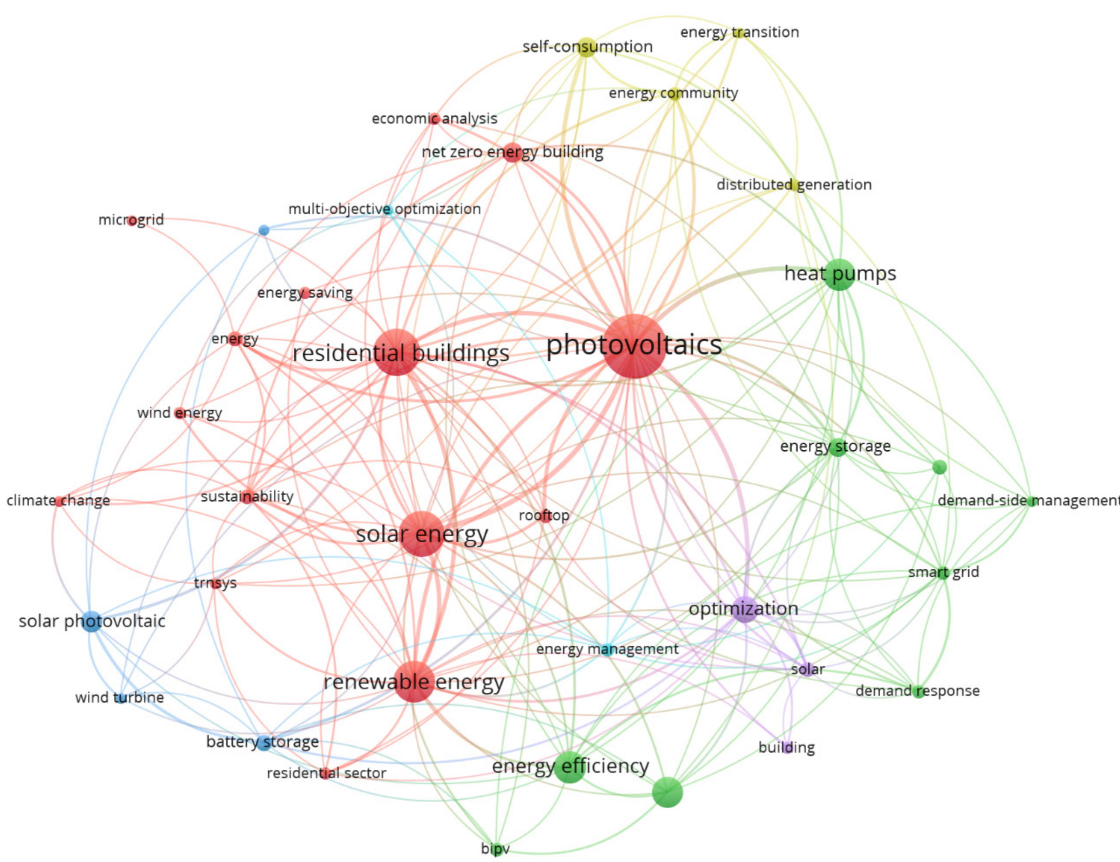

Figure 6. Diagram of a semantic network that is linked to photovoltaic solar energy in family homes. Source: Prepared by the Authors using metadata obtained from Scopus, processed in Vosviewer.

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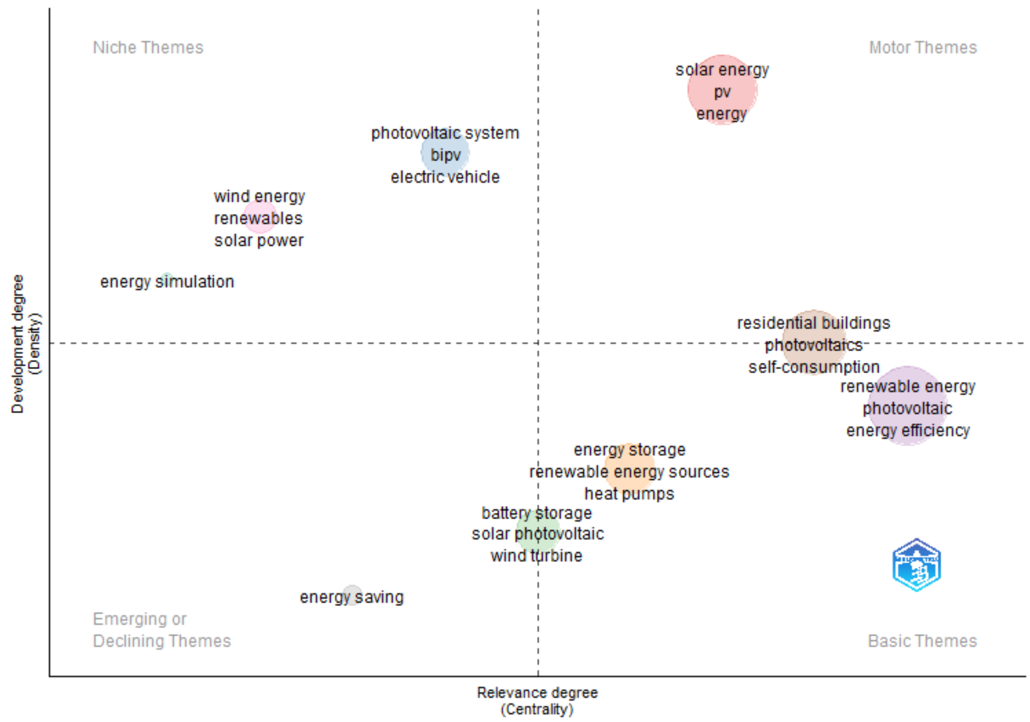


Figure 7. Thematic map. Source: Prepared by the Authors using metadata obtained from Scopus, and the indicators have been analyzed with Bibliometrix.

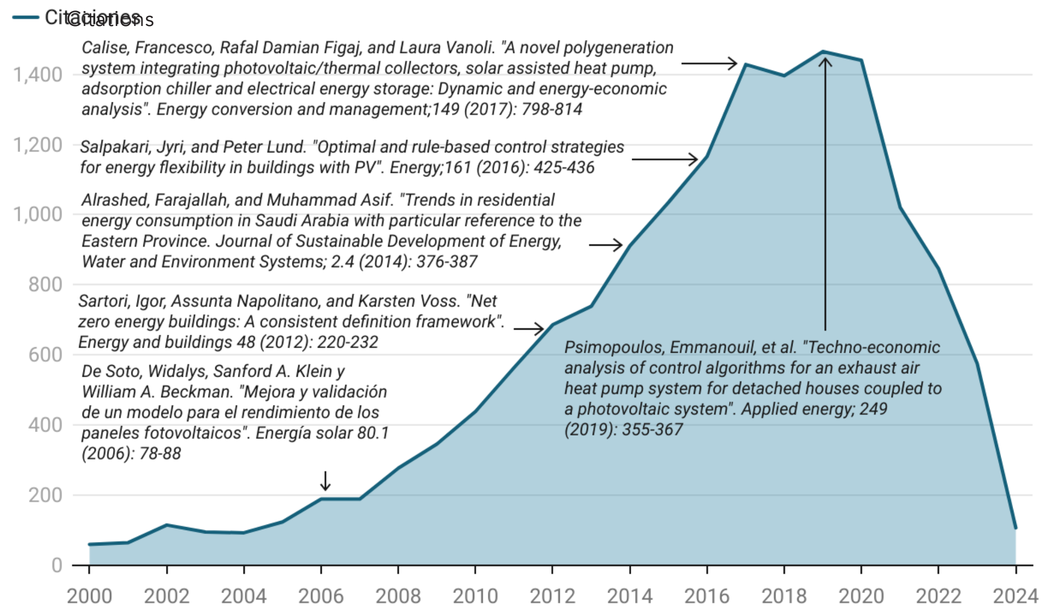
designing, implementing, and optimizing the technical aspects of photovoltaic systems, which are crucial for their effective application in family homes.

Environmental sciences occupy the third place, with 14.5% of the research. This underlines the interest in assessing the environmental impact of adopting this technology, as well as its role in the transition to more sustainable and environmentally friendly energy systems. Other areas, such as Mathematics (8.5%) and Computer science (6.5%), also have a relevant participation, which reflects the use of mathematical models and computational tools to optimize the performance of photovoltaic systems and analyze data related to their implementation. Social sciences (5%) provide a valuable perspective by considering factors such as social acceptance, user behavior, and public policies that encourage the adoption of this technology.

More specific areas, such as Materials Science (3.1%) and Earth and Planetary Sciences (2.8%), focus on the development of new materials for solar panels and the analysis of geographical and climatic conditions that influence their performance. Finally, Physics and astronomy (2.5%) and Chemical engineering (1.5%) are less represented, but their contributions are key to understanding the fundamental principles and chemical processes involved in the conversion of solar energy. In general, the diversity of knowledge areas involved evidences the complexity of the topic and its ability to attract the interest of technical, social, and environmental disciplines, which is fundamental to comprehensively address the challenges and opportunities presented by solar photovoltaic energy in family homes.

The semantic diagram presented in Figure 6 offers a detailed overview of the main thematic areas and conceptual connections related to research on photovoltaic solar energy in family homes. The clusters differentiated by colors reflect thematic groupings that represent the key trends and predominant approaches in this field of study. The central term “photovoltaics” is at the center of the diagram, with a strong connection to areas such as “residential buildings,” “solar energy,” and “renewable energy.” This suggests that much of the research focuses on integrating photovoltaic technologies into residential buildings, with an emphasis on their role within the broader framework of transitioning to renewable energies.

The red cluster, which encompasses terms such as “residential buildings,” “solar energy,” and “renewable energy,” indicates a predominant focus on integrating solar energy into the residential sector and its contribution to energy sustainability. The connection with terms such as “sustainability” and “climate change” underlines the environmental and social relevance of these investigations. In the green cluster, terms such as “energy efficiency,” “heat pumps,” and “optimization” highlight a technical focus on improving the performance and efficiency of solar photovoltaic energy systems. This group reflects the interest in optimizing both energy resources and



Evolution of the references in the field of study, cited by year of publication. Prepared using Bibliometrix.
Created with Datawrapper

Figure 8. Spectroscopy of the year of the mentioned source - Historical origins of the solar photovoltaic energy approach in family homes. Source: Prepared by the Authors, using metadata obtained from Scopus, indicators analyzed in Bibliometrix.

costs, along with the incorporation of complementary technologies such as heat pumps and smart grids. The more peripheral blue cluster encompasses terms such as "solar photovoltaic," "microgrid," and "wind energy," indicating an interdisciplinary exploration that combines various renewable energy sources and their integration into microgrids. This approach highlights the importance of energy diversity and decentralization in energy generation.

The terms "energy storage," "smart grid," and "demand-side management" suggest an emerging trend toward advanced energy management, including storage and consumption optimization. This is essential for maximizing the use of solar energy and addressing challenges such as intermittency and grid stability. In general, the semantic map evidences an expanding field of research that combines technological, environmental, and social aspects. The connections between the terms and clusters indicate a trend towards the integration of photovoltaic technologies in residential contexts, supported by advances in efficiency, storage, and energy management. Furthermore, the inclusion of terms related to sustainability and climate change underscores the global and strategic significance of these investigations.

Figure 7 provides a clear view of the research dynamics on solar photovoltaic energy in family homes, categorizing the topics by their relevance (centrality) and level of development (density). This organization allows identifying the predominant approaches, emerging research areas, and those that are in decline. Such is the case that, in the upper right quadrant, which includes the driving topics, there are concepts such as solar energy, photovoltaics, and energy efficiency. These topics are highly relevant and in development, as they indicate that they are central to research and drive progress in the field. Their position reflects their role as pillars of scientific discussion by highlighting the integration of photovoltaic technologies with energy efficiency approaches and their implementation in residential buildings.

Similarly, the lower right quadrant, which groups the basic topics, includes terms such as renewable energy, energy storage, and wind turbine. These topics are fundamental to the field, but are less developed, suggesting that they serve as a conceptual basis for future research. Their centrality suggests that they are closely connected to other topics, although they could benefit from further in-depth exploration and specialization. In the upper left quadrant, where niche topics are located, concepts such as photovoltaic systems, BIPV (Building Integrated Photovoltaics), and electric vehicles are found. These topics have a high degree of development, but low central relevance, suggesting that they are specialized areas with the potential to become broader trends if they achieve a greater connection with the central problems of the field.

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Finally, in the lower left quadrant, which represents emerging or declining issues, terms such as "energy saving" and "energy simulation" are included. Their low centrality and density suggest that these areas, although they may be relevant in specific contexts, are not currently the primary focus of research. This could indicate a decrease in interest or the need to reformulate their connection with motor subjects. In general, the thematic map reflects an evolving field, where driving topics such as energy efficiency and photovoltaic technologies lead research. In contrast, areas related to energy storage and renewable energies offer bases for new explorations. On the other hand, niche topics present opportunities for advancement in specialized areas while emerging or declining ones might require re-evaluation to maintain their relevance.

Figure 8 shows a historical evolution of citations related to key research on solar photovoltaic energy in family homes. Seminal documents that have marked milestones in the development of this field are highlighted. These studies reflect the consolidation of knowledge over time and its increasing relevance in the academic field. In this sense, the work of Calise et al. (2017) leads the citations due to its innovative approach to poly-generation systems, which include photovoltaic/thermal collectors, solar heat pumps, and energy storage. This study stands out for offering dynamic and economically viable solutions for energy management in buildings, by setting a standard for further research in optimization and sustainability.

Thus, the paper by Salpakari and Lund (2016) focuses on rule-based control strategies to improve energy flexibility in buildings with photovoltaic systems. This work has been widely cited due to its significant contribution to the development of practical and scalable approaches for integrating solar technologies into residential infrastructure. The article by Alrashed and Asif (2014), which analyzes residential energy consumption in Saudi Arabia, focuses on the challenges and opportunities for implementing renewable energy systems. Its relevance lies in providing a reference framework for the energy transition in regions with high levels of solar irradiance. The study by Sartori et al. (2012) establishes a consistent framework for defining zero-energy buildings, a key concept for moving towards more sustainable housing. This work is fundamental for the design and planning of infrastructures that minimize dependence on non-renewable energy sources.

Moreover, the work of De Soto et al. (2006) focused on the development and validation of models to evaluate the performance of photovoltaic panels. As one of the first efforts in this field, their findings have served as the basis for more advanced research in the simulation and optimization of solar systems. The article by Psimopoulos et al. (2019) performs a techno-economic analysis of control algorithms for heat pumps coupled to photovoltaic systems in single-family homes. This study combines technical and economic perspectives, highlighting its practical applicability in real-life scenarios. In other words, the upward trend of citations until 2019 reflects a growing interest and the consolidation of these investigations as essential references. The subsequent decline may indicate a transition towards new areas of focus or the emergence of more recent research that is beginning to redefine the field. These works have been fundamental pillars in the evolution of solar technologies applied to family homes, as they lay the foundations for a more sustainable energy future.

DISCUSSION

The results obtained in this research on photovoltaic solar energy in family homes reflect consistent patterns and some divergences in comparison with the previous studies cited in the analyzed literature. Regarding the leading indicators, the average annual increase of 18.84% in scientific production observed from 2000 to 2024 aligns with the global trend reported by Gallego-Castillo et al. (2021), Hamed Banirazi Motlagh et al. (2023), Mustafa et al. (2022), and Rinaldi et al. (2021). These authors also identified an exponential growth in academic interest towards sustainable systems, particularly in regions with high solar potential. However, while these studies highlight the geographical context as a key factor, the analysis carried out in the following research emphasizes the importance of greater international collaboration, with 27.29% being the main driver of this growth.

Regarding the evolution of publications, the productivity peaks since 2016 coincide with a global increase in sustainability policies and emerging technologies, as observed in Fina et al. (2021) and Wu et al. (2022). The distribution by areas of knowledge reaffirms the multidisciplinary nature of the field, with energy (28.4%) and engineering (23.5%) leading the research. This aligns with the trends identified by De Soto et al. (2006), who emphasize the integration of engineering and energy concepts in the development of photovoltaic technologies.

The principal authors, such as Abdallah R. (Albatayneh et al., 2021; Albatayneh et al., 2022; Monna et al., 2022) and identified journals, such as Applied Energy (Bayer & Pruckner, 2024; Johari et al., 2024; Ramadhani et al., 2024) and Energies (Constantinides et al., 2024; Ollas et al., 2024; Zaboli et al., 2024), stand out as key platforms, confirming the application of Bradford's Law. This finding coincides with the analysis of Sartori et al. (2012), which highlights these journals as pillars in the dissemination of knowledge. Nevertheless, differences in impact indices, such as the Energies h-index (13 vs. 23 for Applied Energy), suggest disparities in academic relevance between publication channels.

The semantic development of the topic reveals thematic clusters integrating "residential buildings" and "renewable energy", aligning with the approaches of Psimopoulos et al. (2019). This study also explores interdisciplinary connections, although in less depth, compared to the broad thematic range that our analysis highlights. The results of this study, which analyzes the patterns and trends in research on solar photovoltaic energy in family homes, find convergences and divergences with recent research. These comparisons allow us to contextualize our findings within the broader scope of the discipline and derive key implications.

First, the driving topics identified in the developed thematic map, such as "solar energy", "photovoltaics," and "energy efficiency", are aligned with the global emphasis on the integration of renewable technologies in family homes. This is consistent with the analysis of Sarker et al. (2023), which highlights the implementation of residential photovoltaic systems in Malaysia as a key strategy to reduce electricity costs and carbon emissions; similarly, the importance of energy storage to maximize the self-consumption of the energy produced is highlighted (Ali Yildirim et al., 2023). Both studies underline the role of these technologies as pillars in the energy transition. However, the findings about emerging topics, such as "energy saving" and "energy simulation", lack robust theoretical integration, which contrasts with studies such as that of Soomar et al. (2022), which explore emerging trends in photovoltaic energy optimization to address economic and environmental constraints. This highlights an opportunity to deepen these issues through more advanced methodological approaches.

In terms of technical challenges, investigations such as those by Bandaru et al. (2021), which review photovoltaic-thermal technology (PVT) in residential applications, highlight structural and financial limitations that coincide with the obstacles identified in our results. In that sense, the costs and planning of storage infrastructure and the grid are important financial and technical challenges (Nordgård-Hansen et al., 2022). These findings underscore the importance of technological innovation in overcoming critical barriers. Thus, the analysis of collaborative density in scientific production reflects the interdisciplinary nature of the field. This result is complemented by the discussion of Tawalbeh et al. (2020), who evaluate the environmental impacts of photovoltaic systems and propose sustainable designs to mitigate greenhouse gas emissions; which is related to the application of metaheuristic optimization algorithms, such as the Multi-Objective Gray Wolf Algorithm (MOGWO), to determine the optimal size of building-integrated photovoltaic systems (BIPV) and battery capacity, to minimize the Levelized Cost of Energy (LCOE) in different climates, which demonstrates the convergence of solar energy engineering with computer science and mathematical optimization (Behzadi et al., 2023). Both studies emphasize the relevance of collaborative approaches to tackling complex problems.

The convergence of these results with recent studies underscores the central role of solar photovoltaics in the transition toward sustainable residential energy models. However, the identification of divergences evidences areas that require greater academic and technical attention, which strengthens the bases for future research in this dynamic field. Finally, the historical roots of the concept align with the seminal findings of Calise et al. (2017), who established standards in the optimization and economic viability of solar systems. This analysis reinforces these antecedents by identifying a sustained growth in citations until 2019, indicating that their role is fundamental in the consolidation of the field.

The main contributions of this study include a comprehensive view of the patterns and trends in research on solar photovoltaic energy in family homes. Key areas, such as international collaboration, multidisciplinarity, and the identification of driving topics, are highlighted. These perspectives are helpful for researchers and policymakers when outlining strategies for the adoption of renewable technologies. However, the study's limitations include its reliance on a single database, which may bias the results in favor of articles indexed in Scopus. In addition, the analysis of metadata, although rigorous, could benefit from triangulation with other databases, such as Web of Science, to validate and enrich the findings. Future research could investigate the impact of emerging technologies, such as smart grids and energy storage systems, on the adoption of photovoltaic systems in homes. In addition, comparative studies between countries or regions with different degrees of technological maturity and public policies could provide additional insights into the factors that drive or limit the adoption of this technology.

CONCLUSIONS

The bibliometric analysis conducted in this research allows comprehensively answering the posed questions, providing a clear overview of the patterns and trends in research on solar photovoltaic energy in family homes. Firstly, a significant and sustained growth in scientific production has been observed since 2000, driven by an increasing focus on sustainability and the transition to clean energy sources. This trend reflects a global interest that has been particularly concentrated over the last two decades, coinciding with the advancement of photovoltaic technologies and international environmental policies.

The stand-out authors in this field present recent contributions, with the majority of their publications dating back to the last decade. This indicates that the topic is in a phase of growth and consolidation, attracting researchers from diverse contexts and disciplines. Nonetheless, most authors have a limited participation in terms of the number of publications, which could suggest a lack of sustained specialization in this specific field.

The most influential magazines, such as Energies and Applied Energy, play a central role in disseminating knowledge about solar photovoltaic energy in homes. These platforms concentrate most of the relevant publications, which reinforces the application of Bradford's Law in the field. The diversity of impact indices among these journals reflects differences in scope and specialization, which provides options for researchers with diverse approaches.

The multidisciplinary nature of the field is evident in the distribution of the areas of knowledge that address it, where energy, engineering, and environmental sciences stand out. This diversified approach allows addressing the complex technical, social, and environmental challenges posed by the implementation of photovoltaic technologies in homes. In addition, the semantic development reflects the interconnection of key terms, such as "sustainability" and "energy efficiency", with emerging perspectives integrating storage and smart grids.

Ultimately, the historical analysis reveals that seminal studies have laid a solid foundation for the field's development, particularly in areas such as system optimization and economic viability. These works have guided subsequent research, which marks milestones in the understanding and application of solar technologies in family homes. This legacy, combined with the continuous generation of knowledge, ensures the relevance of the topic in current debates on renewable energies.

Although the findings of this research are significant, some limitations should be recognized. Reliance on a single database, Scopus, can limit the breadth of analysis and exclude valuable insights from other sources. In addition, the focus on metadata leaves out more in-depth qualitative analyses that could enrich the interpretation of the results. In the future, it is recommended to expand the analysis to additional databases, such as Web of Science, to improve the representativeness and robustness of the results. Similarly, future research could focus on studying the impact of emerging technologies, such as smart grids and energy storage, in the residential context. Cross-country comparative studies would also provide unique insights into how local policies and socioeconomic conditions influence the adoption of these technologies. Together, these actions could strengthen global understanding and foster effective strategies to accelerate the transition to clean energy.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, A.E.M.L.; Data curation, J.G.R.; Formal analysis, J.G.R.; Acquisition of financing; Research, A.E.M.L.; Methodology, J.G.R.; Project management, G.M.H.B., M.U.U; Resources, L.P.A.; Software. A.E.M.L.; Supervision, G. of the P.P.A.; Validation, J.G.R.; Visualization, G.M.H.B., M.U.U, L.P.A.; Writing - original draft, A.E.M.L.; Writing - revision and editing, J.G.R.

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

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

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

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RESUMEN

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

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

ABSTRACT

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

Keywords
thermal comfort, ENVI-met, schoolyard, microclimate

RESUMO

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

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

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INTRODUCTION

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

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

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

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

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

CASE STUDY

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

METHODOLOGY

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

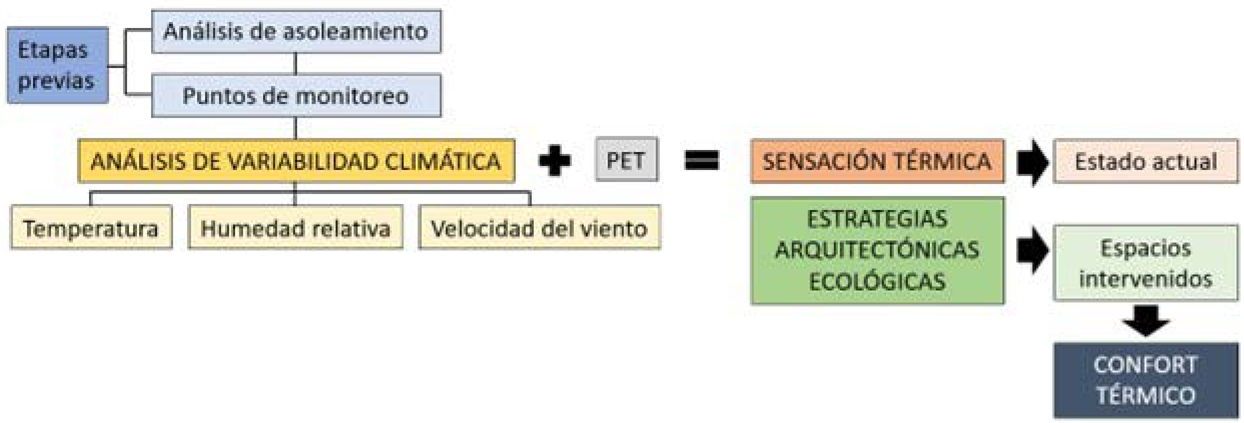

Figure 1. Methodological design. Source: Preparation by the Authors.

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

SUNSHINE ANALYSIS

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

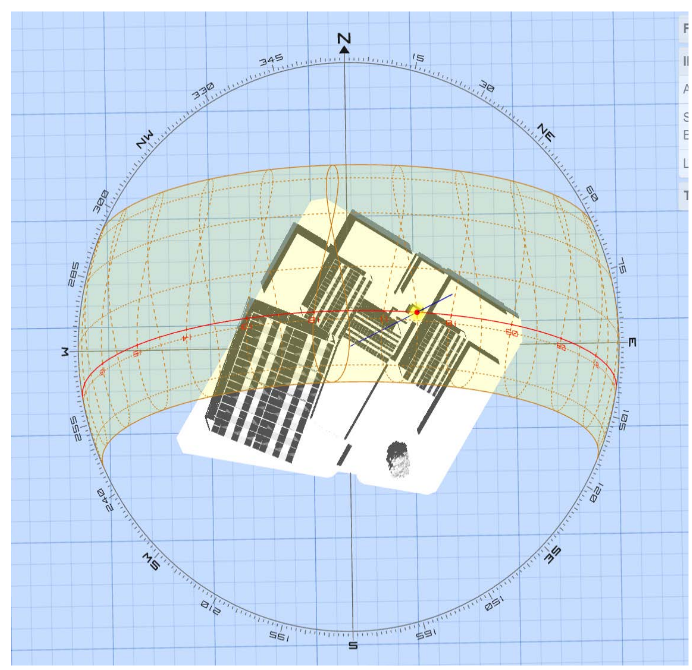

Figure 2. Sunshine at 10:30 a.m. Source: Prepared by the Authors based on Sun Path.

Location of monitoring points

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

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

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

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

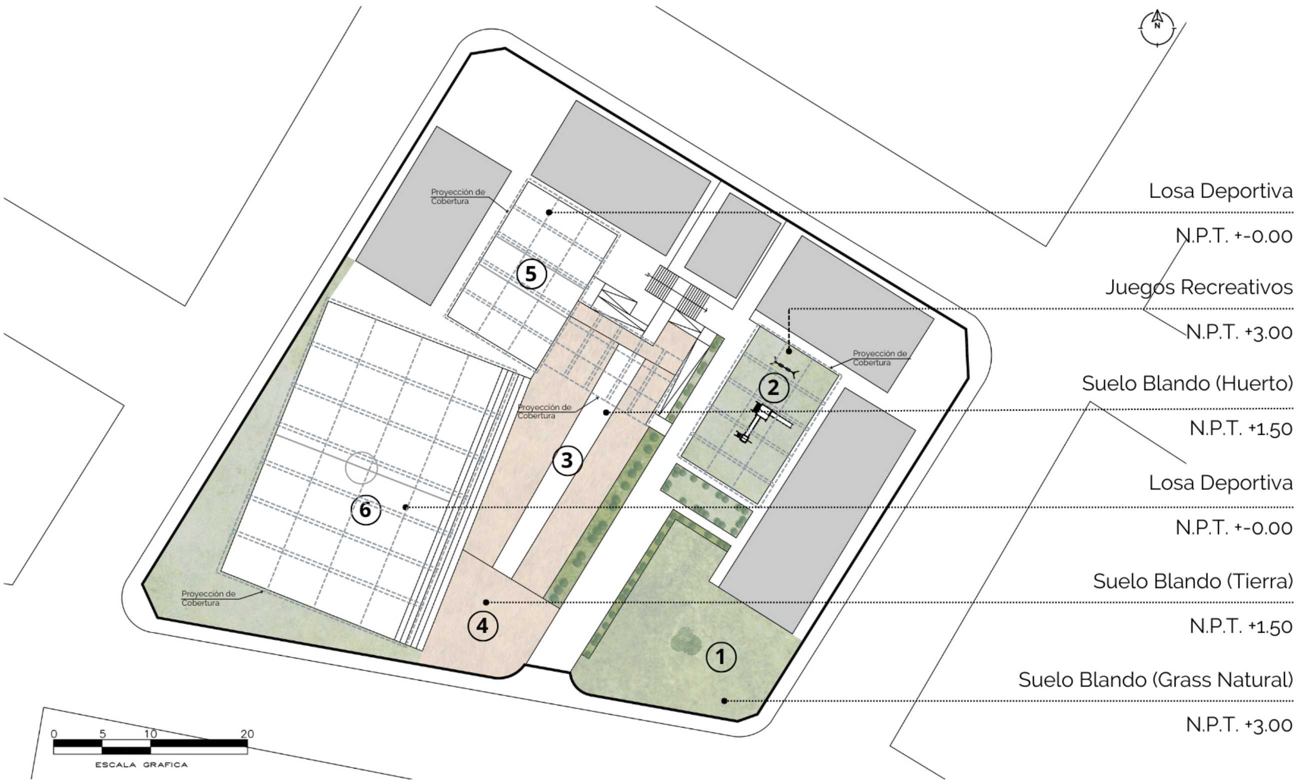

Figure 3. Location of the monitoring points. Source: Preparation by the Authors.

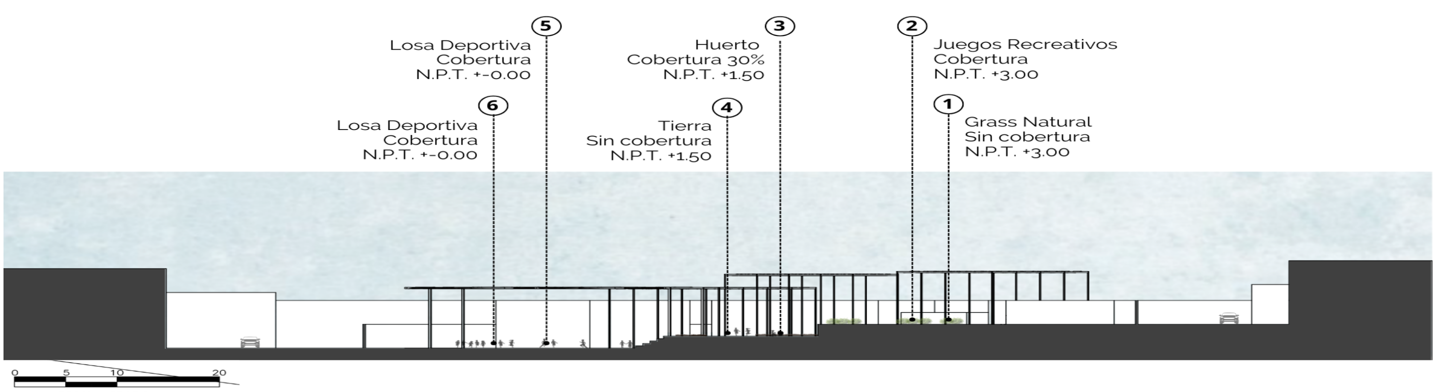

Figure 4. Basic characteristics of the spaces. Source: Preparation by the Authors.

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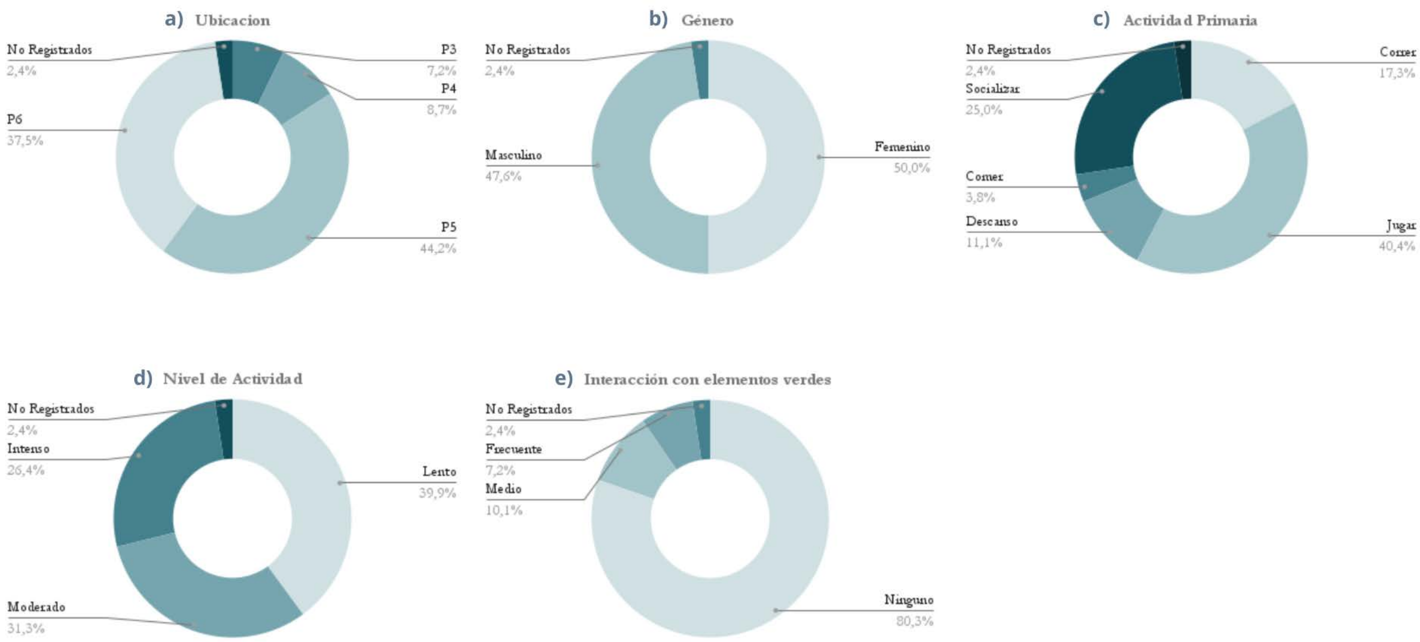

Figure 5. Indicators based on the SOPARC protocol. Preparation by the Authors.

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

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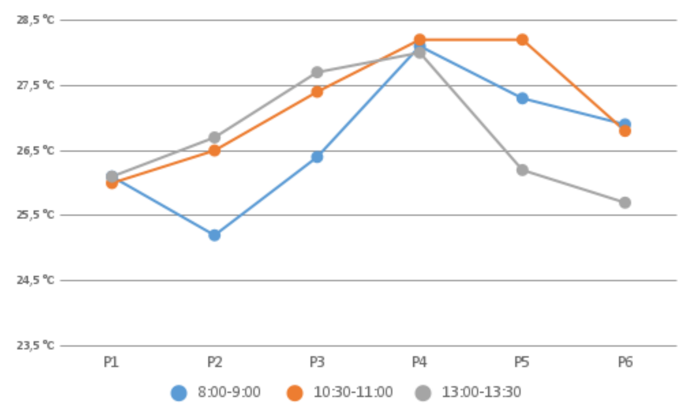

Figure 7. Air temperature. Source: Preparation by the Authors.

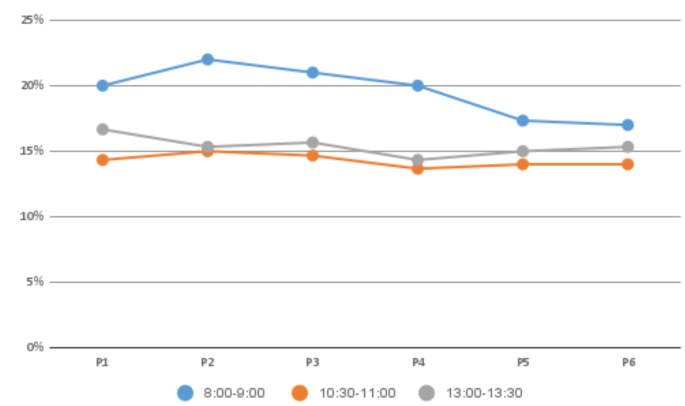

Figure 8. Relative Humidity. Source: Preparation by the Authors.

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

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

RESULTS

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

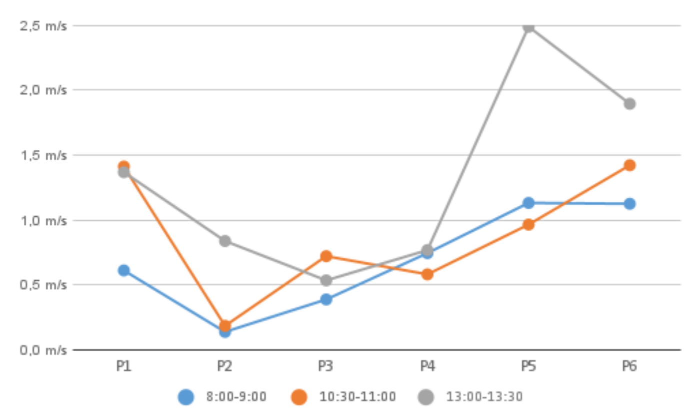

Figure 9. Wind speed. Source: Preparation by the Authors.

CLIMATE VARIABILITY ANALYSIS

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

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

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

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

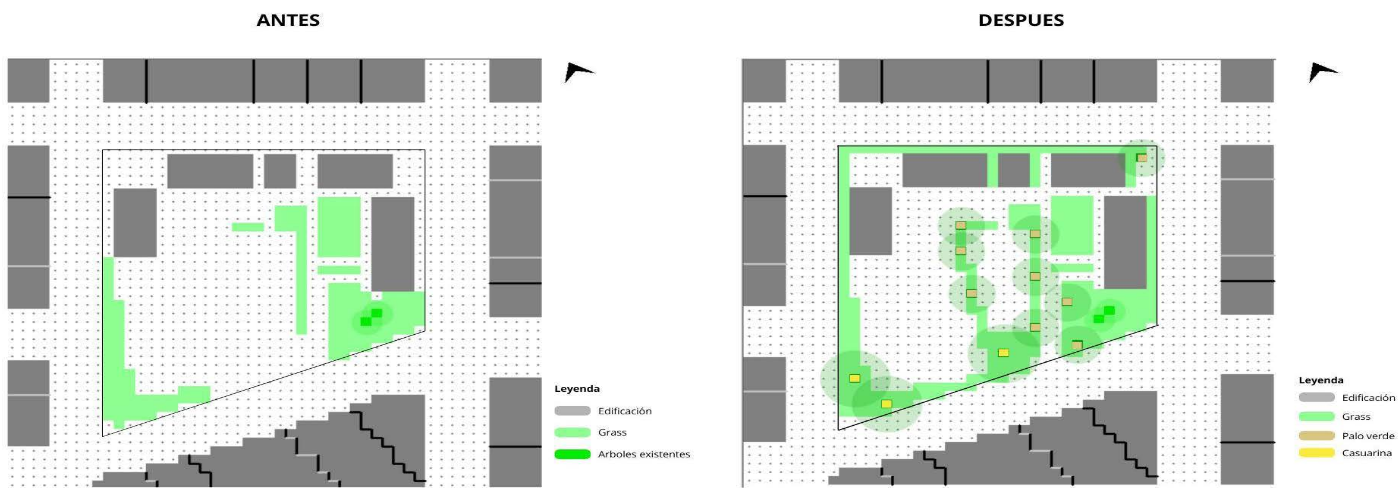

Figure 10. Comparative based on the addition of trees and green areas. Source: Preparation by the Authors.

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

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

THERMAL SENSATION

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

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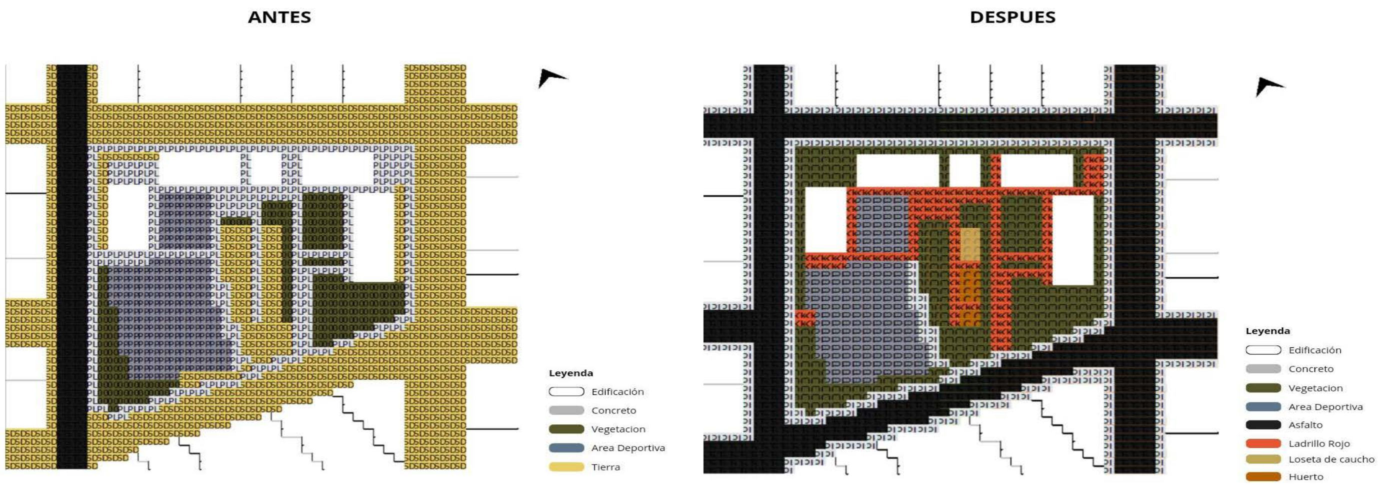

Figure 11. Comparative in terms of materiality. Source: Preparation by the Authors.

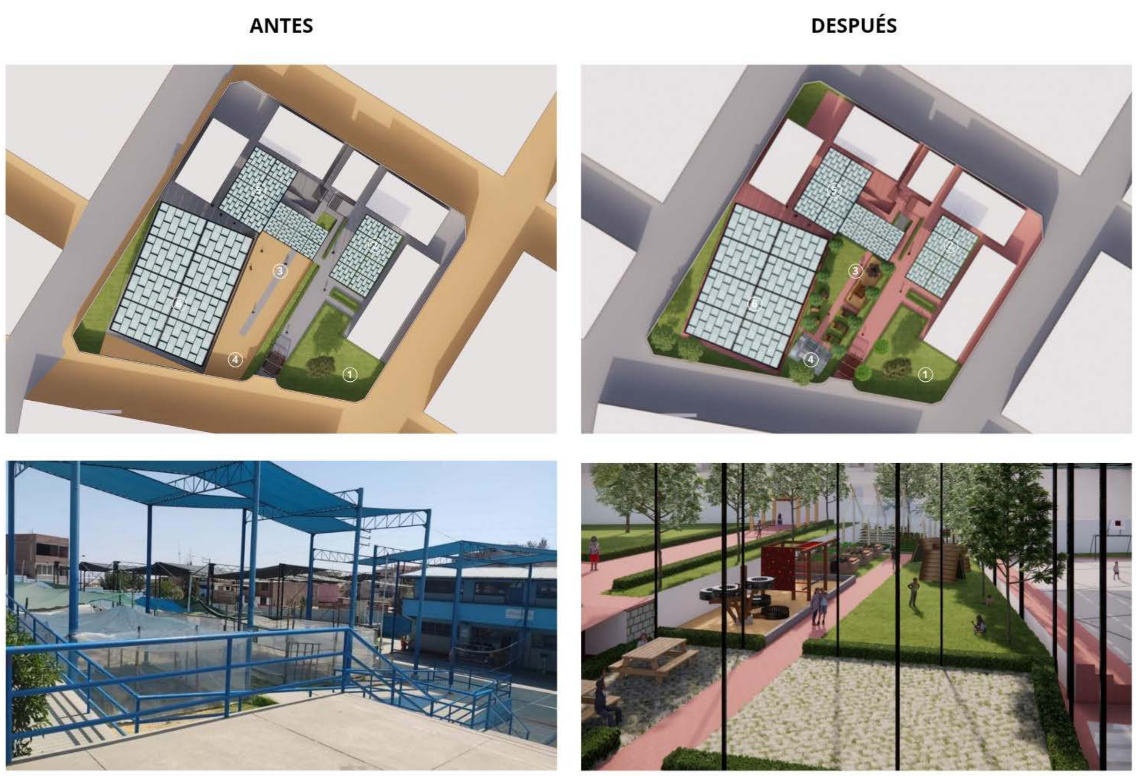

Figure 12. Implementation of ecological furniture. Source: Preparation by the Authors.

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

APPLICATION OF ECOLOGICAL ARCHITECTURAL STRATEGIES

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

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

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

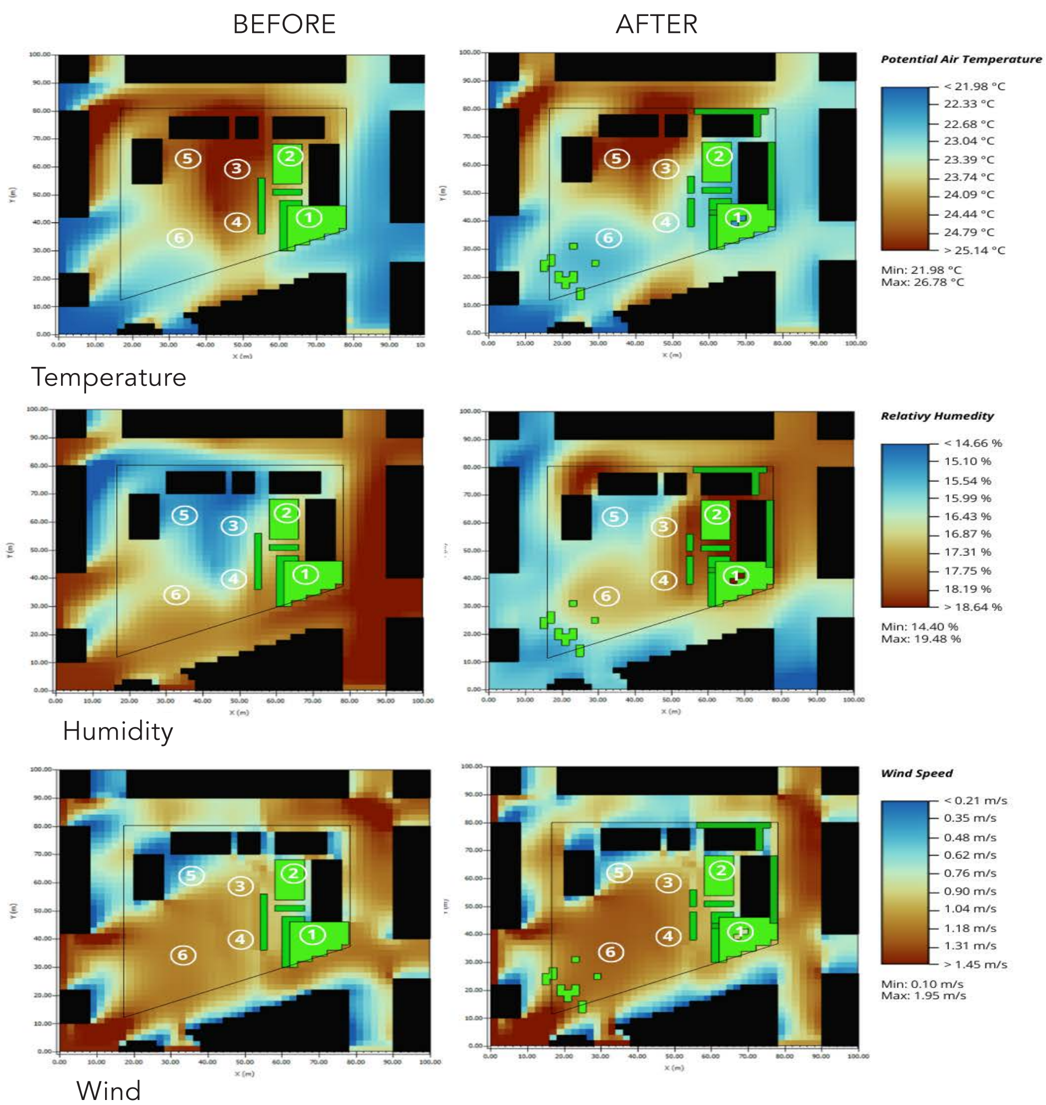

Figure 13. Comparative analysis of climate variability. Source: Preparation by the Authors.

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

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

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

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

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

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

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

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

COMPARISON OF THE CURRENT STATE WITH THE INTERVENTION BY SIMULATION

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

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

DISCUSSION

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

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

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

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

CONCLUSIONS

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

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

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

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

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

CONTRIBUTION OF AUTHORS CREDIT

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

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THERMAL COMFORT ANALYSIS OF DWELLINGS WITH DIFFERENT CONSTRUCTION SYSTEMS LOCATED ABOVE 3000 M.A.S.L. IN THE RURAL ANDEAN ZONE OF ECUADOR

ANÁLISIS DEL CONFORT TÉRMICO DE VIVIENDAS CON DIFERENTES SISTEMAS CONSTRUCTIVOS UBICADAS SOBRE 3000 M.S.N.M. EN LA ZONA RURAL ANDINA DE ECUADOR

ANÁLISE DO CONFORTO TÉRMICO DO HABITAÇÃO COM DIFERENTES SISTEMAS CONSTRUTIVOS LOCALIZADOS ACIMA DOS 3.000 METROS DE ALTITUDE ZONA RURAL ANDINA DO EQUADOR

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RESUMEN

Esta investigación analiza el confort térmico de cuatro unidades de vivienda no climatizadas con diferentes sistemas constructivos, ubicadas en una zona rural andina de Ecuador sobre los 3000 m.s.n.m., para determinar estrategias pasivas de diseño. Para esto se describen características del entorno y constructivas de dos viviendas neo vernáculas con materiales naturales (TRA-01 y TRA-02) y dos viviendas con materiales modernos (CON-01 y CON-02). Se monitorizaron las variables de temperatura y humedad relativa exterior e interior durante 8 días, así como temperaturas de superficies de la envolvente y se evaluó el rango de confort mediante la temperatura operativa. Los resultados mostraron que tres viviendas presentaron temperaturas interiores estables, aunque solo la vivienda de fardos de paja estuvo parcialmente dentro del rango de confort. El estudio concluye que el aislamiento térmico de la envolvente, el diseño bioclimático y calidad constructiva son necesarios para mantener temperatura adecuada en estas zonas de clima frío.

Palabras clave
aislación térmica, arquitectura bioclimática, eficiencia energética, sistemas constructivos

ABSTRACT

This research examines the thermal comfort of four non-air-conditioned dwellings located in a rural Andean region of Ecuador, at an altitude of 3,000 meters above sea level (masl), to identify passive design strategies. The study describes the environmental and construction characteristics of two neo-vernacular dwellings built with natural materials (TRA-01 and TRA-02) and two dwellings with modern materials (CON-01 and CON-02). Indoor and outdoor temperature and relative humidity variables were monitored for eight days, along with envelope surface temperatures. The comfort range was evaluated using the operating temperature. The results showed that three dwellings had stable indoor temperatures, although only the straw bale dwelling was partially within the comfort range. The study concludes that the envelope's thermal insulation, bioclimatic design, and construction quality are needed to maintain adequate temperatures in these cold climate zones.

Keywords
thermal insulation, bioclimatic architecture, energy efficiency, construction systems

RESUMO

Esta pesquisa analisa o conforto térmico de quatro unidades habitacionais sem ar condicionado, localizadas numa zona rural andina do Equador a uma altitude de 3000 metros acima do nível do mar, para determinar estratégias de design passivo. Para tal, são descritas as características ambientais e construtivas de duas casas neovernaculares construídas com materiais naturais (TRA-01 e TRA-02) e de duas casas com materiais modernos (CON-01 e CON-02). As variáveis temperaturas exterior e interior e humidade relativa foram monitorizadas durante 8 dias, assim como as temperaturas das superfícies do invólucro, a gama de conforto foi avaliada através da temperatura operacional. Os resultados mostraram que três casas apresentaram temperaturas interiores estáveis, embora apenas a casa de fardos de palha estivesse parcialmente dentro do intervalo de conforto. O estudo conclui que o isolamento térmico da envolvente do edifício, o design bioclimático e a qualidade da construção são necessárias para manter a temperatura adequada nessas zonas de clima frio.

Palavras-chave:
isolamento térmico, arquitetura bioclimática, eficiência energética, sistemas construtivos

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INTRODUCTION

In recent years, emissions from the construction industry and those related to the operation of buildings have been responsible for 38% of global CO_2 emissions (Guillén Mena et al., 2015). Part of this situation is because there is a growing interest among people in improving their quality of life by adjusting the thermal environment of buildings (Chang et al., 2021).

In this sense, it has been observed that some vernacular constructions, typically located in rural areas of China and India, may require fewer energy resources to regulate the thermal environment of buildings, partly due to their passive design, and because rural residents tend to naturally adapt to the climate (Chang et al., 2021; Dhaka et al., 2015). For example, adaptation strategies include opening or closing doors and windows, ingesting hot or cold drinks, and adjusting the number of layers of clothing. (Dhaka et al., 2015; Indraganti, 2010). However, studies show that vernacular buildings can achieve energy savings in cooling and heating compared to modern or low-cost alternatives, mainly due to their passive design strategies and the use of local materials (Cojocaru & Isopescu, 2021).

A study conducted in the Andean highlands of Peru by Harman (2010) found that homes built with modern materials, such as concrete or steel, have a lower thermal resistance capacity, resulting in prolonged exposure to very low temperatures that negatively impact the health of families. However, another study in Peru found that the use of more efficient passive heating strategies resulted in an average increase of 9.5 °C inside high-Andean homes located between 3,000 and 5,000 meters above sea level (Cerrón Contreras, 2022).

Although there is not enough research regarding the analysis of thermal comfort in buildings located in Ecuador (Gallardo et al., 2016; Mino-Rodríguez, 2021), and even less in vernacular buildings (Tapia, 2017; Moscoso-García & Quesada-Molina, 2023), it is also important to note that several constructions using traditional architecture may be relevant, especially those located in unfavorable climatic conditions. A study on vernacular buildings in these climatic conditions can significantly contribute to identifying effective passive strategies, thereby guiding the development of future buildings, since it should be borne in mind that just as buildings respond to a unique context, culture, and climate, so do the needs of thermal comfort and the expectations of the inhabitants (Gallardo et al., 2016).

The primary objective of this research is to analyze the thermal comfort of housing units located above 3000 masl, which have different characteristics, including construction systems, materials, envelope thicknesses, number of floors, and orientation, to determine the most effective passive air conditioning strategies. To achieve this, a description of the characteristics of four housing units is proposed, two with neo-vernacular construction systems and two with modern construction systems. Subsequently, environmental variables such as air temperature and relative humidity, both inside and outside the buildings, as well as surface temperatures within the envelope, are monitored asynchronously. In this way, the research provides evidence of the effectiveness of passive design strategies in homes located in Andean areas above 3000 masl to achieve thermal comfort. Similarly, the research addresses the question of whether houses with neo-vernacular construction systems exhibit better thermal performance in cold climates than houses that use only modern materials.

CONDITIONS OF THE PLACE OF STUDY

The parish of San Juan (-1.633887, -78.781584), situated at an altitude of 3,160 masl, is located 16 km from the city of Riobamba, Ecuador. The Ecuadorian Construction Standard, in its Energy Efficiency chapter NEC-HS-EE (Ministry of Urban Development and Housing, 2018), classifies settlements located between 3000 and 5000 masl as a cold climate zone 5, equivalent to climate zone 5c according to the ASHRAE 90.1 classification. In the central Andes of Ecuador, thermal oscillation is not related to the seasons of the year; rather, it is characterized by a marked diurnal oscillation that occurs between day and night due to its geographical location at high latitudes and altitudes. Figure 1 presents the average monthly temperature for the 2018-2022 period, indicating an average monthly temperature of 10.55 °C. The coldest months are July, August, and September, with an average temperature of 9.71 °C. The hottest month is February, with an average temperature of 11.17 °C (INAHMI, 2023). This climatic information exhibits low seasonal variation, characteristic of high mountain climates in tropical regions. It also records high daily thermal amplitudes, as observed on November 3rd, 2020, when the minimum temperature was 0.3 °C and the maximum was 21.2 °C, an amplitude of 20.9 °C. These data allow contextualizing and justifying the climatic conditions under which the thermal comfort of the homes under study is evaluated, which, together with other environmental parameters such as relative humidity and wind direction, contribute to a better understanding. Regarding relative humidity, the monthly average is 80.82%, with its

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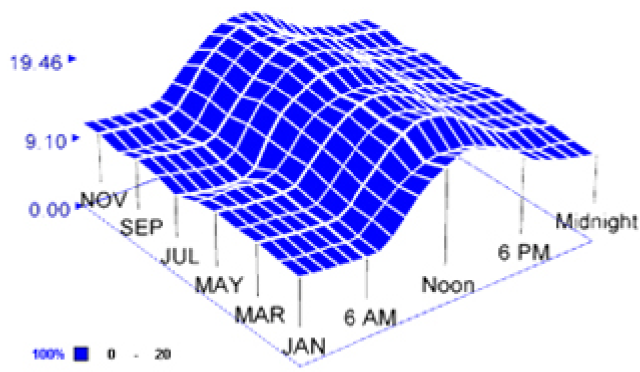

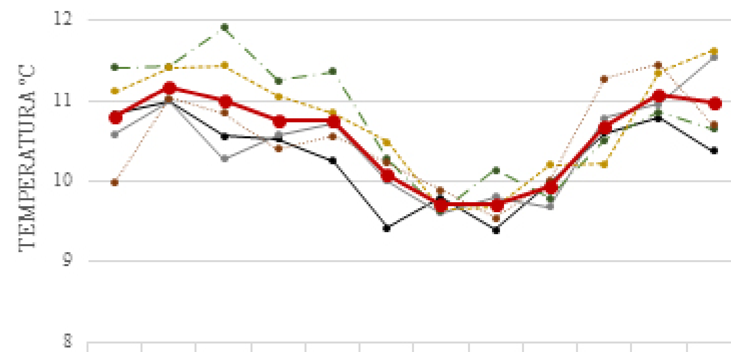

	ENE	FEB	MAR	ABR	MAY	JUNI	JUL	AGO	SEPT	OCT	NOV	DIC
2022	10,83	11,00	10,56	10,52	10,25	9,43	9,80	9,39	9,98	10,60	10,79	10,38
2021	10,59	10,99	10,27	10,57	10,71	10,00	9,61	9,80	9,68	10,79	10,96	11,54
2020	11,42	11,43	11,91	11,26	11,37	10,28	9,63	10,14	9,80	10,51	10,86	10,65
2019	11,12	11,41	11,44	11,05	10,85	10,48	9,66	9,68	10,20	10,21	11,36	11,63
2018	10,00	11,03	10,85	10,40	10,56	10,22	9,89	9,55	10,00	11,27	11,46	10,69
PROMEDIO	10,79	11,17	11,01	10,76	10,75	10,08	9,72	9,71	9,93	10,68	11,08	10,98

Figure 1. Average monthly temperature of the 2018-2022 period. Source: INAHMI (2023).

highest values occurring in April, May, and June. The predominant wind direction originates from the East-Southeast, with August and September being the windiest months, with average speeds of 2.41 and 2.48 m/s, respectively (INAHMI, 2023).

The first inhabitants of this parish were descendants of the Puruhá, who built their homes with stone, mud, or adobe as an envelope and load-bearing structure and straw or tile for the roof (Villacís, 2010). In the last four housing censuses conducted in Ecuador, in 1990, 2001, 2010, and 2022, it was observed that in the Parish of San Juan, the use of brick or adobe decreased by 41%, 22%, 14%, and 5%, respectively. Meanwhile, the use of bricks or blocks increased from 57% in 1990 to 86% in 2022 (National Institute of Statistics and Censuses [INEC], 2024). As for the roof, the use of straw has been replaced by zinc, tile, fiber cement, and a concrete slab, with the latter being the most common, at 43%.

This phenomenon not only leads to the loss of the thermal qualities associated with vernacular constructions that use local materials and passive strategies adapted to the environment, but also the loss of a valuable source of ancestral knowledge—a key resource for offering sustainable solutions relevant to contemporary design. (Moscoso-García & Quesada-Molina, 2023).

METHODOLOGY

The proposed methodology comprises four phases: the description of four case studies, monitoring of the houses, determination of the thermal comfort range, and its respective analysis. This last phase is addressed in the presentation of the results and the discussion.

PHASE I: SELECTION OF CASE STUDIES

For this study, four houses were chosen: two neo-vernacular houses built with natural materials, TRA-01 (108.72 m²) with one floor and restored brick walls, and TRA-02 (171.51 m²) with two floors and straw bale walls, featuring a contemporary design. Additionally, there are two modern houses, one of which is a single-floor house (CON-01, 89.20 m²) constructed with brick, and the other is a two-floor house (CON-02, 127.41 m²) made of concrete blocks (Figure 2). The construction systems, materials, and envelope thicknesses found in the houses are presented in Table 2. There is no mechanical cooling system installed in any house, nor is a heating system in operation.

As for the immediate surroundings of the houses, they are located within a 2 km radius. CON-02 is in the center of the town of San Juan, with a semi-urban environment, unlike the other isolated houses. As a result, they have better lighting and interior ventilation, but are more influenced by the prevailing easterly winds (Table 1).

Figure 2. Selected case studies: (a) TRA-01 traditional brick dwelling; (b) TRA-02 straw bale dwelling; (c) CON-01 brick dwelling; (d) CON-02 concrete block dwelling. Source: Preparation by the Authors.

Table 1. Characteristics of the dwelling. Source: Preparation by the Authors.

House ID	Area (m2)	Altitude (m.a.s.l.)	# of floors	Orientation of the main facade	Prevailing wind direction	Heating system	Location/Context	Infiltrations
TRA-01	108.72	3,263	1	E	E	None	Detached in a non-urban context, with partial enclosure	Yes
TRA-02	171.51	3,243	2	N	E	None	Detached in a non-urban context, without enclosure, with a vegetation barrier	Yes
CON-01	89.20	3,276	1	E	E	None	Detached in a non-urban context, located on a hill, without enclosure	Yes
CON-02	127.41	3,229	2	NW	E	None	Detached, built in a semi-consolidated urban context, without neighbors, with enclosure	Yes

Table 2. Construction systems, materials, envelope thicknesses, and Thermal Transmittance (U-value). Source: Preparation by the Authors.

House ID	Component	Material	Thickness (cm)	U [1] (W/m²K)
TRA-01	FOUNDATION	Continuous stone foundation	40	-
	STRUCTURE	Self-supporting brick	80	-
	EXTERIOR WALLS	Paint+Fiberglass Mortar+Brick+Mortar+Paint	1.5+80+1.5	0.94
	INTERIOR WALLS	Paint+Cement Mortar+Brick+Cement Mortar+Paint	15	-
	FLOOR	Concrete slab+Half pine stave	40+2.5	1.53
	ROOF	Aluminum sheet+Wooden beams+Air chamber+Gypsum board	0.6+5+1.2	2.87
	WINDOWS	Wooden frame+glass	4+0.6	1.51
TRA-02	FOUNDATION	Concrete foundation slab	0.15	-
	STRUCTURE	Eucalyptus ladder-type wooden post and beam	40	-
	EXTERIOR WALLS	Lime+Clay plaster+Straw bales+Clay plaster+Lime	0.5+2.5+35+2.5+0.5	0.21
	INTERIOR WALLS	Lime+Clay plaster+quincha+Clay plaster+Lime	0.5+2.5+6+2.5+0.5	-
	FLOOR	Concrete slab+Pumice+Wood forging+Triplex board+Floating floor	10+15+6+1.8+1.4	0.55
	ROOF	Asphalt sheet+triplex board + Straw between beams+tetrapack board and totora reed mat	0.2+1.8+15+1.2+1.5	0.45
	WINDOWS	Glass +Air chamber +Glass. PVC Frame	0.6+6+0.6	2.75
CON-01	FOUNDATION	Insulated concrete footings	120	-
	STRUCTURE	Metal structure	-	-
	EXTERIOR WALLS	Paint+Mortar Cement+Brick+Mortar+Paint	1+10+1	3.10
	INTERIOR WALLS	Paint+Mortar Cement+Brick+Mortar+Paint	1+10+1	-
	FLOOR	Concrete subfloor +Tile	40+0.4	2.00
	ROOF	Corrugated fiber cement sheet or translucent sheets + Gypsum board	0.4+1.2	5.21
	WINDOWS	Aluminum frame+Glass	0.4	5.73
CON-02	FOUNDATION	Insulated concrete footings	120	-
	STRUCTURE	Reinforced concrete	-	-
	EXTERIOR WALLS	Mortar plastering+Concrete block+Mortar plastering	1.5+10+1	2.83
	INTERIOR WALLS	Paint+Mortar+Concrete Block+Mortar+tile	1+0.7+1.5	-
	FLOOR	Concrete subfloor +Tile	25+0.4	2.54
	ROOF	Flat concrete slab+pumice blocks	25	4.02
	WINDOWS	Aluminum frame+Blue glass	0.4	5.73

1 Thermal Transmittance values calculated based on Ministry of Urban Development and Housing, 2018; Ministry of Housing and Urban Agenda, 2022

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Table 3. Detailed information on the measuring equipment. Source: Preparation by the Authors.

#	Commercial Name	Description	Measurement parameters	Range	Precision
1	ESP32	Microcontroller with wireless connectivity	Wi-Fi connection 802.11 b/g/n, Bluetooth 4.2 and BLE	150 Mbps	
2	LM35	Integrated circuit temperature sensor	Temperature	-55 to 150°C	± 0.5°C
3	Datalogging traceable barometer	Digital recorder of room temperature, relative humidity, and barometric pressure	Room temperature	0 to 65°C	± 0.4°C
			Humidity	0% to 95%	±3%
			Barometric pressure	500 mbar to 1030 mbar	±4 mbar

PHASE II: HOUSING MONITORING

At this stage, equipment for measuring air temperature, relative humidity, and surface temperature sensors was used. Figure 3 illustrates the locations in the architectural plans and photographs, showing the placement of interior and exterior elements, while Table 3 presents the specifications of the measuring equipment.

The relative humidity and air temperature variables of the four houses were monitored every 5 minutes for 8 days each, between May 20th and July 31st, 2023. The frequency and period of monitoring are based on the study by Quesada Molina and Bustillos Yaguana (2018). The measurement of the dwellings was not synchronous, as equipment availability allowed for one dwelling to be measured at a time, which is discussed in the limitations of the study.

Three thermohygrometers were placed in each house (Figure 3), one outside (A), another in the indoor social area (B), and the third in the coldest bedroom (C). The indoor sensors were placed in the center of the rooms or at least 1m away from the exterior walls, and at a height of 1.10m that follows the guidelines of the Spanish Standard UNE-EN ISO 7726, which indicates that "when it is not possible to interrupt the ongoing activity, it is necessary to place the sensors in positions such that the thermal exchanges are approximately equal to those to which the person is exposed" (UNE-EN ISO 7726, 2020). The outdoor sensors were placed in a place protected from rain and direct solar radiation.

The temperature measurements of the interior surfaces were conducted at six locations, as indicated by Atecyr (2010), including one wall for each orientation, the roof, and the floor in contact with the ground. The monitoring was carried out in the house's social area (B) every 30 minutes for three days, and an average was obtained for each day. Measurements were taken on the surfaces to calculate the mean radiant temperature (MRT). With this value, the operative temperature (Opt) was determined, which will serve as a basis for a comprehensive comfort evaluation.

To acquire the temperature data of the interior surfaces, ESP32 microcontrollers were used wirelessly, each with an LM35 sensor that is capable of measuring the temperature in a range from -55°C to 150°C with a sensor output interval of 10mV for each degree Celsius, and sending it to a master microcontroller that records the information in an SDCARD memory in a .txt extension file, to process the information later.

PHASE III: DETERMINATION OF THE THERMAL COMFORT RANGE

To understand the role that the envelope plays in the homes' thermal comfort, the aim is to define the thermal comfort range of the 4 case studies. As mentioned by Chang et al. (2021) in their study, the operating temperature (Opt) is one of the most widely used thermal comfort indices relevant to this study, as it considers the effects of outdoor air temperature and radiation (ASHRAE Standard 55, 2020). The Opt calculation is shown in Equation 1, where (MRT) is the mean radiant temperature obtained based on Equation 2, which uses the temperature of the house's surfaces when the walls, floor, and roof are at different temperatures (Atecyr, 2010).

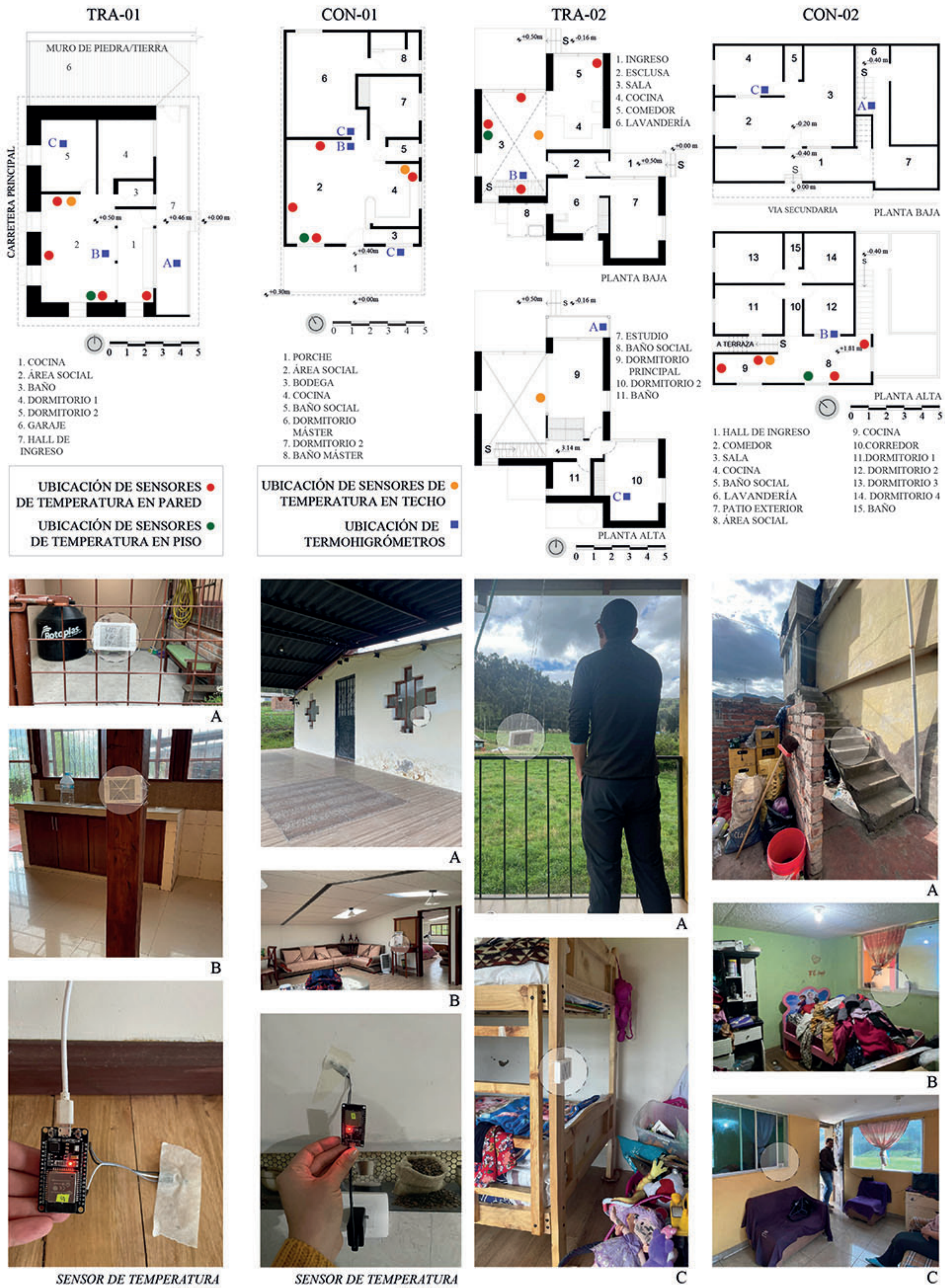

Figure 3. Floor plans and equipment location in case studies. Source: Preparation by the Authors.

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Once the Opt was obtained, the thermal comfort range in the studied homes (Table 4) was determined using the Berkeley Thermal Comfort CBE Tool (Tartarini et al., 2020), based on the adaptive method outlined in the UNE-EN 16798-1 Standard. With this tool, the comfort ranges (classes) were determined using the predominant average outdoor temperature, which responds to "the arithmetic mean of the average daily outdoor temperature for a period of not less than 8, nor more than 30 consecutive days prior to the day in question" (ASHRAE Standard 55, 2020).

The EN 16798 Standard establishes three classes of thermal comfort, which vary according to their level of demand and acceptance. The comfort hours of each house will be based on the Thermal Comfort Class III range.

$$T_{op} \approx \frac{T_{rm} + T_s}{2}$$

$$T_{rm} = \frac{(0{,}08(T_{s\,techo} + T_{s\,suelo}) + 0{,}23\,(T_{s\,derecha} + T_{s\,izquierda}) + 0{,}35(T_{s\,dante} + T_{s\,detrás}))}{2(0{,}08+0{,}23+0{,}35)}$$

RESULTS AND DISCUSSION

INDOOR AND OUTDOOR TEMPERATURE MONITORING

Figure 4 shows the minimum, maximum, and average temperatures of the monitored spaces. When monitoring the house's outdoor air temperature (Figure 5), the lowest temperatures were recorded in the early morning, between 3:00 a.m. and 6:00 a.m. In contrast, the highest temperatures were recorded between 2:00 p.m. and 4:00 p.m.

The TRA-01 one-story house recorded a minimum outdoor temperature of 3.77°C, a maximum of 29.33°C, and an average of 12.22°C. In the social area (B), the absolute minimum temperature was 11.70°C, while in the bedroom (C) it was 11.80°C, with an average temperature of about 13.00°C. The 0.80 m thick brick walls contributed a low thermal transmittance (Table 2) and a maximum thermal amplitude of 3 °C to the interior.

The TRA-02 house had a minimum outdoor temperature of 6.15°C, a maximum of 21.95°C, and an average of 12.07°C. The social area ranged from 16.43 to 21.95°C, and the room ranged from 17.50 to 24.05°C. The average temperature in the social area was 19.88°C, and in the room, 20.46°C. On the second floor, it is slightly higher, possibly due to solar radiation captured on the roof. The maximum thermal amplitude was 7.52°C; the contemporary design included straw bale walls as an insulating material. This system contributes to increasing the indoor

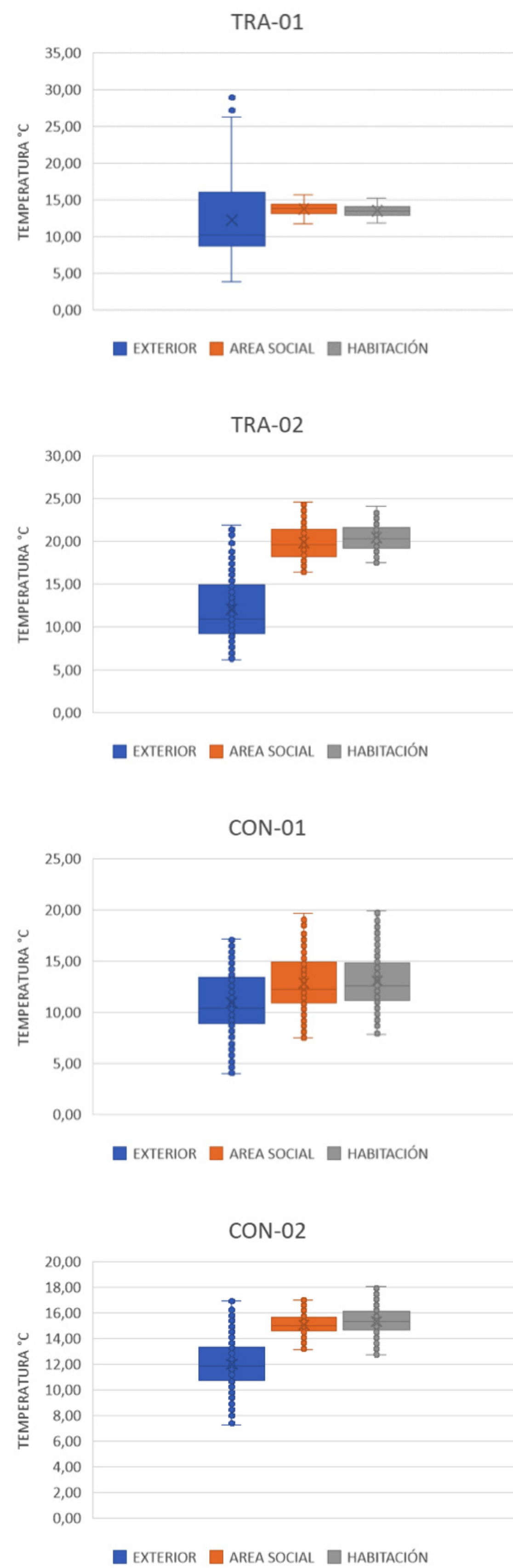

Figure 4. Minimum, maximum, and average temperatures of each case study. Source: Preparation by the Authors.

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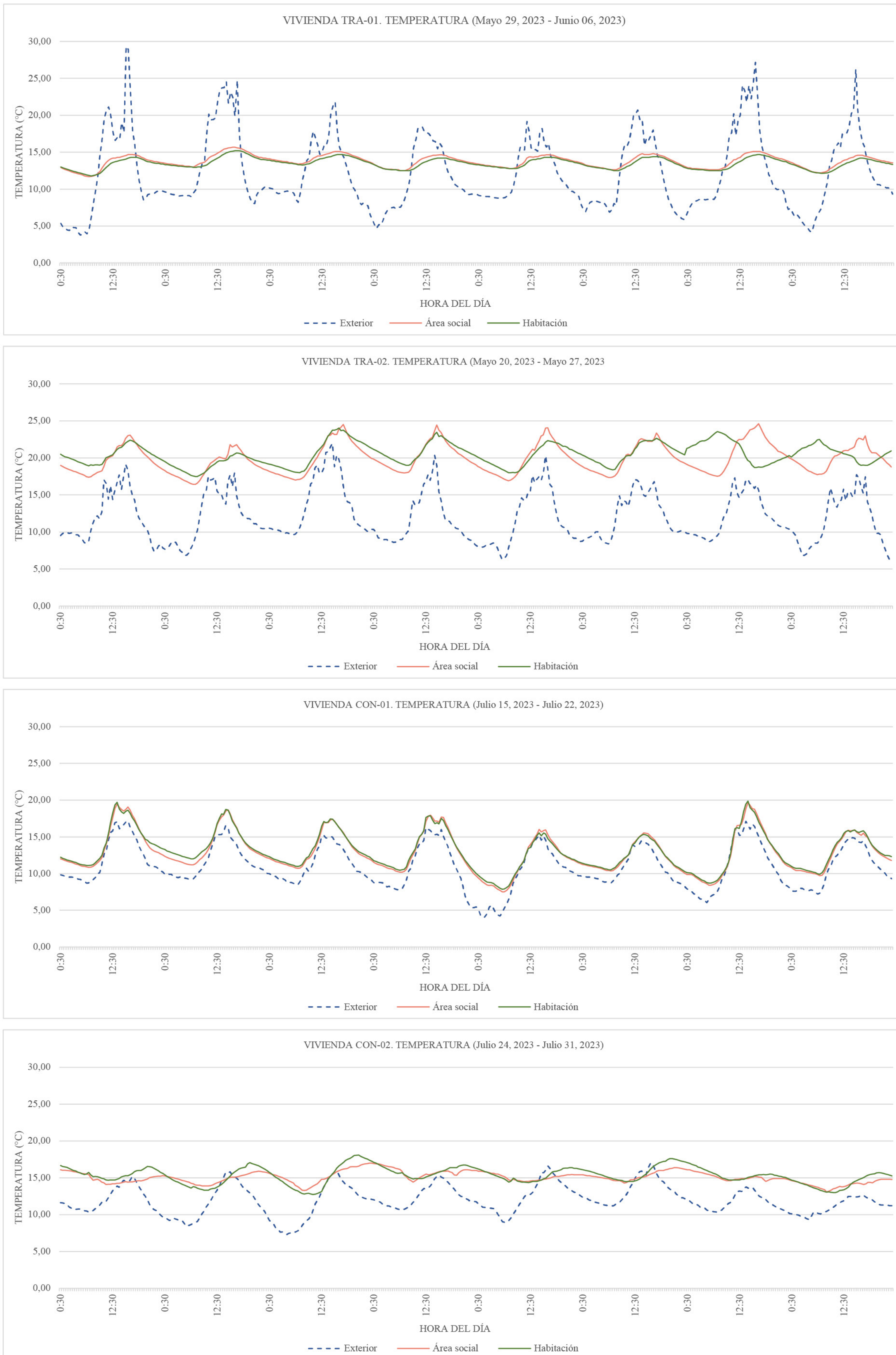

Figure 5. Indoor and outdoor temperature monitoring. Source: Preparation by the Authors.

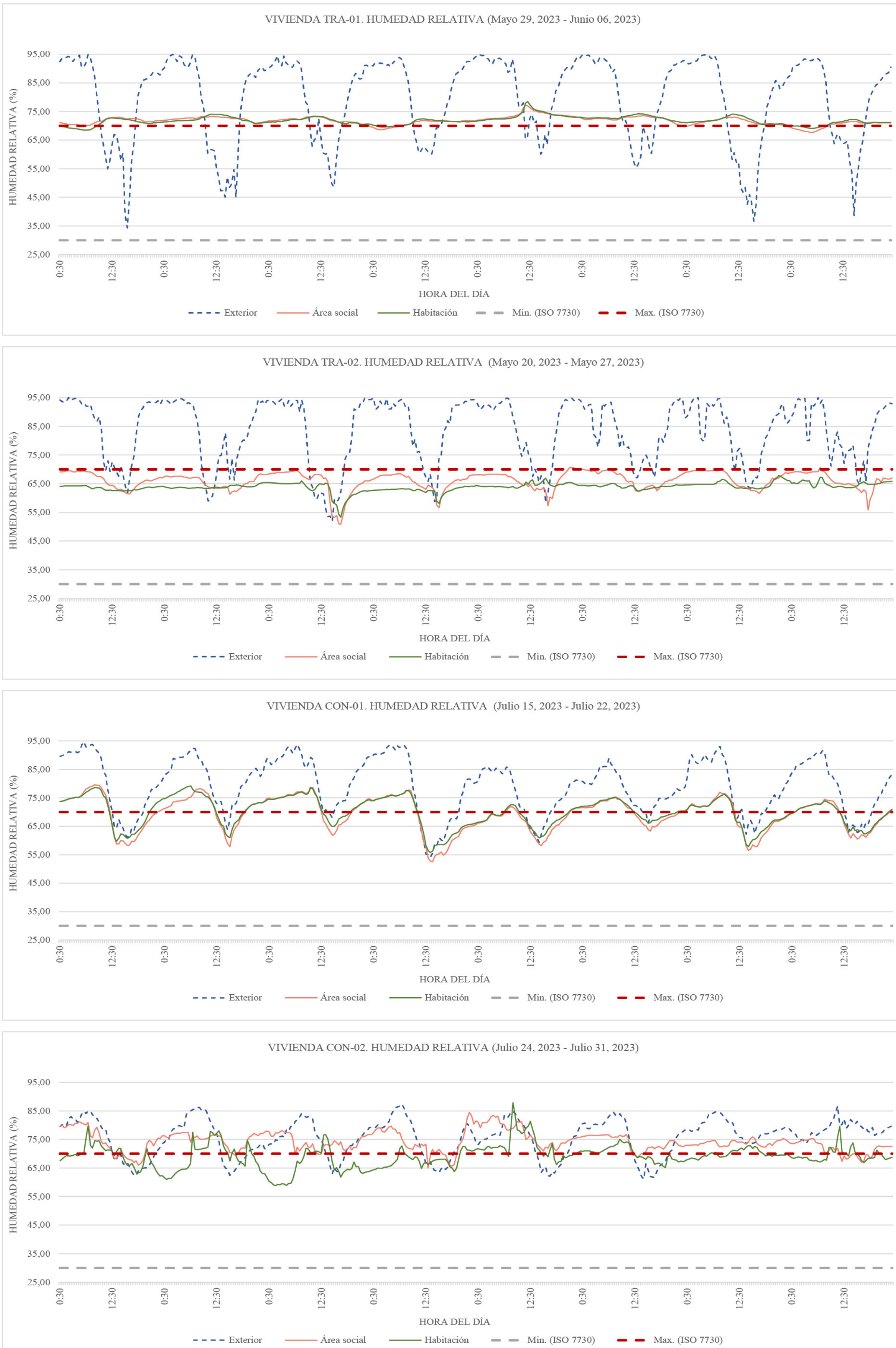

Figure 6. Indoor and outdoor relative humidity monitoring. Source: Preparation by the Authors.

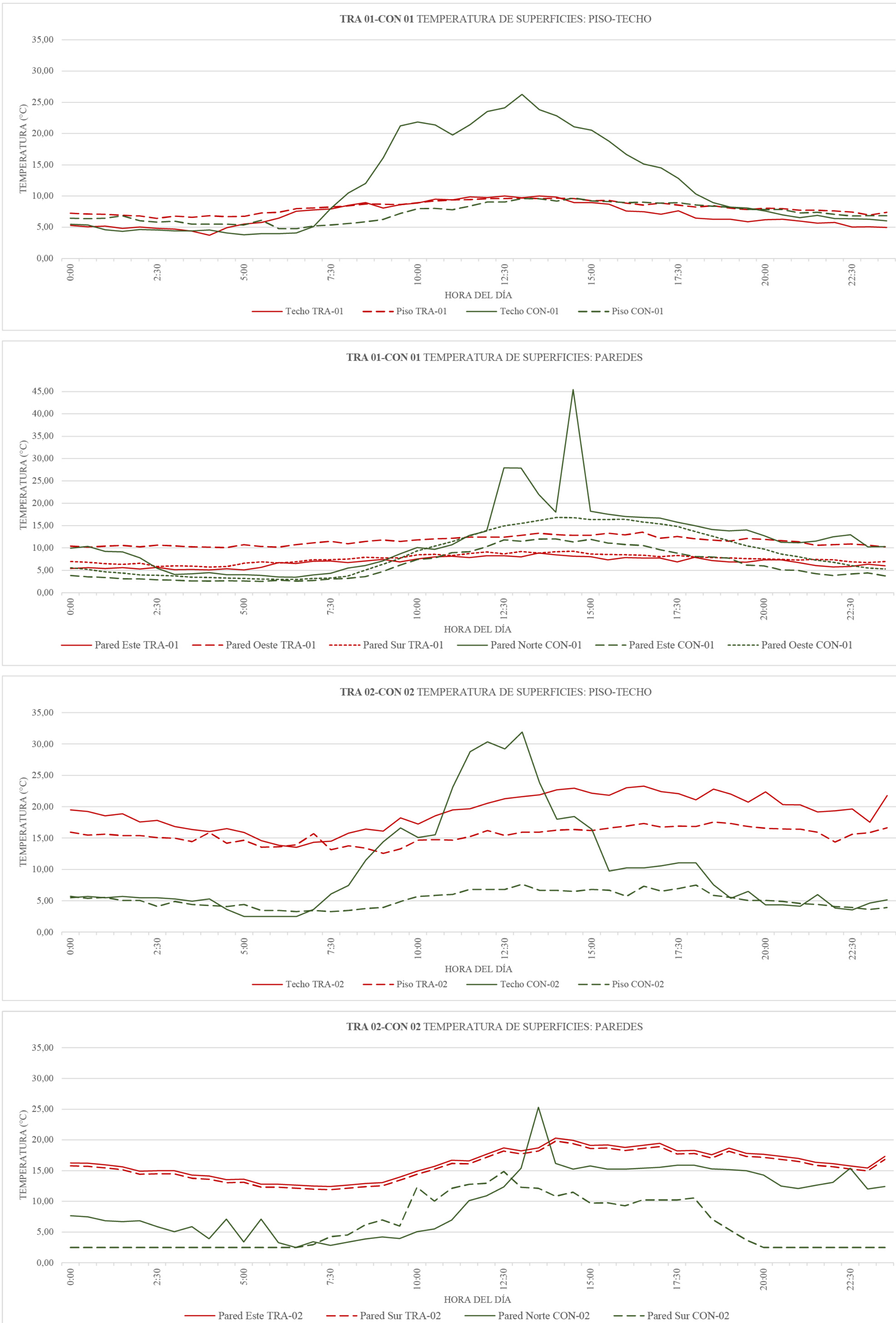

Figure 7. Surface temperatures. Source: Preparation by the Authors.

Table 4. Range of comfort assessment of dwellings. Source: Tartarini et al., (2020).

House ID	Predominant average outdoor temperature (°C)	Comfort range Class I (°C)	Comfort range Class II (°C)	Comfort range Class III (°C)
TRA-01	12.22	19.8 - 24.8	18.8 - 25.8	17.8 - 26.8
TRA-02	12.07	19.8 - 24.8	18.8 - 25.8	17.8 - 26.8
CON-01	10.95	19.4 - 24.4	18.4 - 25.4	17.4 - 26.4
CON-02	12.00	19.8 - 24.8	18.8 - 25.8	17.8 - 26.8

temperature by up to 9°C compared to the outside, according to Suasaca Pelinco et al. (2020).

The one-story CON-01 house, featuring 0.10 m-thick brick walls, exhibited a maximum thermal amplitude of 11.17°C. In the social area (B), the absolute minimum temperature was 7.52°C, and in the bedroom (C) it dropped to 7.87°C. The average indoor temperature was approximately 13°C, and the outside temperature was 11°C, with similar day-to-night temperature fluctuations both indoors and outdoors.

CON-02, a two-story concrete and block structure, exhibited regular thermal oscillation. The average temperatures outside were 12°C, with a social area of 15.07°C and a bedroom of 15.33°C. The interior spaces showed minimum temperatures of 13.10°C (B) and 12.75°C (C), and maximum temperatures of 17°C (B) and 18°C (C).

INDOOR AND OUTDOOR RELATIVE HUMIDITY MONITORING

The relative humidity (RH) outside the four homes studied fluctuates between 35% and 95%, being higher when the temperature is lower and vice versa (Figure 6).

As for the indoor RH, the limits according to the Ecuadorian Technical Standard [NTE] INEN-ISO 7730 are 30% to 70%. The social area (B) of the TRA-01 housing was within the limits only 9.92% of the time monitored, similar to the bedroom (C) with 10.44%. In CON-01, the social area (B) and the bedroom (C) were within the limit of 48.56% and 46.48%, respectively. This result is due to the high thermal transmittance of the roofing materials used in the CON-01 house, specifically fiber cement and translucent sheets, which allow for the accelerated transmission of heat. This increases the indoor temperature at certain times of the day, thereby decreasing the relative humidity value.

During the entire monitoring period, the TRA-02 house remained within the RH limits. The social area (B) of the home CON-02 was only 12.53% of the time, unlike the bedroom (C), which was within the limits, 59.79% of the time. This is because the social area (B) of CON-02 is located on the ground floor, and due to the presence of a masonry enclosure and the absence of a glazed surface, no radiant heat is able to enter.

SURFACE TEMPERATURE MONITORING

In TRA-01, the floor and ceiling temperatures, with U-values of 1.53 W/m²K and 2.87 W/m²K, respectively (Table 2), exhibited minimum oscillations of 3.22°C and 6.28°C. The CON-01 house, with a roof U-value of 5.21 W/m2K, presented an internal surface temperature variation of up to 20°C. This marked oscillation could be associated not only with the roof's low thermal performance but also with high exposure to solar radiation during the day and the presence of translucent surfaces. The wall surface temperatures in the TRA-01 house, which have a U-value of 0.94 W/m²K despite having low temperature values, were maintained within a minimum and constant oscillation range (Figure 7). In the CON-01 house, the walls have a U-value of 3.10 W/m²K, as shown in Figure 8, indicating accelerated heat gain and loss.

As for the two-story houses, the TRA-02 house, with a U-value of 0.55 W/m²K in the floor and 0.45 W/m²K in the roof, remained in a constant oscillation range, despite the daily thermal amplitude of the exterior. However, the roof of the CON-02 house, which has a U-value of 4.02 W/m²K, exhibits significant heat gain and loss (Figure 7).

The same was seen in TRA-02, with a minimum and constant oscillation range in the walls, which has a U-value of 0.21 W/m2K. On the other hand, the temperature of the walls of the CON-02 house, whose U-value is 2.83 W/m²K, underwent an abrupt change of at least 20°C between 11:00 am and 3:00 pm.

EVALUATION OF THERMAL COMFORT

The houses TRA-01, TRA-02 and CON-02 presented a predominant average outdoor temperature value of 12°C and the CON-01, which is the house with the

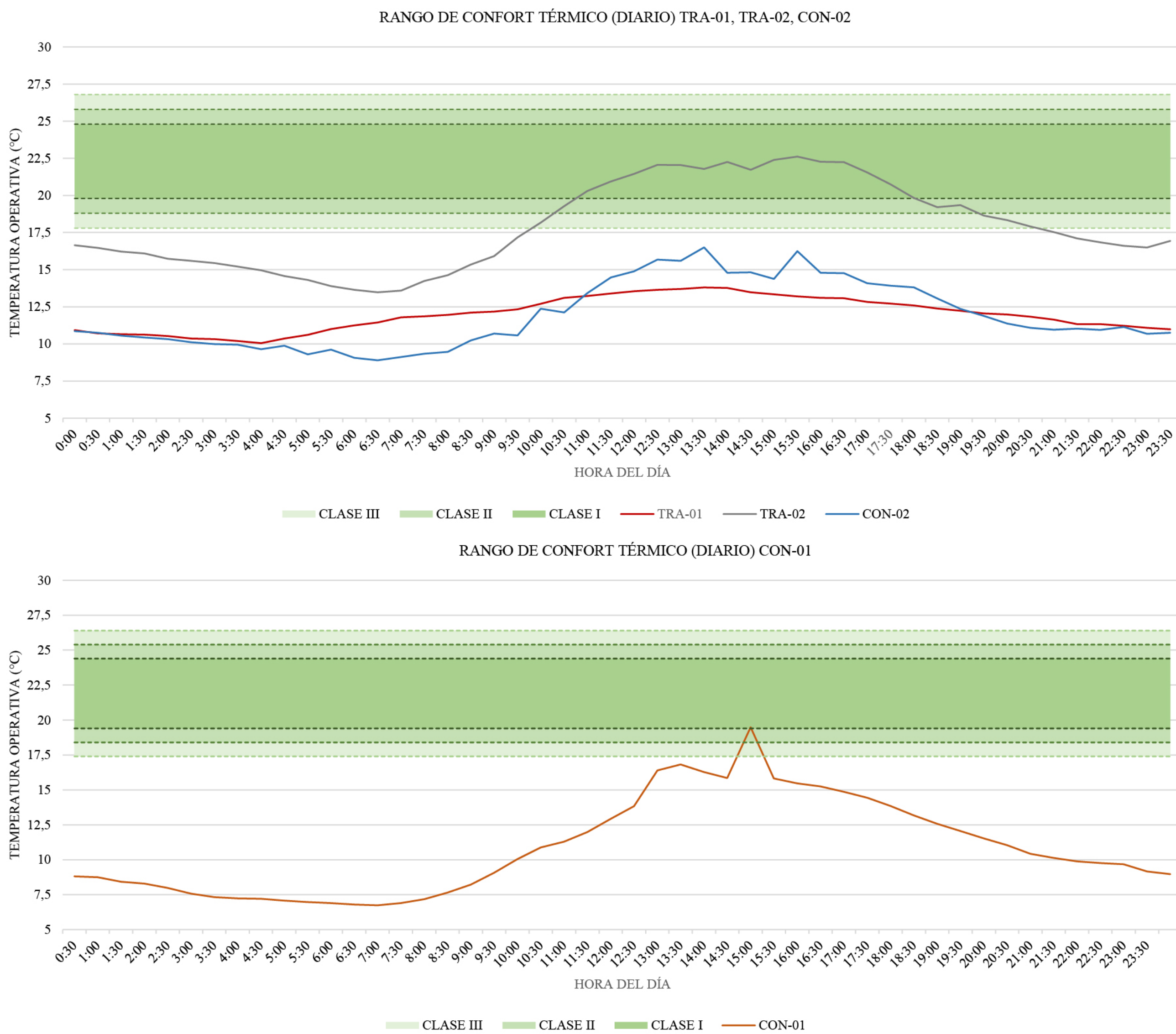

Figure 8. Thermal comfort of case studies. Source: Preparation by the Authors.

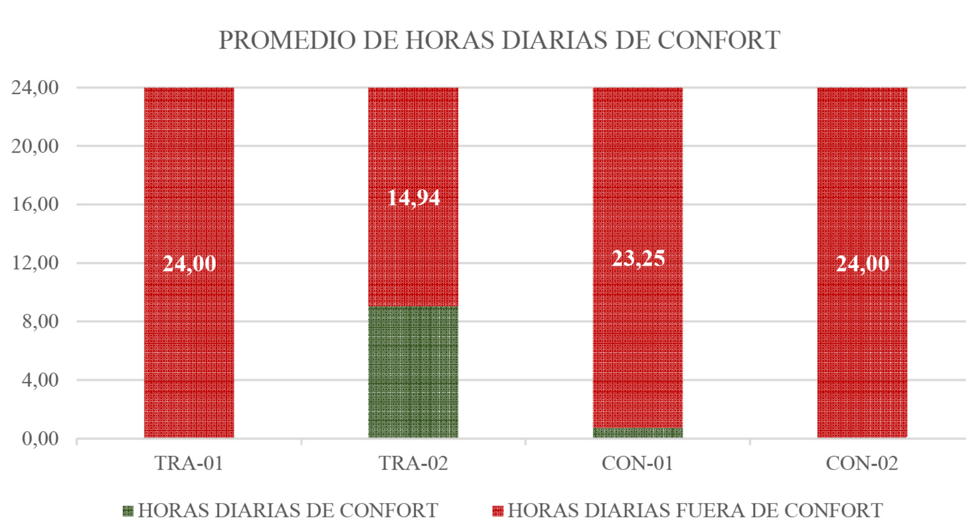

Figure 9. Average number of hours of daily thermal comfort. Source: Preparation by the Authors.

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highest altitude, had a value of 10.95°C, so 3 of the 4 houses will be evaluated with the same comfort range and CON-01 will be evaluated with a slightly lower range (Table 4).

The TRA-01 and CON-01 dwellings are located below the comfort zone, as shown in Figure 8. However, TRA-01 has a more constant temperature than CON-01. In the latter, the higher temperature peaks caused it to reach, on average, a daily comfort period of 0.75 hours (Figure 9).

In TRA-01, the operating temperature ranged from 4°C to 8°C, which is outside the thermal comfort range, compared to CON-01, where there are hours during the day when the outdoor temperature reaches 12°C, also outside the thermal comfort range.

Regarding the TRA-02 house, with extreme temperatures outside, it is barely 4°C outside the thermal comfort range and has 9 hours of comfort per day on average (Figure 9). This is due to the use of insulating materials in the envelope and the use of glazed surfaces with a U-value of 2.75 W/m2K. For CON-02, despite having an average of 0 hours of daily comfort, there are hours during the day that it is barely 1°C outside the comfort range, and in the most extreme temperatures, it is 10°C outside the thermal comfort range.

IDENTIFICATION OF PASSIVE STRATEGIES

The passive air conditioning strategies identified in the different houses were the following: (TRA-01) the orientation concerning the predominant wind, the thermal mass and the attached greenhouse, (TRA-02) the search for the optimal orientation, the perimeter vegetation barrier, the facade and roof color, the thermal mass and the correct selection of the type of glass and carpentry, and in the house (CON -02) the thermal mass on the roof, the color of the facade and the existing enclosure.

Due to the low night and morning temperatures, it is necessary to capture the heat in the morning. The sector's vernacular architecture uses regular shapes, is small, of low height, and has minimal openings. The TRA-02 house divides the space into several volumes that capture sunlight from the east and west. The bedrooms can face east with vertical windows to capture the early morning heat.

Insulation is indispensable in all components of the envelope, including the floor, walls, and roof. Components with U-values above 3 W/m²K are not very efficient at maintaining thermal comfort inside. For a cold climatic zone 5, the envelope requirements according to the NEC-HS-EE (Ministry of Urban Development and Housing, 2018) are U-2.8 on roofs and U-2.35 on walls of non-air-conditioned housing. It is suggested to replicate the wall and roof solutions of TRA-01 and TRA-02, as well as the roof of CON-02, whose pumice block lightening becomes a thermal insulator.

It is necessary to avoid overheating of the spaces due to solar radiation between 12:00 p.m. and 4:00 p.m. Glazing can be minimized or supplemented with solar protection on the west and north facades. Passive ventilation is possible during the middle of the day to regulate the temperature and renew the air. However, the openings should avoid being oriented in the direction of the prevailing winds.

LIMITATIONS OF THE STUDY AND FUTURE RESEARCH

Regarding the study's limitations, the in situ monitoring of temperatures and humidity for the four case studies was recorded asynchronously and over a limited period. Future research may include more extended periods of monitoring to record potential moisture effects during the rainy season of the year. Full-year digital simulations could also be conducted to compare the data recorded in this research.

On the other hand, a methodological limitation is the absence of data on the interior height and vertical location of the sensors, as well as the volumetric and morphological differences between the houses, which limits the comparability between the cases. However, lessons can be learned from passive strategies for achieving adequate thermal comfort inside housing units located between 3,000 and 5,000 masl.

CONCLUSIONS

This study contributes to the field of sustainable habitats, with an empirical focus on dwellings located in cold, high-mountain climates in the Andean region. The context is poorly researched, and thermal comfort becomes important due to the limited availability of active air conditioning systems in the local market. The information obtained from the censuses indicates a growing tendency to replace traditional construction systems with modern solutions, which, in most cases, have inferior thermal performance and also result in a significant loss of built heritage. Therefore, it is essential to explore passive conditioning strategies rooted in traditional knowledge.

To identify passive strategies to improve the thermal comfort conditions of homes located above 3000 masl in the Andean region, the temperature and humidity of 4 homes, two neo-vernacular (TRA-01 and TRA-02) and two homes with modern materials, were described and monitored. (CON-01 and CON-02).

The results showed that the neo-vernacular dwellings maintained a stable indoor temperature, with an average oscillation of 2.13°C for TRA-01 and 5.29 °C for TRA-02. However, TRA-01 is outside the comfort range 100% of the time, and TRA-02 stays within the comfort range 37.75% of the time. This difference in comfort shows that using low thermal transmittance materials, such as straw and the double-glazed system in the windows, allows the interior temperature to be raised. For future research, it is recommended to expand upon the analysis of this typology and explore the potential of using straw as a sustainable construction material with high thermal properties.

In the case of the modern house, CON-01, it is observed that the indoor temperature presents a daily trend similar to that of the outdoor temperature, with a thermal oscillation of up to 11.22°C inside. As for the modern CON-02 house, it shows a more stable thermal behavior, with fewer variations throughout the day. This difference is mainly attributed to the roof's constructive characteristics: while the CON-02 roof incorporates materials with a higher thermal mass, which favors the damping of thermal fluctuations, the CON-01 roof has a lower thermal inertia capacity, which facilitates heat gains or losses, for example when there was an absolute minimum temperature of 7.52°C inside, there was 4.73°C outside, that is, the envelope at the most critical moment of the day only produced an increase of 2.79°C in temperature inside compared to outside.

Taking into account the envelope requirements for opaque elements and windows in non-air-conditioned living spaces of climatic zone 5, according to NEC-HS-EE, even though the standard has a low requirement, only the housing envelope of TRA-02 meets these values. These values are the result of using insulating elements throughout the house's envelope. TRA-01 does not comply with the roof envelope requirement, and CON-01 and CON-02 do not comply with the roof and wall envelope requirements. It is worth mentioning that the four houses meet the window and floor envelope requirements.

These results indicate that a house's thermal response does not depend exclusively on the thermal transmittance value of the materials used, but also on their ability to store and release heat, that is, their thermal inertia. Similarly, it is suggested that other factors, such as orientation and the proportion of glazed surface, among others, may have a significant impact on the indoor thermal behavior. Therefore, it is recommended that these aspects be addressed in future research to achieve a more comprehensive analysis of the thermal performance of homes in Andean areas above 3000 m.a.s.l.

On the other hand, it was seen that in the vast majority of traditional homes in San Juan, parts of the deteriorated vernacular materials have been replaced by modern materials that are more affordable, easier to install, and cheaper, which in some cases has led to a decrease in the quality of the indoor climate. In other cases, the hybrid nature of the solutions demonstrates that the coexistence of traditional materials with contemporary bioclimatic architectural design supports research that has shown the importance of incorporating vernacular architecture to achieve sustainability in modern architectural practices (Moscoso-García & Quesada-Molina, 2023). In this sense, the documentation and analysis of the vernacular architecture of the sector and province are recommended.

Finally, a significant limitation of the study was the inability to conduct simultaneous monitoring between dwellings, which affects the direct comparability of the results. Additionally, it was not possible to take measurements at different heights inside the house to account for the vertical thermal gradient. Therefore, it is recommended that more exhaustive measurements, calibrated thermal simulations, and a more in-depth analysis of the hygrothermal behavior of vernacular materials be incorporated into future research.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, A.N.M.A., V.F.G.M.; Data Curation, A.N.M.A.; Formal analysis, A.N.M.A., V.F.G.M.; Acquisition of A.N.M.A. financing; Research, A.N.M.A.; Methodology, A.N.M.A.; Project management, A.N.M.A.; Resources, A.N.M.A.-N.M.S.H.; Software. A.N.M.A.; Supervision, V.F.G.M.; Validation, A.N.M.A., V.F.G.M., N.M.S.H.; Visualization, A.N.M.A.-N.M.S.H.; Writing - original draft, A.N.M.A.; Writing -revision and editing, A.N.M.A.-N.M.S.H.

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REVITALIZATION OF THE KICHWA SARAGURO ANCESTRAL WATTLE AND DAUB, ECUADOR: CONSERVATION, ADAPTATION, AND DISSEMINATION OF CONSTRUCTIVE HERITAGE

REVITALIZACIÓN DEL BAHAREQUE ANCESTRAL DEL PUEBLO KICHWA SARAGURO, ECUADOR: CONSERVACIÓN, ADAPTACIÓN Y DIFUSIÓN DEL PATRIMONIO CONSTRUCTIVO

REVITALIZAÇÃO DO BAHAREQUE ANCESTRAL KICHWA SARAGURO, ECUADOR : CONSERVAÇÃO, ADAPTAÇÃO E DIFUSÃO DO PATRIMÔNIO CONSTRUTIVO

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RESUMEN

La construcción con bahareque ha evolucionado con el tiempo, pero hoy enfrenta el riesgo de desaparecer debido a la escasez de materiales, la falta de mano de obra y la preferencia por sistemas "más duraderos y versátiles". Este estudio explora la revitalización del bahareque, técnica constructiva ancestral del pueblo kichwa Saraguro - Ecuador, mediante un enfoque metodológico mixto con varias etapas: análisis de materialidad, diseño, análisis estructural y construcción de un panel de bahareque que integra iconografía andina y se adapta a pórticos contemporáneos de hormigón, metal y madera; desarrollo de un taller práctico para divulgar y evaluar la viabilidad de construcción mediante mingas. Los resultados destacan la viabilidad del bahareque en construcciones actuales, con costo accesible y eficiencia estructural. Se promovió su uso al fomentar la participación comunitaria y la transmisión de conocimientos ancestrales. Es una alternativa para la construcción contemporánea, que preserva la identidad cultural y se adapta a desafíos ambientales.

Palabras clave
arquitectura tradicional, técnica mixta, paneles modulares, participación comunitaria

ABSTRACT

Construction with wattle and daub has evolved over time, but today faces the risk of disappearing due to material scarcity, a lack of labor, and a preference for "more durable and versatile" systems. This study explores the revitalization of wattle and daub, an ancestral construction technique of the Kichwa people of Saraguro, Ecuador, through a multi-stage mixed-methodological approach: material analysis, design, structural analysis, and the construction of a wattle and daub panel that integrates Andean iconography and adapts to contemporary concrete, metal, and wood porticos; and a practical workshop to disseminate and evaluate the feasibility of construction through mingas (communal participation). The results highlight the viability of wattle and daub in contemporary construction, with its affordable cost and structural efficiency. Its use was promoted by encouraging community participation and the transmission of ancestral knowledge. It is an alternative for contemporary construction, preserving cultural identity and adapting to environmental challenges.

Keywords
traditional architecture, mixed construction, modular panels, community participation

RESUMO

A construção Bahareque evoluiu ao longo do tempo, mas hoje corre o risco de desaparecer devido à escassez de materiais, à escassez de mão de obra e à preferência por sistemas "mais duráveis e versáteis". Este estudo explora a revitalização do bahareque, uma técnica de construção ancestral do povo Kichwa de Saraguro - Equador, por meio de uma abordagem metodológica mista com várias etapas: análise de materialidade, projeto, análise estrutural e construção de um painel bahareque que integra a iconografia andina e se adapta aos pórticos contemporâneos de concreto, metal e madeira; Desenvolvimento de workshop prático para disseminar e avaliar a viabilidade da construção por meio de mutirões. Os resultados destacam a viabilidade do bahareque na construção moderna, com custo acessível e eficiência estrutural. Seu uso foi promovido pelo incentivo à participação comunitária e à transmissão de conhecimentos ancestrais. É uma alternativa para a construção contemporânea, preservando a identidade cultural e adaptando-se aos desafios ambientais.

Palavras-chave:
arquitetura tradicional, técnica mista, painéis modulares, participação comunitária

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INTRODUCTION

Approximately 650 to 700 million people worldwide still reside in homes constructed with earthen materials, including adobe, mud, and stone. This represents about one in every 10 or 12 people on the planet. (Marsh & Kulshreshtha, 2021). In Ecuador, according to the population and housing census (National Institute of Statistics and Censuses [INEC], 2022), the use of traditional materials in constructions decreased from 28.7% to 13.3% between censuses held every 10 years; these percentages of housing with natural materials are observed: bahareque (wattle and daub) 5.2%, adobe and tapia (crude bricks) 2.5%, and wood 0.6%. The introduction of new industrialized materials has marginalized traditional construction techniques, such as wattle and daub, replacing them with modern alternatives that alter the cultural landscape and compromise environmental sustainability (Pesántez Pesántez & Tapia Vera, 2018).

The accelerated loss of ancestral construction knowledge, the scarcity of intergenerational transmission, and the decline in the practice of these techniques in communities of indigenous peoples and nationalities have made it difficult to access housing solutions that strengthen their cultural identity and promote sustainability. This phenomenon, prevalent in Ecuador and various regions of Latin America, poses a risk to both tangible and intangible cultural heritage, as well as a challenge to social and environmental resilience (Cordero et al., 2003).

In the Latin American context, research presented at the Ibero-American Seminar of Architecture and Earth Construction (SIACOT, in Spanish) and the reports of the PROTERRA Network have extensively documented the loss of ancestral earth construction techniques and their socio-cultural impact (Cevallos Salas, 2003). In Mexico, recent projects in Oaxaca have promoted the revival and adaptation of wattle and daub, which strengthens the social fabric and improves the energy efficiency of housing (López-Martínez & Torres Garibay, 2023). In Colombia, studies in the department of Cauca integrate traditional techniques with modern construction solutions, which increase the durability and thermal comfort of rural housing made with wattle and daub (Cristancho Barrios, 2024). In Peru, Corrales Blanco et al. (2021) highlight the integration of ancestral knowledge with new technologies to create resilient solutions to extreme weather events. In Bolivia, SIACOT has promoted the valorization of traditional adobe and wattle and daub techniques in projects that reduce environmental impact and preserve cultural heritage (Cordero et al., 2003; Neves et al., 2017).

In Ecuador, studies such as those of Pesántez and Tapia Vera (2018) highlight the value of wattle and daub as a cultural expression, tangible heritage, and sustainable alternative. Likewise, experiences of improving the *bahareque* or wattle and daub technique have been developed, such as the modular panels proposed by Vacacela Albuja and Astudillo Cordero (2015), evidencing a growing interest in adapting the ancestral technique to contemporary construction models. This situation reflects a generalized trend in Latin America, where the abandonment of ancestral techniques has marginalized collective knowledge essential for the habitat (Cordero et al., 2003).

The architecture of the original peoples reflects an expression and relationship between ancestral knowledge and the natural environment. In the case of the Kichwa Saraguro people of the province of Loja, in southern Ecuador, their traditional construction system, known as *bahareque*, has evolved in response to the region's environmental and cultural variations. It is a technique that promotes community participation and is based on principles of reciprocity fundamental to collective life (Corrales Blanco et al., 2021).

These practices have been passed down through generations, often through collective work or communal gatherings known as *mingas*. However, globalization has limited the continuity of knowledge transmission, leading to a decline in its practice. Revitalizing these processes is essential to address housing problems in communities of indigenous peoples and nationalities, where solutions usually come from natural materials that, if used sustainably, offer viable alternatives. The recovery of these techniques is part of the UNESCO guidelines (2024) on safeguarding intangible heritage and the SDG11 Sustainable Development Goals, which promote sustainable and resilient cities.

The local *bahareque*, appreciated for its seismic resistance and thermal efficiency, is at risk of disappearing; this threatens ancestral knowledge and cultural identity (Lozano Guamán, 2021). Its rescue and adaptation are fundamental to preserving the heritage. Spreading good constructive practices with *bahareque* (wattle and daub) is essential to revitalize this technique and recognize its value (Corrales Blanco et al., 2021).

VERNACULAR ARCHITECTURE

Vernacular architecture is a cultural testimony that arises from the adaptation of communities to their natural environment, using local materials and techniques transmitted across generations (ICOMOS, 1999; Guerrero Baca, 2017). It represents an anonymous and collective way of being; it reflects the history and customs of the community (Calderón, 1985; UNESCO, 2003). Historically linked to the geographical, social, and economic context, it has been adapted to respond to housing needs with the available resources. It is functional, sustainable, and a means to preserve the cultural identity of the indigenous peoples over time.

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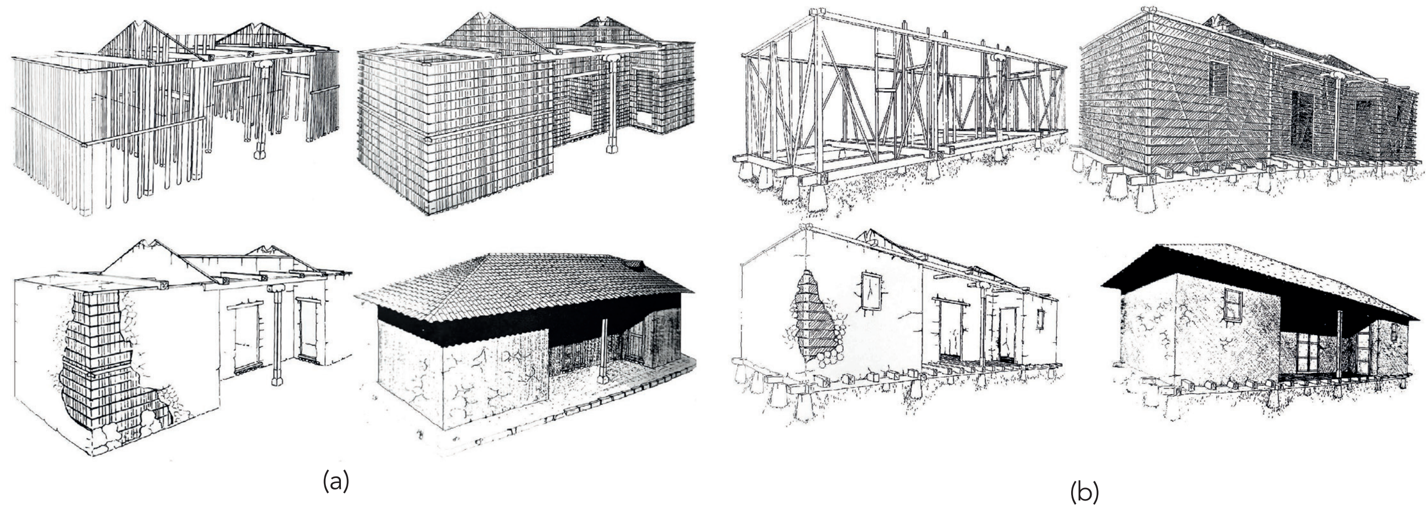


Figure 1. (a) Upright bahareque; (b) galluchaki bahareque. Source: Images taken from Calderón (1985).

BAHAREQUE IN THE KICHWA SARAGURO PEOPLE

The *bahareque*, in its local form, is used by the Kichwa people of Saraguro in the southern Ecuadorian highlands. It uses local materials such as wood, clay, and chincha (suro or *Chusquea scandens Kunth*). There are two variants in Saraguro: the upright *bahareque* and the *galluchaki bahareque* (or houndstooth) (Figure 1).

The upright *bahareque* has a vertical wooden framework anchored in the ground with stone bases to prevent moisture, which provides greater resistance (Calderón, 1985). It takes advantage of the orientation of the sun and the wind to improve indoor comfort (Pacheco, 2007). Deforestation and environmental regulations have led to the replacement of the "hill wood" (native term) with eucalyptus. The *galluchaki bahareque* is raised on stones to avoid moisture. The floors and beams are assembled between the carved wooden pillars, which improves structural stability (Calderón, 1985). The mud mixture, which covers the *chincha chagleado* (latticework), incorporates páramo straw (*Calamagrostis effusa*) and dry leaves, which gives a resistant and versatile finish.

In addition to their architectural value, these systems encourage community cooperation in building *mingas* and rituals, such as the *huarcuna*, which involves swinging from a structural part of the house after the *embarre* (rural community construction process) and weaving to validate its resistance. *Bahareque* is fundamental to the preservation of the cultural identity of Andean communities; its revitalization is essential to address the current housing and climate challenges (Lozano Guamán, 2016).

The purpose of this research is to revitalize the traditional *bahareque* construction system used by the Kichwa Saraguro people, through its characterization and updating from an integral approach that articulates both technical and cultural dimensions. It seeks to rescue this ancestral knowledge not only as a current constructive technique but also as a manifestation of both material and intangible heritage, which strengthens community identity and promotes sustainable practices in the region. To achieve this purpose, the following specific objectives are proposed: to characterize the traditional materials and techniques of *bahareque*; to experimentally evaluate the resistance and adhesion of the earth combined with local vegetable fibers; to design and structurally analyze a modular panel adaptable to contemporary porch systems; and to validate its technical and socio-cultural feasibility through a participatory practical workshop.

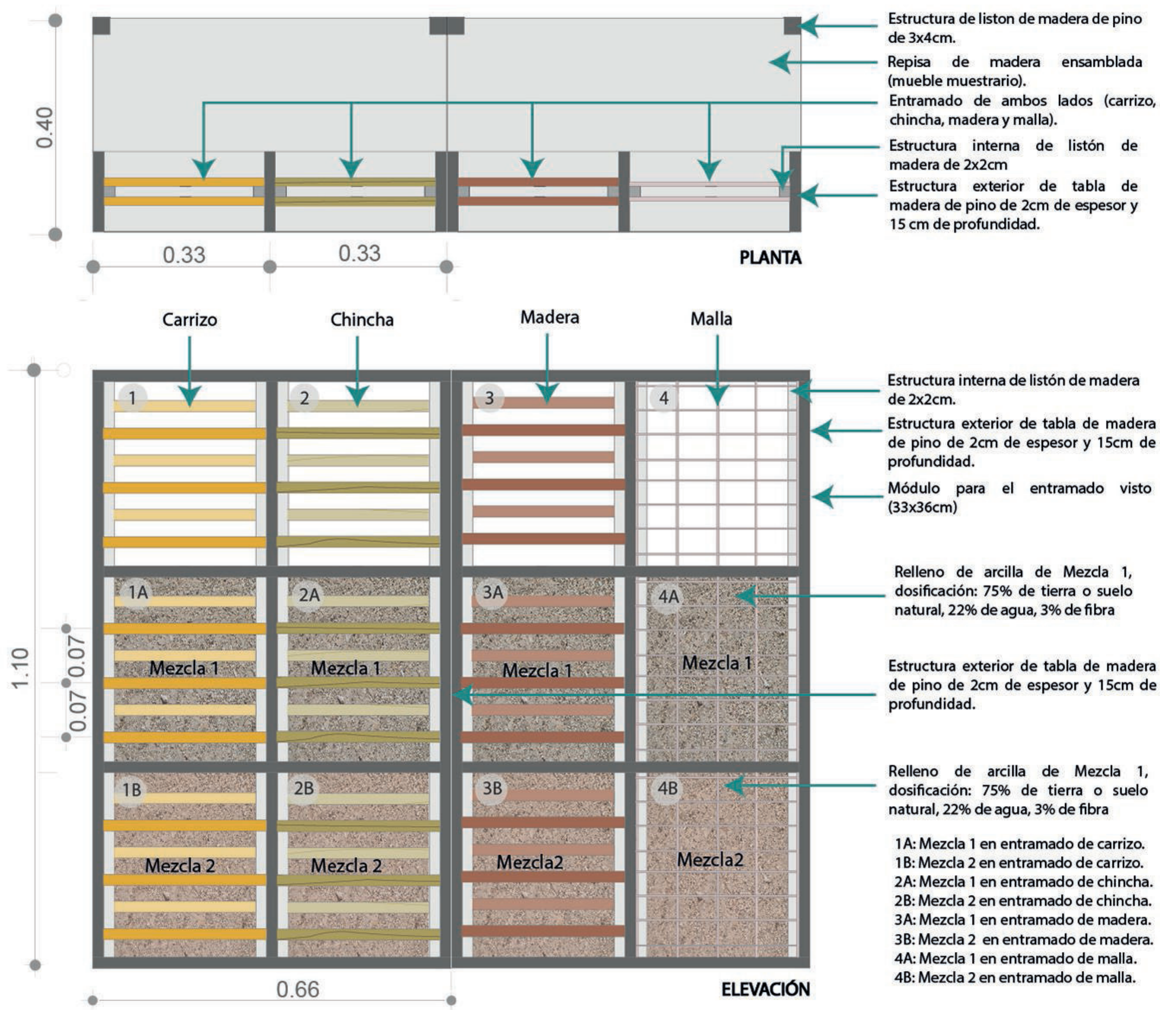
METHODOLOGY

This research employs a mixed-methods approach, combining qualitative and quantitative analysis with descriptive and experimental methods, as well as practical and community validation. It was organized in four main stages: selection and analysis of materials; design and structural analysis of the *bahareque* panel; application proposal and practical workshop; monitoring and evaluation.

SELECTION AND ANALYSIS OF MATERIALS

The selection of soils, materials for trusses, and fibers from the locality, along with the analysis of their physical characteristics, evaluation of compressive strength, and adhesion tests, was carried out.

Two soil samples were taken, sample 1 was taken near the Saludable Park of Saraguro, where the *bahareque* panels were later built, and sample 2 was from the community



DOSIFICACIÓN DE LA MEZCLA:

75% de tierra= 13607,76g (30lb)
22% de agua= 4000g (4 lt)
3% de fibras= 544,56g (1 1/2 lb)

Por cada 200 gr (30 libras de tierra, 4 litros de agua y una libra y media de fibra: 0,75lb de hojas de pino, 0,75lb de hoja de puquín.

Figure 2. (a) Floor plan and elevation of the truss sampler. (b) Preparation of the dosed mixture. (3) Application of the mixture in the reeds, chincha, wood, and mesh structures. Source: Preparation by the Authors.

of Las Lagunas, where the practical workshop was later held. The proximity to existing earthen constructions and the construction site, as well as the availability of suitable soils, were the key criteria for selecting these locations.

The field and laboratory tests on the samples included analysis of particle size, moisture content, liquid limits, and plasticity. At the same time, field sedimentation tests were conducted to analyze the soil's properties under humid conditions and classify it according to its texture. This procedure makes it possible to classify soils into strips of clay, silt, or sand, determining their applicability in various construction techniques (Pahaut et al., 2020).

The field test of the roll was carried out to identify simply the amount of clay in the soil samples and determine the appropriate dosages for use in the construction system: the soil sample is ground to a fine material; water is added to form a paste and a roll of 2 cm in diameter is formed. The breakage strength of the roll was evaluated according to the protocol of Pahaut et al. (2020): at 7 cm, the clay is insufficient; between 7 and 14 cm is ideal, and at more than 14 cm, it is excessive.

Earth test bodies were made with páramo straw fibers, pine leaves and puquín (dried leaves of the corn cob), the Spanish regulations UNE-EN 1015-11:2000/A1

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(2007) were used, which establishes the test methods to determine flexion and compression resistance in masonry mortars, with adaptations for materials such as earth, taken from the analysis methodology used by Gonzalo Sánchez (2012).

According to the standard, the dosage of 75% soil or natural soil, 22% water and 3% of a mixture of naturally dried fibers (8g of fiber per 200g of soil) was used to make five 10x5x5 cm specimens for each soil sample, they were dried for seven days and then subjected to compression tests in the laboratory.

Additionally, an adhesion analysis was conducted by constructing modular panels with various lattice types (Gonzalo Sánchez, 2012). In each module, a mixture of mud with páramo straw, pine, and puquín fibers was applied (1.5g of each fiber). For three weeks, the adherence of each mixture in the different lattices was monitored (Figure 2).

The adhesion of a mixture of earth and natural fibers on different lattices was evaluated, and the level of cracking was observed in a thickness of 12 cm. In the traditional method of the Kichwa Saraguro people, the use of the chincha (Andean bamboo or zuro) offers high adhesion due to its rough and irregular surface, which reduces the separation between materials. To compare their performance, similar tests were applied on rectangular wooden slats, chicken coop mesh, and peeled reed. These tests show the difference in the cohesion of the materials, highlighting the effectiveness of the traditional system (Gonzalo Sánchez, 2012).

DESIGN AND STRUCTURAL ANALYSIS OF BAHAREQUE PANEL

The formal design of the panel was based on the *bahareque* construction system technique, *galluchaki*, and aesthetically reflected in Andean iconography, as seen in the graphics comprising diagonal and successive elements, which are found in the textiles of the Kichwa

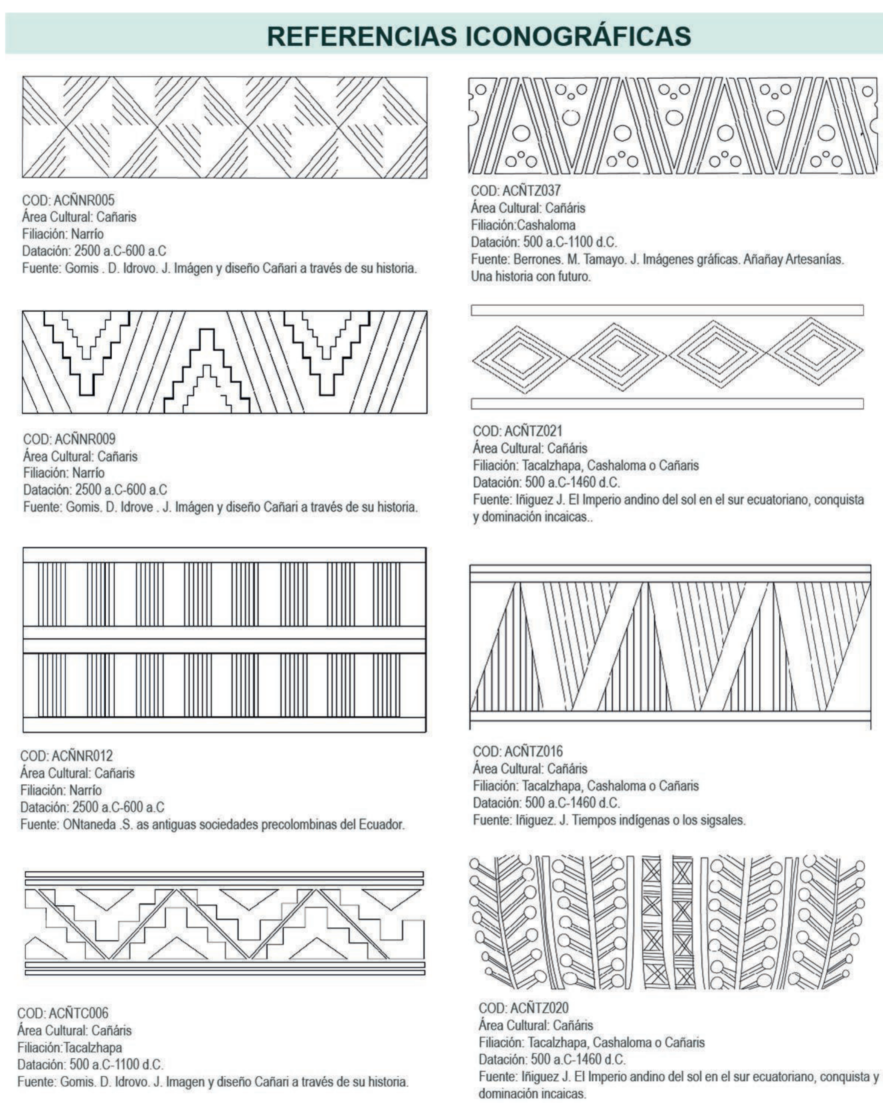
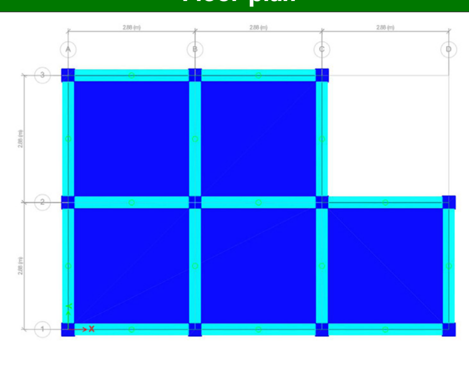
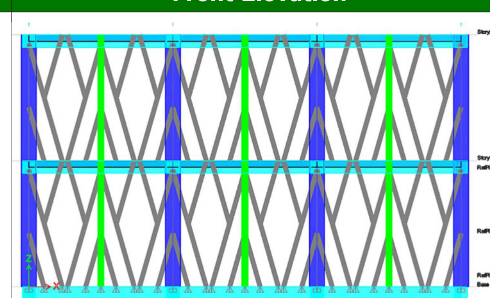


Figure 3. Iconographic references for the development of proposals for the structural geometry of bahareque panels. Source: Image taken from Martínez et al. (2015).

Table 1. Properties of eucalyptus for the panel structure. Source: Junta del Acuerdo de Cartagena (1984).

Type : B	Property	Value
EMIN	Modulus of elasticity.	75,000 kg/cm2
SW	Specific weight	1,000 kg/m3
EPROM	Modulus of elasticity	100,000 kg/cm2
FM	Resistance to momentum	150 kg/cm2
FC	Resistance to parallel compression	110 kg/cm2
FC P	Perpendicular compressive strength	28 kg/cm2
FV	Resistance to parallel cutting	12 kg/cm2
FT	Parallel tensile strength	105 kg/cm2

Table 2. Analysis model with reinforced concrete gantry system. Source: Preparation by the Authors.

Detail	Value	Floor plan	Front Elevation
Number of floors	2		
Mezzanine height	2.52 m		
Distance between the X-axis	2.88 m		
Distance between the Y-axis	2.88 m		
Irregularity in the floor plan	Yes		
Irregularity in elevation	No		

Saraguro people and their neighboring Kichwa Cañari counterparts (Figure 3).

The design of the panel considered the possibility of adapting it to wooden portico structures, reinforced concrete, metal, or even stone or adobe load-bearing walls. The proposal aimed to optimize the use of materials, reduce costs, and construction times, while using materials accessible in the local market.

The resistance of the panel was analyzed using the SAP2000 software, which considered the structural material to be eucalyptus wood, with the properties listed in Table 1.

The interaction between the wooden panels and a porticoed structure was analyzed structurally. The *bahareque*-type panels were incorporated into a reinforced concrete porticoed system to evaluate their impact on the transmission of loads and the rigidity of the structure (Table 2). Gravitational and seismic loads were included.

The standards NEC-SE-DS (Ministry of Urban Development and Housing [MIDUVI], 2014a) for seismic analysis, NEC-SE-GC (MIDUVI, 2014b) for non-seismic loads, and NEC-SE-HM (MIDUVI, 2014c) for reinforced concrete were applied.

The constructive details of the panel were developed using Archicad. An attempt was made to facilitate prefabrication and assembly and reduce the mud-caking time.

The prototype of the panel was built based on the results obtained; eucalyptus and chincha wood were used. For the first filling layer, soil from samples 1 and 2 was used in equal proportions, combined with fibers such as puquin and pine leaves. For the plastering, sample 1 was used, which included 15% finely chopped fibers and natural additives such as cane honey, aloe, and white glue.

The unit price analysis (UPA) of a panel was performed after its construction, when the performance was clear.

PROPOSAL FOR IMPLEMENTATION - PRACTICAL WORKSHOP

Three proposals for the application of the panel in different types of porticos were developed to demonstrate the

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possibilities of integration in wooden, concrete, or metal structures. For this, the distribution of porticos used in the structural analysis was used. Archicad was used as a visualization tool.

To disseminate the proposal and evaluate its feasibility for construction through *mingas*, a practical workshop was held, where students, parents who are community members, teachers, and professionals in architecture participated. The workshop was held over two days, beginning with an introduction to the importance of bioconstruction in today's world. Then, the procedures for identifying the types of soil were explained. The natural fibers were prepared, and the mud was mixed, which was applied as the first layer on the wall of the Community Educational Center *Inti Raymi* (CECIB *Inti Raymi*). Finally, the mortar for plastering, incorporating binders and natural fibers, was prepared and applied to a *bahareque* wall of the Andean House, a ceremonial space within the community school.

MONITORING/EVALUATION

To evaluate the technical, social, and cultural impact of the practical workshop, a longitudinal follow-up process was proposed from a participant observation perspective. Given her membership in the community technical team of Chukidel Ayllullacta, the principal researcher is in a strategic position to continuously document the appropriation and replication of the construction system at different scales of the region.

THE FOLLOW-UP INCLUDES:

- Registration of spontaneous adoption processes of the system, especially by families or groups that did not participate directly in the workshop.
- Evaluation of the level of understanding and autonomous reproduction of the techniques taught.
- Identification of improvements or adaptations made by users.
- Observation of the social and symbolic dynamics associated with the construction with bahareque.

This process enables the assessment not only of the system's technical effectiveness, but also its transformative potential as a tool for architectural, social, and cultural revitalization in the region. Special attention is paid to how traditional constructive knowledge is re-signified in contemporary contexts, and how collective practice (*minga*) favors its intergenerational transmission.

In summary, this methodology integrates technical design, constructive experimentation, and socio-cultural evaluation in a holistic process that articulates academic and community knowledge around the vernacular architecture of the Kichwa Saraguro people.

RESULTS AND DISCUSSION

ANALYSIS OF MATERIALS

The granulometric analysis of the soils in the laboratory indicated that the composition of sample 1, with a moisture content of 17.71%, was 67.3% sand and 32.7% fines. In contrast, sample 2, with a moisture content of 32.69%, consisted of 1% gravel, 19.4% sand, and 79.6% fines (silt and clay).

When comparing the results of the sedimentation test with those of the laboratory, similar data were obtained. In the soil classification pyramid (Pahaut et al., 2020), it is observed that sample 1 is a sandy loam soil, while sample 2 is on the boundary of a clay loam and a loam soil. This means that Sample 1 is more recommended for plasters, and Sample 2 for fillers (Figure 4).

At the roll test (Figure 5), in sample 1, with a single dosage, the average breakage occurred at 8 cm, ideal for *bahareque*; with 1 part sand and 1 part clay, it was at 6 cm, suitable for plasters. In sample 2, without rupture in three tests, it indicates a high amount of clay, ideal for craftsmanship, but for *bahareque* it needs more fiber to avoid cracks; with 1 part of clay and 2 parts of sand, it occurred at 11 cm, suitable for *bahareque*, and with 1 part of clay and 3 parts of sand, at 7 cm, suitable for plasters. This clay can also be used in paints and plaster, providing glossy finishes.

In the laboratory tests of the compressive strength of the bars (Table 3), the results show that the fibers significantly increase the resistance of the samples, with pine and puquín leaves being the most effective, which justifies their use in panel construction. The páramo straw was discarded due to its ecological role in the Andean páramos, where it is essential for water conservation. In its replacement, pine and puquín leaves were used, materials that offer a viable alternative to straw and a lower environmental impact.

In the adhesion tests, the materials proved to be suitable for the trusses, but they showed different adhesion behaviors with the first layer of clay and fiber:

- **Common reed grass (*Carrizo*):** High adhesion due to its smooth and round surface, but it is affected by the retraction of the mud; its lack of irregularities or porosity prevents a complete fixation, so a crack is generated between both materials. To improve its performance, it is recommended to divide the thick canes and place the more porous face towards the mud.
- **Chincha:** Favorable adhesion is achieved thanks to its wide canes and its semi-smooth, more porous outer surface, which allows for better interaction with mud and fiber, as the cracking between the materials

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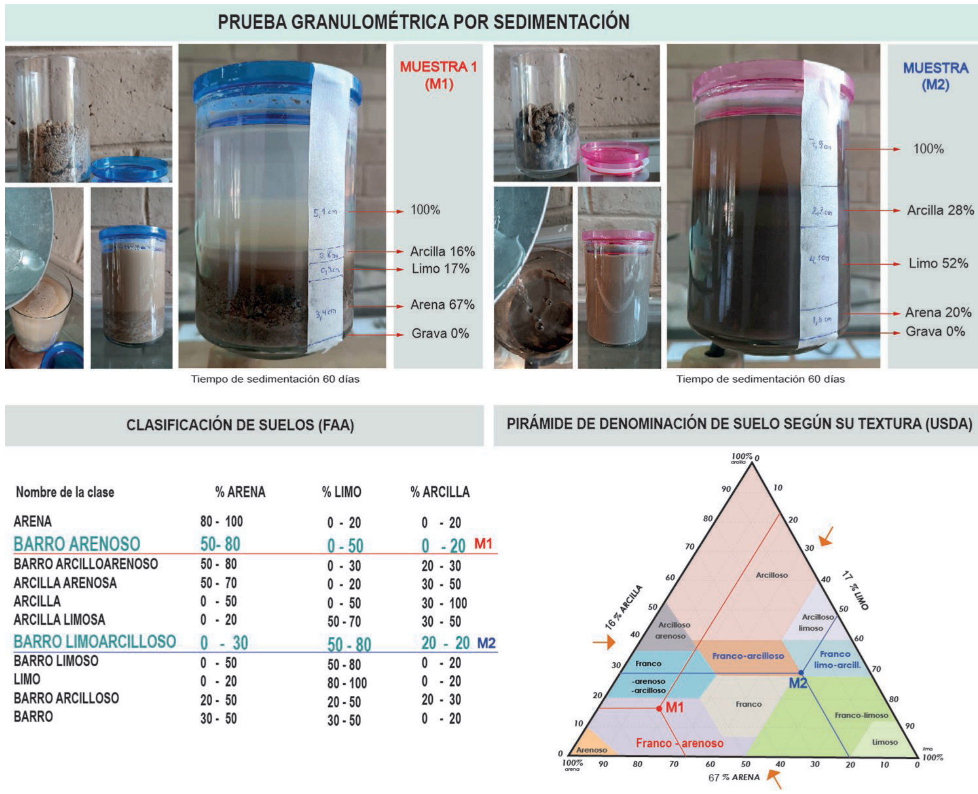

Figure 4. Granulometry results of samples 1 and 2 in the soil classification pyramid according to their texture. Source: Preparation by the Authors based on Pahaut et al. (2020).

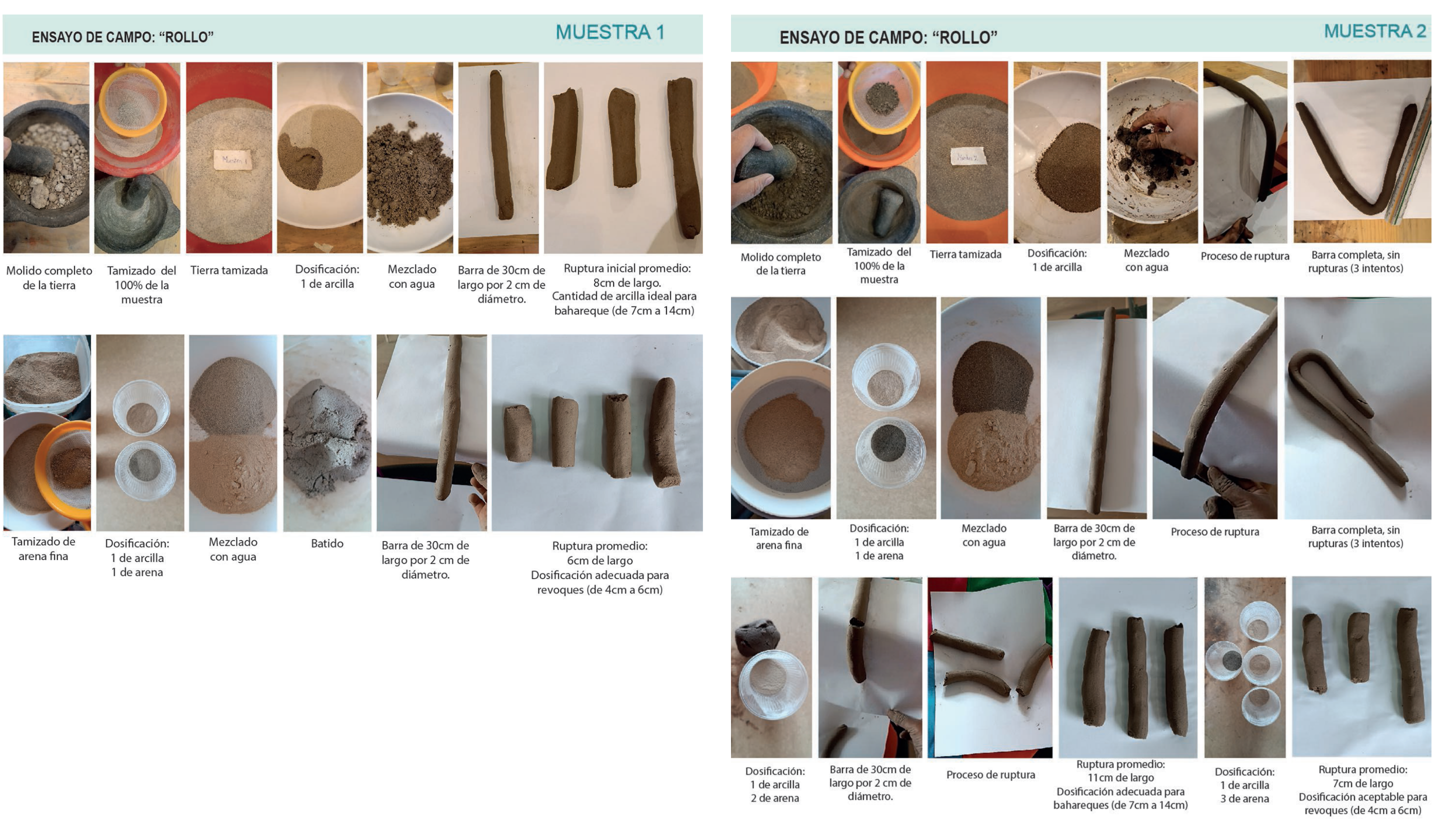

Figure 5. Roll-type field test (a) Sample 1; (b) Sample 2. Source: Preparation by the Authors based on Pahaut et al. (2020).

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Table 3. Results of the compressive strength in bars, samples 1 and 2. Source: Preparation by the Authors.

	Description	Área (cm²)	Load (Kg)	Resistance (Kg/cm²)
Sample 1	Empty	33.75	1455	43.11
	Straw	45	15460	343.56
	Pine	45	13876	308.36
	Puquín	45	27040	600.89
	3 fibers	45	10029	222.87
Sample2	Empty	33.75	2975	88.15
	Straw	45	13325	296.11
	Pine	45	14622	324.93
	Puquín	45	22205	493.44
	3 fibers	45	13405	297.89

is minimal. It is suggested to use the chincha in an inversely proportional way to ensure efficient drying with minimal shrinkage.

- Wood: The high porosity of its faces favors adhesion with the filling. The slats, placed between 5 and 7 cm apart, retain the fibers and prevent slipping and cracking during drying.
- Mesh: Excellent adhesion due to the metal structure and the small diameter of its rods, but it was seen that it is not an indigenous material and can overheat, which affects the internal humidity of the mud. It is recommended to use it in interior plasters where there is limited exposure to sunlight to avoid unfavorable cracking.

DESIGN AND STRUCTURAL ANALYSIS OF THE BAHAREQUE PANEL

The design of the *bahareque* panel incorporates geometric elements derived from Andean iconography such as triangles, rhombuses, and figures of axial symmetry. These patterns not only symbolically enrich the proposal but also serve a structural function, as the triangles and rhombuses are integrated as external diagonal braces and internal reinforcements of the lattice, providing rigidity and stability to the panel. In this way, the structural functionality of the system is merged with the Andean symbology and cosmovision.

An abstract symbol of the corn cob and geometric patterns present in the textiles and festivities of the Kichwa Saraguro culture were identified (Figure 6). These represent the duality of life, balance and cosmic order, which were adapted to build a contemporary structural system. In the Kichwa language, *Sara* (maize) and *Kuru* (worm) further enrich the cultural significance of the proposal.

Figure 6. Iconographic analysis and geometry design concept. Source: Preparation by the authors based on Martínez et al., 2015, and Inga, 2021.

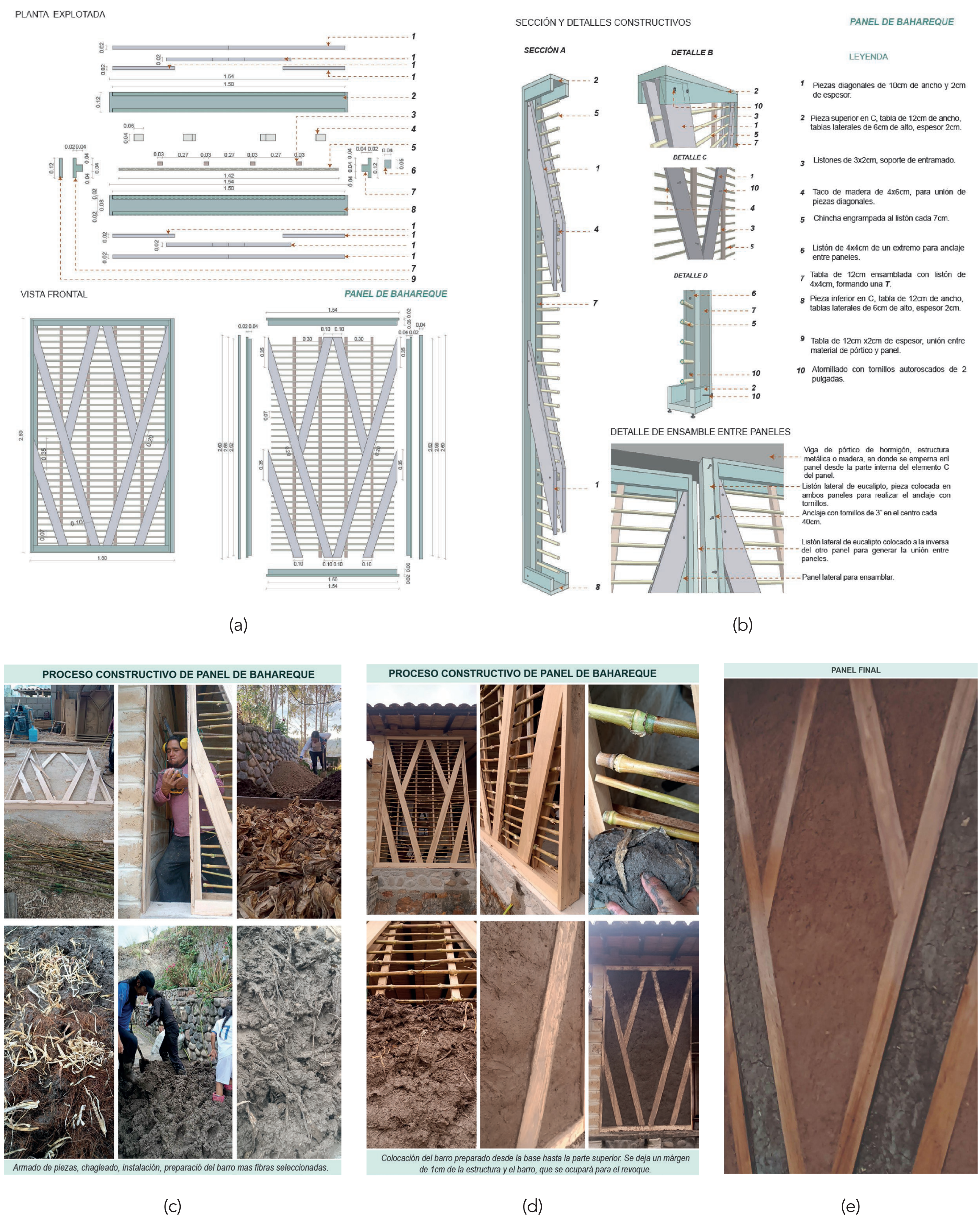

Figure 7. Proposed panel (a) disassembly; (b) details; (c) Photographs of the construction process, and (d) final result of the panel. Source: Preparation by the Authors.

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Table 4. Tests for resistance to elastic buckling and compressive strength. Source: Preparation by the Authors.

Element	Section diameter (m)	Effective length (m)	Critical buckling Pcr (kg)	Compressive strength (fc= 110 kg/cm2)	Maximum axial (Kg-m)	State
Vertical frame	0.12	1.6	39242	12441	1806	Complies with
Main diagonal brace	0.8	2.43	3356	5529	474	Complies with

Table 5. Flexion resistance check. Source: Preparation by the Authors.

	Section diameter (m)	Resistance to momentum (Kg-m)	Maximum momentum (Kg-m)	State
Vertical frame	0.12	509	22	Complies with
Upper horizontal frame	0.12	509	727	Complies with
Main diagonal brace	0.8	151	116	Complies with

The panels that make up the structure are made of 3x4 cm eucalyptus slats (the element that holds the chagliding), 4x4 cm (the element to join the panels), and 12x2 cm boards. Their construction and installation are simplified by using self-tapping screws, staples, and white glue putty. Figure 7 illustrates the proposed panel design.

Through the structural analysis of the panel, it was possible to verify that it meets the requirements for resistance to elastic buckling, compression, and flexion. The data obtained are presented in Tables 4 and 5.

STRUCTURAL ANALYSIS FOR THE APPLICATION OF THE PANELS IN PORTICOS

The inclusion of *bahareque* panels in structures with porticos reduces the vibration period from 0.31 seconds to 0.21 seconds, thereby improving the seismic response by decreasing flexibility and reducing the current seismic forces. Although this effect may be favorable, it requires a specific analysis in each case, as wooden panels and porticos (made of concrete, metal, or earth) absorb energy differently. When the panels have no structural function, the porticos must be designed in accordance with the corresponding regulations. Additionally, it is necessary to provide a technical joint between the panel and the portico to prevent unwanted rigidities or adverse effects.

The panel is fixed to the portico using an intermediate piece of wood (0.12m x 0.04m anchor plank) that is previously bolted to the existing portico, whether made of concrete, metal, or earth. This part serves as a flexible connector, protecting the integrity of the panel and facilitating its assembly. At the base of the system, there must be a stone stem wall or a wooden floor beam anchored to the floor or foundation, which levels and isolates the panel from direct contact with the ground, allowing the preservation of the natural moisture level of the panel materials. This modular joining system allows the adaptation of panels to various structural types without compromising their behavior or physical properties.

APPLICATION PROPOSAL

To visualize the application of the panels, housing proposals were made that used the same distribution of porticos used in the structural tests for one-, two-, and three-story houses (Figure 8).

- Wooden portico: A solution is proposed for one-story houses that integrates *bahareque* panels in conventional wooden structures. This allows reducing the amount of wood required, which maintains stability and functionality.
- Reinforced concrete portico: The application of *bahareque* panels is feasible in this system, with modifications to the height of the panels and the distribution of the porticoes to accommodate two-level buildings.
- Metal structure portico: In constructions of up to three floors, *bahareque* panels offer an efficient and sustainable solution that maximizes the use of local materials and integrates into the metal structure.

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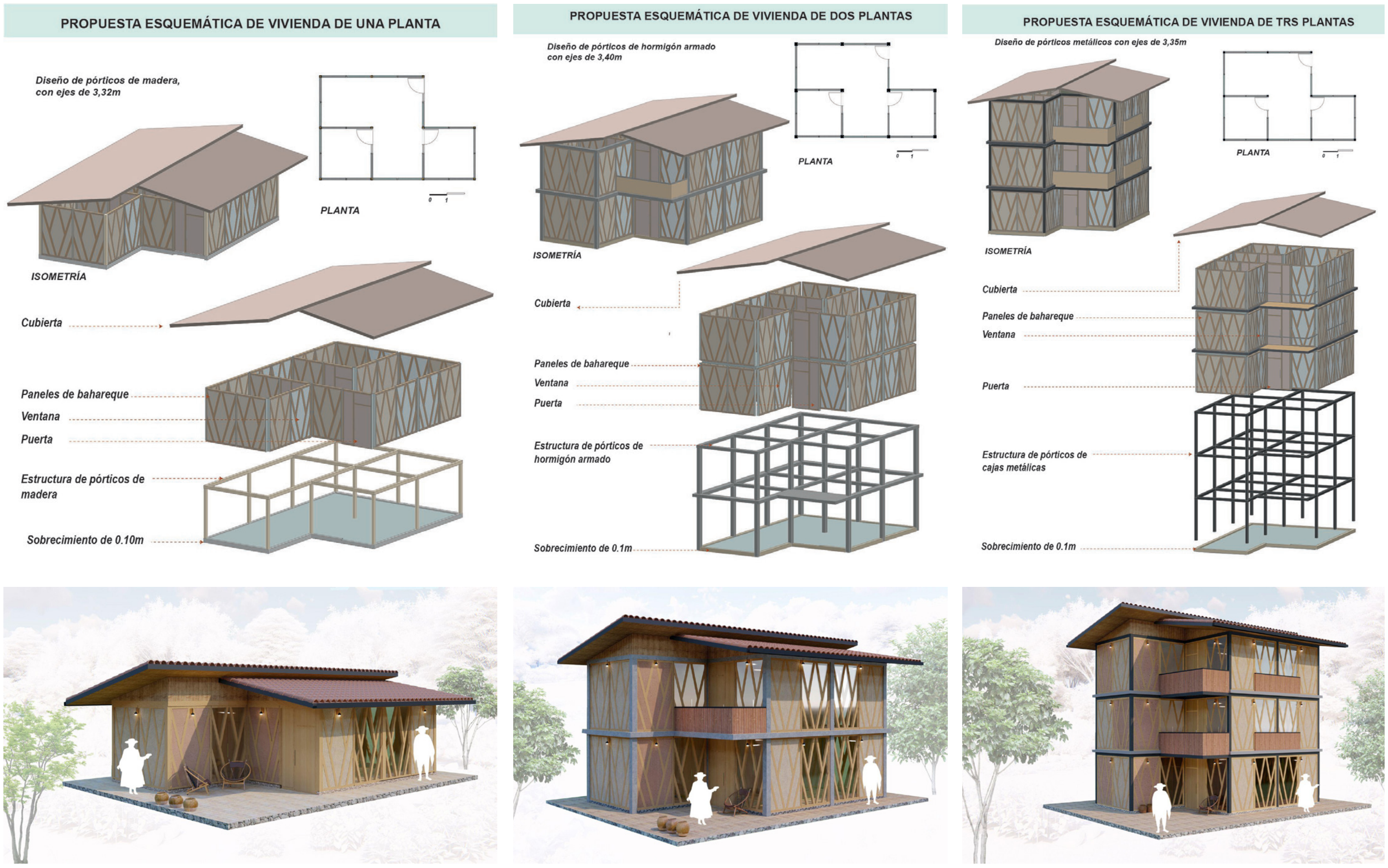

(a) (b) (c)

Figure 8. Schematic application of panels (a) Single floor house; (b) Two floor house; (c) Three floor house. Source: Preparation by the Authors.

BAHAREQUE PANEL UNIT PRICE ANALYSIS

The unit price analysis for a 1.60 m x 2.60 m bay panel considers four components: equipment, labor, materials, and transportation. A 5% charge is included for hand tools (USD 0.05) and the participation of a laborer and a mason, totaling USD 10.01. The materials (eucalyptus wood, screws, chinchas, mud with fibers, among others) total USD 132.00. Transportation is USD 3.00. The direct cost amounts to USD 145.06, to which 15% is added for indirect costs (USD 21.76) and 5% of profit (USD 7.25), totaling USD 174.07 as the offered value.

This amount is the cost per unit of the panel (4.16 m^2), equivalent to USD 41.84 per square meter. When compared to a block wall, which costs USD 64.39 per square meter (including cladding, plastering, and painting), the *bahareque* panel is 35% cheaper. Although wood finishes can increase the final value, the use of recycled and local materials helps keep costs down, positioning *bahareque* as a viable and accessible alternative within sustainable construction.

APPLICATION – SOCIALIZATION

Approximately 50 people participated in the bioconstruction workshop at CECIB *Inti Raymi*. The event took place over two days, with one hour dedicated to the theoretical workshop and 15 hours to the practical workshop. This activity facilitated the transmission of ancestral knowledge about construction, as it promoted interaction between generations and created a collective learning environment. Students from the last school grades, young local architects, and those from other cities worked together, overcoming the barriers of age, gender, and academic level.

Bioconstruction is not limited to fixed formulas, but should be an experimental and experiential process, as emphasized by Guerrero Baca (2017). The participants learned about the preparation of mud, the dosage of soils, and experimented with local fibers to improve the construction technique. This event allowed the youngest to reconnect with the *allpa mama* (Mother Earth) and strengthen their sense of belonging to the community and culture. In addition, it stressed the importance of sustainability and environmental care, raising awareness

Figure 9. Images of the application workshop. Source: Preparation by the Authors.

about the need to preserve ancestral building practices and promote the responsible use of local resources. (Figure 9).

EVALUATION - IMPACT ON THE COMMUNITY

Following the workshop, coordination was conducted with community authorities to construct new spaces that promote collective participation and community gatherings, known as *mingas*. Additionally, in its professional practice, there was a growing interest in utilizing local materials for family projects. The dissemination of these collaborative processes has motivated councils of communities, such as Chukidel Ayllullacta, Gera, and Ilincho, of the Kichwa Saraguro people, in Saraguro Canton, Loja Province, south of Ecuador, among others, to undertake community *mingas* to build new spaces and revitalize existing ones.

Following the socialization of the construction process through the practical earth workshop and its dissemination on CECIB digital channels, Inti Raymi initiated a community process to build a collective kitchen using *galluchaki bahareque*. In addition, construction of a single-family house in the community began, in its traditional form, with a stone foundation, uprights on plinths, a diagonal brace, chincha and reed *chagleado*, and *embarre* (a rural local construction technique) using local natural fibers. An architectural object with metal porticos and *bahareque* panels was also proposed for commercial and tourist use within the community context.

The positive impact of promoting the preservation of constructive knowledge is observed, while also exploring new combinations of materials and strengthening confidence in the use of local resources, such as land, wood, and chincha, which adapt the system to the current needs of the population.

CONCLUSIONS AND RECOMMENDATIONS

The constructive system of *bahareque* of the Kichwa Saraguro people, particularly in its variant *galluchaki*, demonstrates a remarkable capacity for structural adaptation and material sustainability. Its implementation allows for a significant reduction in the use of industrialized materials by taking advantage of local natural fibers and ancestral methods with low environmental impact. The proper identification of the soil, the precise dosage of components, and the incorporation of plant structures have opened up possibilities for innovative applications in structural geometries, architectural finishes, and the active preservation of cultural identity.

This research contributes to the state of the art by systematizing constructive practices that integrate material and immaterial value, recognizing *bahareque* not only as a technique but also as a living cultural expression. Its contemporary application not only preserves what has been built but also reactivates community practices and rituals, which establish a bridge between ancestral knowledge and current habitat needs.

Although the structural calculations support the resistance of the constructions, the requirements for *bahareque* houses of one to three floors can be flexible, depending on the context and project conditions. An understanding of the basic principles of porticos and cross-beams is sufficient to ensure structural stability, as it allows a wide margin for experimentation and adaptation of this system to different architectural forms. The feasibility of these proposals will depend on economic factors and the level of detail in the construction, while also considering local traditions and their relevance in the current context.

The *bahareque* houses address housing needs and are a testament to the solidarity and collective work of the native peoples. Through this research, it has been demonstrated that the resistance and adaptability of the materials, as well as the acceptance they receive when participatory processes are promoted to disseminate the construction technique and its particularities properly, are key factors.

Finally, it is recommended that future research examine the quantitative aspects of the system more closely, such as the density and resistance of the mixtures, the final weight per module, thermal transmittance coefficients, and strategies to prevent thermal bridges between panels. Such data will allow refining the technical criteria for its normative validation, without compromising its cultural essence or its potential as a sustainable solution for rural and peri-urban habitats in the Andes.

CONTRIBUTION OF AUTHORS CRediT

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

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EXPLORING MICROALGAE APPLICATIONS IN BUILDING FACADES: A BIBLIOMETRIC PERSPECTIVE

INVESTIGACIÓN DE APLICACIONES DE MICROALGAS EN FACHADAS DE EDIFICIOS: UNA PERSPECTIVA BIBLIOMÉTRICA

ESTUDO DE APLICAÇÕES DE MICROALGAS EM FACHADAS DE EDIFÍCIOS: UMA PERSPECTIVA BIBLIOMÉTRICA

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RESUMEN

Las microalgas son microorganismos con un gran potencial para su aplicación en tecnologías medioambientales sustentables por su capacidad de fotosintetizar, producir biomasa, absorber dióxido de carbono y tratar aguas residuales. Estas propiedades versátiles permiten integrar las microalgas en los sistemas arquitectónicos de fachadas. Los fotobiorreactores que pueden integrarse en la fachada cumplen funciones como la generación de energía, la mejora de la calidad del aire, el sombreado y el tratamiento de aguas residuales. En este contexto, aunque existen muchos estudios bibliométricos en la literatura sobre el uso de microalgas en los campos medioambiental e industrial, no hay ningún estudio bibliométrico exhaustivo que se centre en el uso de microalgas en diseños de fachadas arquitectónicas. Este estudio pretende revelar sistemáticamente las tendencias de la investigación en este campo examinando la bibliografía sobre el uso de microalgas en fachadas de edificios y sistemas de revestimiento mediante un análisis bibliométrico. Según los resultados de la investigación, la literatura científica sobre el uso de microalgas en fachadas de edificios ha aumentado rápidamente en los últimos años con colaboraciones interdisciplinarias y se centra en los temas de sustentabilidad, eficiencia energética e interacción biológica. Los estudios publicados entre 2012 y 2024, liderados por países como Alemania, Estados Unidos, China y Países Bajos, se configuran en torno a palabras clave como microalgas, biorreactor, fachada verde, y biointegración, centrados en la eficiencia energética, la sustentabilidad y la biotecnología de la construcción. Como resultado, esta investigación hace visible la posición actual de las tecnologías de microalgas y ofrece recomendaciones estratégicas para orientar futuros trabajos académicos.

Palabras clave
microalgas, fotobiorreactor, arquitectura sostenible, diseño de fachadas, análisis bibliométrico, biomasa, producción de energía

ABSTRACT

Microalgae are microorganisms that offer promising potential for application in sustainable environmental technologies due to their ability to photosynthesize, produce biomass, absorb carbon dioxide, and treat wastewater. These versatile properties allow microalgae to be integrated into architectural façade systems. Photobioreactors that can be integrated into architectural facades can be used for energy generation, air quality improvement, shading, and wastewater treatment. In this context, although there are many bibliometric studies in the literature on the use of microalgae in environmental and industrial applications, no comprehensive bibliometric study focuses on the use of microalgae in architectural facade designs. This study aims to systematically reveal the research trends in this field by examining the literature on the use of microalgae in building facades and cladding systems through bibliometric analysis. According to the research findings, the scientific literature on the use of microalgae in building facades has been increasing rapidly in recent years, with interdisciplinary collaborations focusing on the themes of sustainability, energy efficiency, and biological interaction. The studies published between 2012 and 2024, with leading contributions from countries such as Germany, the USA, China, and the Netherlands, are shaped around keywords such as microalgae, bioreactor, green facade, bio-integration, with a focus on energy efficiency, sustainability, and building biotechnology. As a result, this research makes the current position of microalgae technologies visible and provides strategic recommendations to guide future academic work.

Keywords
microalgae, photobioreactor, sustainable architecture, façade design, bibliometric analysis, biomass, energy production

RESUMO

As microalgas são microorganismos que apresentam um potencial promissor para aplicação em tecnologias ambientais sustentáveis devido à sua capacidade de fotossíntese, produção de biomassa, absorção de dióxido de carbono e tratamento de águas residuais. Essas propriedades versáteis permitem que as microalgas sejam integradas aos sistemas de fachadas arquitetônicas. Os fotobiorreatores que podem ser integrados às fachadas arquitetônicas podem ser usados para geração de energia, melhoria da qualidade do ar, sombreamento e tratamento de águas residuais. Neste contexto, embora existam muitos estudos bibliométricos na literatura sobre o uso de microalgas em aplicações ambientais e industriais, nenhum estudo bibliométrico abrangente enfoca o uso de microalgas em projetos de fachadas arquitetônicas. O objetivo deste estudo é identificar de forma sistemática as tendências de pesquisa nesse campo, por meio da análise bibliométrica da literatura sobre o uso de microalgas em fachadas de edifícios e sistemas de revestimento. De acordo com os resultados da pesquisa, a literatura científica sobre o uso de microalgas em fachadas de edifícios tem aumentado rapidamente nos últimos anos, com colaborações interdisciplinares focadas nos temas de sustentabilidade, eficiência energética e interação biológica. Os estudos publicados entre 2012 e 2024, com contribuições importantes de países como Alemanha, EUA, China e Países Baixos, concentram-se em palavras-chave como microalgas, biorreator, fachada verde, biointegração, com foco em eficiência energética, sustentabilidade e biotecnologia aplicada à construção. Assim, esta pesquisa torna visível o estágio atual das tecnologias de microalgas e oferece recomendações estratégicas para orientar futuros trabalhos acadêmicos.

Palavras-chave:
microalgas, Fotobiorreactor, Arquitetura Sustentável, Design de Fachadas, Análise Bibliométrica, Biomassa, Produção de Energia

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INTRODUCTION

Microalgae are single-celled algae that are capable of photosynthesis and contain different pigments, especially chlorophyll-a. Using sunlight, they produce oxygen from carbon dioxide. Due to their rapid biomass production, CO_2 absorption capacity, biofuel generation potential, and effectiveness in wastewater treatment, microalgae are considered a sustainable biological resource with applications across diverse fields such as energy, healthcare, and environmental management (Umdu & Univ, 2020). Microalgae can thrive in both natural and artificial environments. Naturally, they are found in freshwater habitats (lakes, rivers, ponds), saline waters (seas, oceans, lagoons), moist soils, and on tree bark. Artificial cultivation systems include open ponds and closed photobioreactors. Open systems are installed outdoors and directly use sunlight. In contrast, closed systems involve the controlled cultivation of algae within glass, tube, or panel-based photobioreactors, where factors such as humidity, temperature, and pressure are accurately regulated. Notably, closed photobioreactor systems offer significant potential for integration into architectural applications (Carvalho et al., 2014). When incorporated into building façades, these systems can contribute to energy generation, improved air quality, and wastewater treatment (Öncel et al., 2016; Yaman et al., 2024).

Photobioreactors utilize the photosynthetic capability of microalgae to produce energy on building façades. These reactors produce oxygen and biomass by capturing sunlight and absorbing carbon dioxide through panels, tubes, or glass systems integrated into the building envelope. The biomass created is then transformed in different ways into energy. The biomass can be converted into biogas, which can be used as a fuel, while biodiesel can help satisfy the building's power requirements (Arora et al., 2024; Talaei & Prieto, 2024). Different types and forms of photobioreactors have been developed for the frontline use of microalgae. There are various formal classifications for photobioreactors in the literature. They can be flat, horizontal and vertical tubular (Yoo et al., 2013); tubular, flat-slab and helicoidal (Yılmaz, 2006); horizontal tubular, vertical tubular, vertical column and flat plates (Ugwu et al., 2008; Bitog et al., 2011; Wang et al., 2012) or tubular, flat panels, vertical bubble column and vertical airlift (Sedighi et al., 2023). The species characteristics, along with the technical and environmental requirements of the façade, are decisive in the use of photobioreactors on facades. However, light, temperature, humidity, and maintenance conditions differ according to microalgae species. The light requirements, growth rates, temperature tolerances, and biomass production amounts of different algae species also vary (Singh & Singh, 2015). Conversely, facade design might also reflect different needs, including climate, orientation, solar control, shading, and thermal insulation. Thus, both the appropriate conditions for algae to thrive and the functional and architectural needs of the facade should be considered jointly when selecting the type of photobioreactor for the facade. The system's performance depends much on this balance (Huang et al., 2017).

Because algae can produce energy, clean wastewater, and improve air quality, it is a crucial research topic for sustainable architectural approaches. Considering the many advantages of microalgae, more research on their application in building facades is imperative. Thus, new research on façade systems utilizing microalgae is crucial for achieving sustainable urbanization and mitigating climate change. Numerous bibliometric analysis studies on microalgae have been carried out in the literature at various points in time. The study by Rumin et al. (2020) examined the development of research on microalgae worldwide, in Europe, and in the Euro-Atlantic Region from 1960 to 2019. This study analyzed 79,020 publications to assess the evolution of research topics, collaborations between countries and institutions, prominent and declining research concepts, the most studied species, and relevant journals. Purba et al. (2024) analyzed 1,339 research articles on the use of microalgae in wastewater treatment for environmental sustainability from 1990 to November 2023. Kinawy et al. (2024) conducted a bibliometric analysis covering the use of microalgae in the cosmetics industry in the last two decades. Gao et al. (2022) analyzed 10,201 articles on using algae as biofuels from 1980 to 2019 and evaluated their publication performance, social networks, and research trends. Silva et al. (2020) analyzed research, patents, industry and market trends on microalgal pigments over the last decade. Li & Zhu's (2021) study analyzed 2,621 studies on the use of microalgae in wastewater treatment in the last 20 years in terms of publication characteristics, collaborations, and research trends. Melo et al. (2022) analyzed the bibliometric research on microalgae cultivation in wastewater from agricultural industries. As a result, existing studies have focused on environmental and industrial applications of microalgae, such as energy production, environmental sustainability, or wastewater treatment. However, there is no research in the literature that addresses the use of microalgae in architectural façade designs with a comprehensive bibliometric analysis. Therefore, this study aims to systematically reveal the research trends in the field by analyzing the literature focusing on the use of microalgae in building facades and cladding systems with the science mapping method. In this respect, the study aims to make a unique contribution to the literature by highlighting the role of microalgae technology in architectural applications, mapping interdisciplinary research areas, and providing strategic directions for future research.

METHODOLOGY

Within the scope of this study, a systematic and comprehensive literature search was conducted on the Web of Science (WoS) database on May 8, 2025,

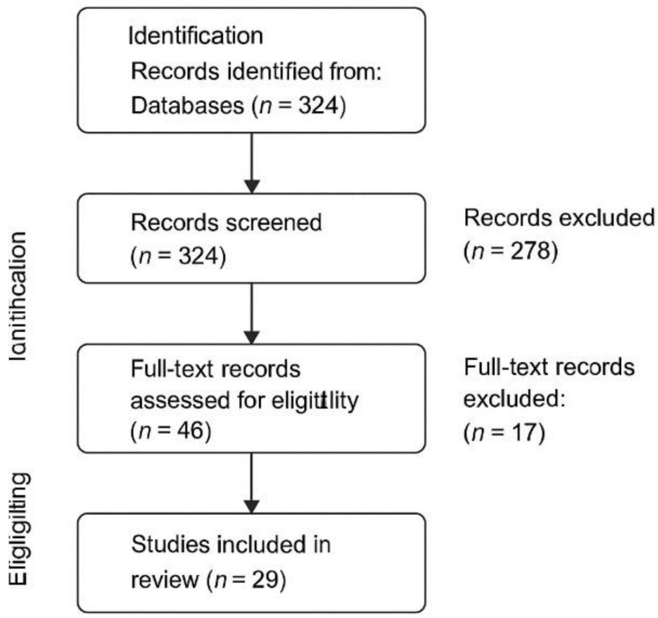


Figure 1. PRISMA flow diagram of the study. Source: Prepared by the authors.

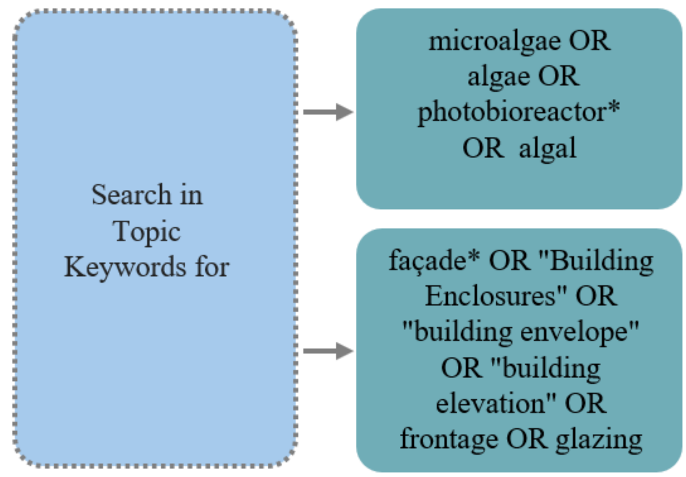


Figure 2. Search in the Web of Science Database. Source: Prepared by the authors.

aiming to identify academic publications related to the application of algae in building façades. The search strategy employed a combination of topic-based keywords to capture relevant studies from diverse disciplinary backgrounds. The bibliographic data retrieved were exported and subsequently analyzed using the Bibliometrix R-package to perform a bibliometric analysis. This included evaluating publication years, journals, subject areas, countries, institutions, authorship patterns, international collaborations, and keyword distributions.

In line with current international standards for systematic reviews, the study was conducted following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The entire review process, including identification, screening, eligibility assessment, and final inclusion of studies, was documented using the PRISMA flow diagram and checklist. The flowchart summarizing the study selection process is presented in Figure 1, while the corresponding PRISMA checklist is provided in the supplementary materials.

The search in the Web of Science database was conducted using topic-based keywords. The first group of keywords included: "microalgae" OR "algae" OR "photobioreactor" OR "algal", which allowed filtering the literature related to microalgae and photobioreactor systems. The second group focused on building façades and included the terms: "façade" OR "Building Enclosures" OR "building envelope" OR "building elevation" OR "frontage" OR "glazing", identifying studies related to building envelopes. Combining these two keyword groups, 232 academic sources were retrieved. These sources formed the dataset for analysis and were utilized in the bibliometric evaluation of this study (Figure 2). Studies were included based on predefined eligibility criteria: (1) focus on microalgae applications in building façades, (2) peer-reviewed English-language articles, (3) publications between 1986–2025. Exclusion criteria included reviews that did not focus on architectural integration or studies that lacked experimental design.

RESULTS

The search conducted in the Web of Science database on May 8, 2025, identified 232 studies. Only articles written in English were included in the bibliometric analysis process.

In this context, this bibliometric analysis, based on 217 English-language articles published between 1986 and 2025, reveals that the field has shown steady growth with an annual growth rate of 5.48%, and has emerged as a highly collaborative academic field. With contributions from 743 authors, the documents demonstrate an average of 4.53 co-authors per publication, and only 11 single-author papers, indicating that research in this field is predominantly conducted through teamwork. The rate of international co-authorship is 23.5%, highlighting strong global collaboration within the field. The documents have an average age of 7.88 years and have each received an average of 17.35 citations, reflecting significant academic impact. A total of 795 keywords and 7,585 references indicates the diversity of research content and the extensive scope of the literature reviewed (Figure 3).

Figure 3. Main information of the studies. Source: Prepared by the authors.

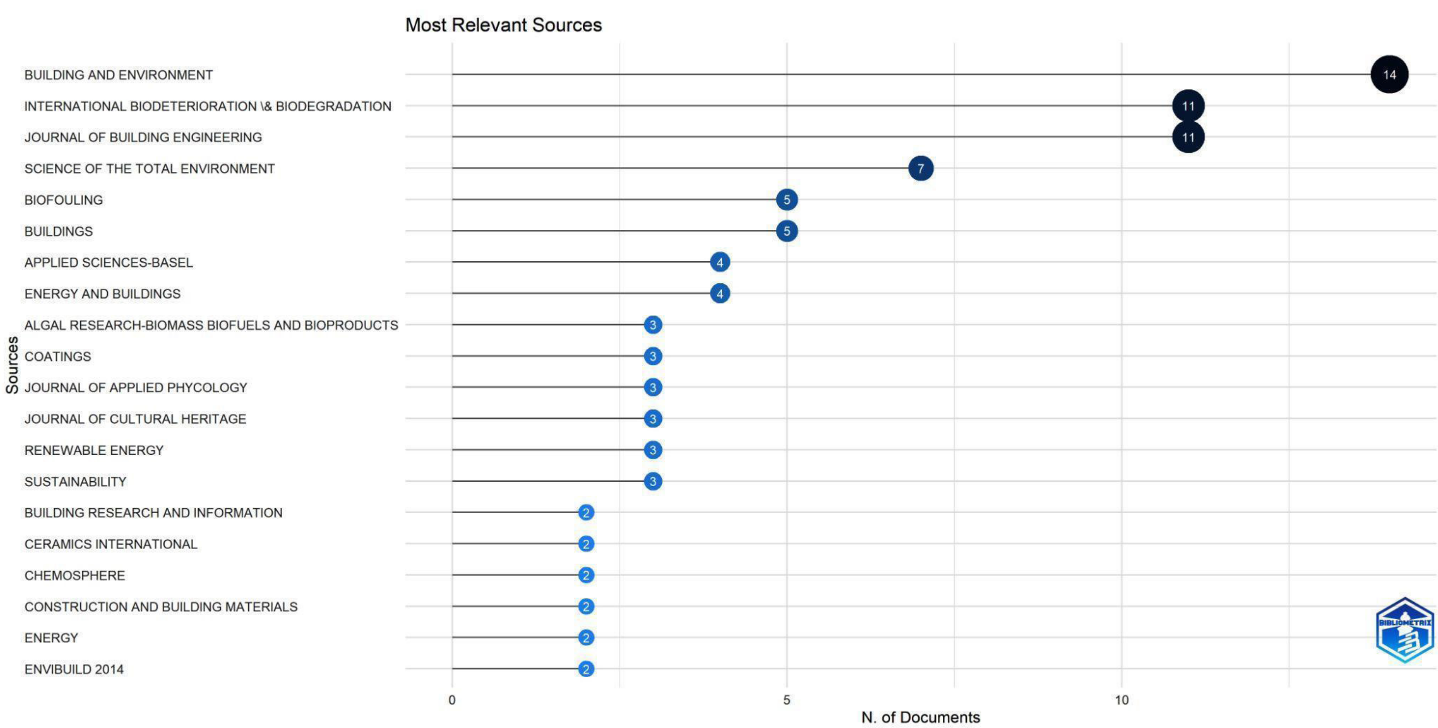


Figure 4. Most Relevant Sources. Source: Prepared by the authors.

The data presented in the "Most Relevant Sources" graph (Figure 4) clearly demonstrates the interdisciplinary nature of research on the application of algae in building façades. One of the journals with the highest number of publications, Building and Environment (14 documents), occasionally features studies evaluating the environmental performance, energy efficiency, and sustainability of algae-integrated façade systems. While some studies have explored algae-integrated façade systems, these remain relatively limited within the broader scope of published works. Sources such as International Biodeterioration & Biodegradation (11 documents) and Biofouling (5 documents) highlight the significant focus on the microbiological aspects of algae, including their biological effects, degradation processes, and interactions with material surfaces. Similarly, publications in journals such as the Journal of Building Engineering, Energy and Buildings, and Applied Sciences-Basel emphasize the engineering solutions and energy production contributions of algae-based façade systems. Furthermore, the presence of specialized journals such as Algal Research, Journal of Applied Phycology, and Renewable Energy indicates that algae are also being explored for their potential in renewable energy production and biotechnological applications within the context of architectural façade

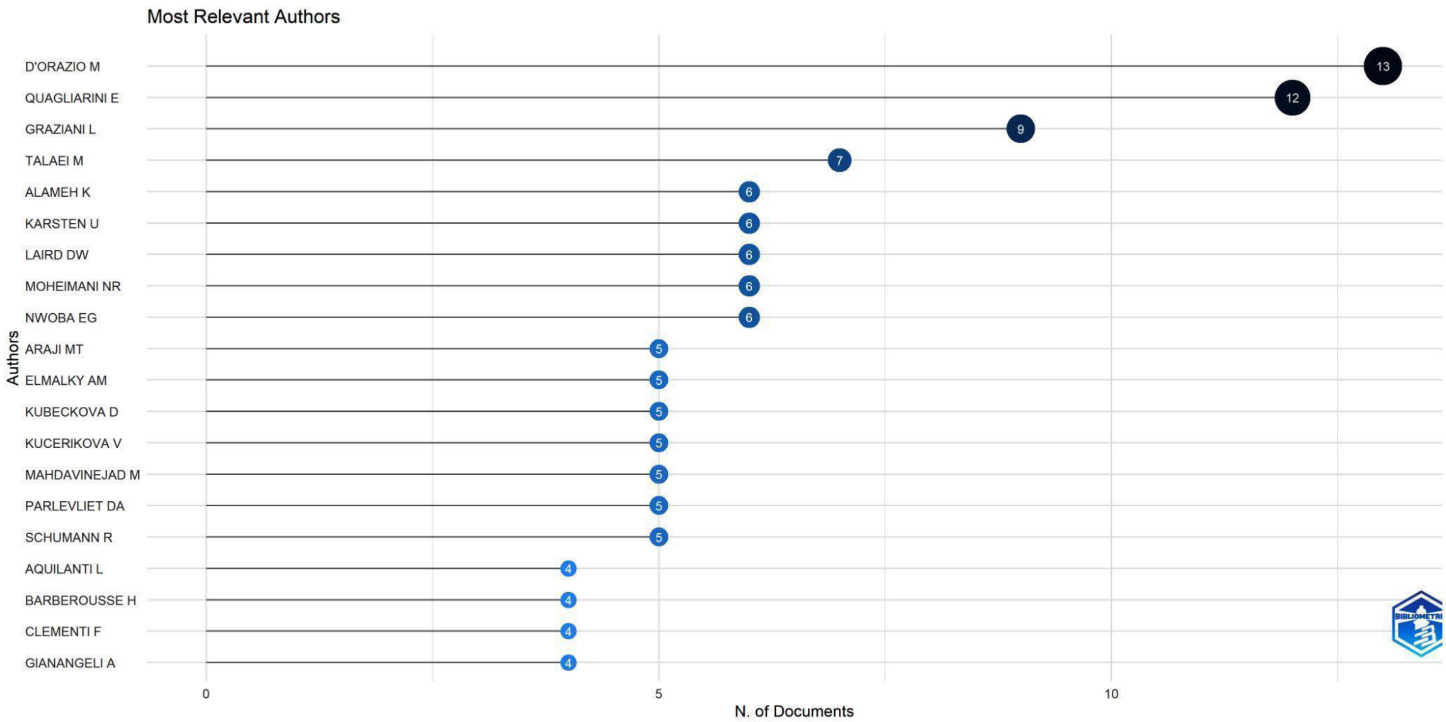


Figure 5. Most Relevant Authors. Source: Prepared by the authors.

integration. This distribution clearly shows that the topic is addressed not only in the field of architecture but also across environmental science, biotechnology, and energy engineering, reflecting its multidisciplinary research landscape.

The data in the graph of the most relevant authors (Figure 5) shows the most influential authors in the academic work on the use of algae in facades and reveals the profiles of the researchers on whom the scientific production in this field is focused. D'Orazio, M. (13 documents) and Quagliarini, E. (12 documents) are among the most prominent researchers in the field of biological effects of algae on building surfaces, their consequences on material strength, and the integration of these organisms into façade systems. Graziani L. (9 documents) and Talaei M. (7 documents) have also produced studies exploring the possibilities of algae-based façade designs in terms of both environmental and energy performance. Other prominent authors, such as Alameh K., Karsten U., Moheimani N.R., and Nwoba E.G., have contributed in the context of algal biology, photosynthetic efficiency, and biotechnological façade systems, bringing environmental science, engineering, and biotechnology perspectives to the topic.

The Most Relevant Affiliations graph (Figure 6) shows the distribution of academic publications on the use of microalgae in façades by university. Università Politecnica delle Marche (Italy) (32 papers) and Murdoch University (Australia) (31 papers) stand out among the institutions with the highest number of publications. This shows that these universities are leading research centers in biotechnological and sustainable architectural approaches, such as the use of microalgae in building facades. Notably, Universidade Nova de Lisboa (Portugal), University of Technology - Sydney (Australia), and the University of Waterloo (Canada) also contribute with 12-17 articles. The data provide an important direction for academic collaboration and knowledge sharing for researchers interested in integrating microalgae into building facades.

The Countries' Scientific Production map (Figure 7) shows the geographical distribution of scientific production on the use of microalgae in building front applications. The countries highlighted in dark blue on the map have the highest academic production in this field. Germany (90 publications) is the clear leader in this field, followed by France (68), Australia (58), and Italy (53). This indicates that European countries are taking a leading role in integrating microalgae technologies into sustainable frontier systems and that the research infrastructure in these countries is robust. In particular, countries such as Germany and France are pioneers in terms of both applied research and industry-academia collaborations. On the map, Australia's intensive academic production shows that studies on biotechnological façade systems that utilize the continent's climatic advantages stand out. The fact that countries such as Iran, China, and the US also have an increasing production capacity in this field shows that microalgae-based innovations are becoming widespread globally and that this technology will be integrated into broader geographies in the future.

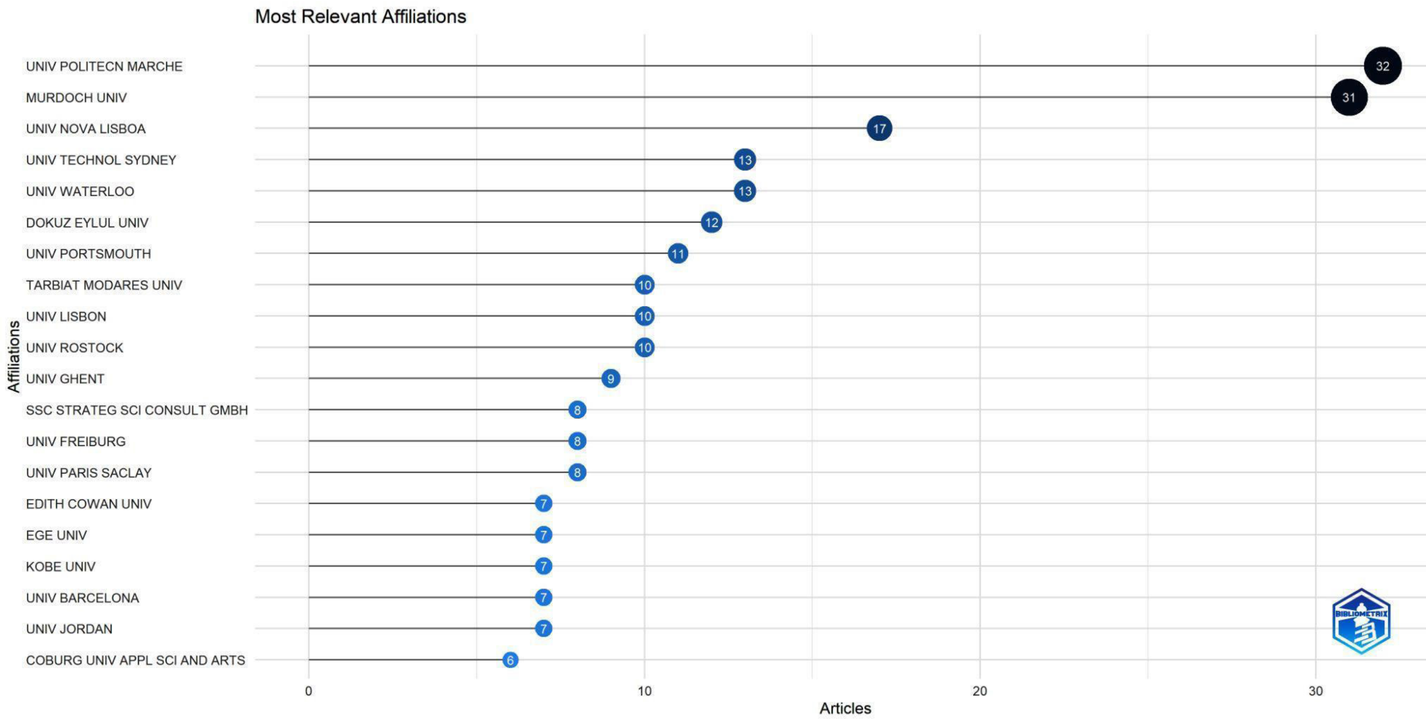


Figure 6. Most relevant affiliations. Source: Prepared by the authors.

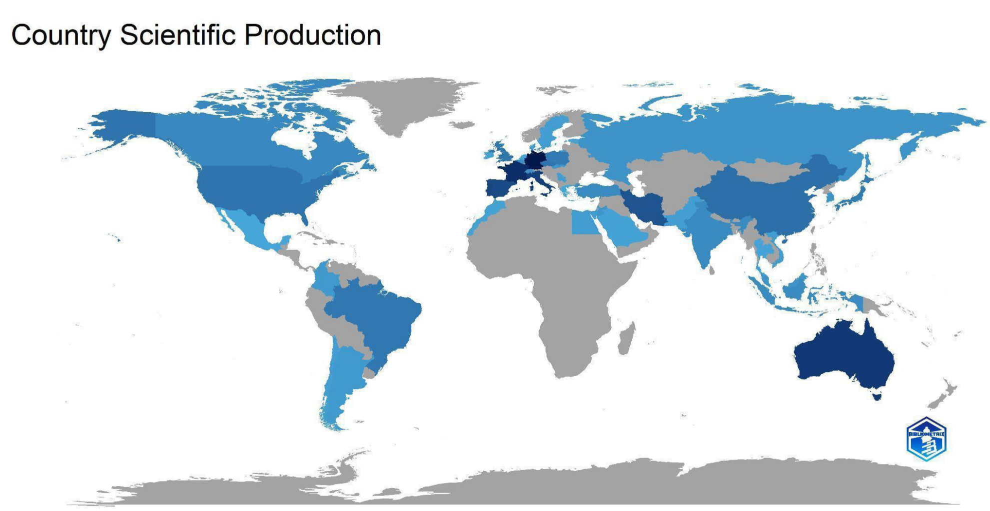


Figure 7. Countries' Scientific Production. Source: Prepared by the authors.

The keywords in the graph (Figure 8) show the themes around which the use of algae on façade surfaces has been examined in the academic literature. The most commonly used terms, "microalgae" (n = 32) and "algae" (n = 31), indicate that the focus of these investigations is on microalgae species. While terms like "biodeterioration" (n=10), "biofouling" (n=7), and "bioreceptivity" (n=6) reflect extensive research on the interaction of algae with surfaces, biological effects on facade materials, and the suitability of surfaces for algal growth, the terms "photobioreactor" (n=16) and "cyanobacteria" (n=14) indicate that the focus is on the production of these organisms in controlled systems and species diversity. Academic interest in the durability of facades, their surface characteristics, and their impact on algal colonization is further highlighted by building material-oriented keywords, such as "facade" (n=7), "durability," and "porosity" (n=6). These results suggest that algae are being considered in façade systems from disciplinary perspectives that incorporate both environmental and material considerations.

The trending topics in the graph (Figure 9) illustrate the evolution of algae use in facades over time. In the post-2013 period, the increasing frequency of terms

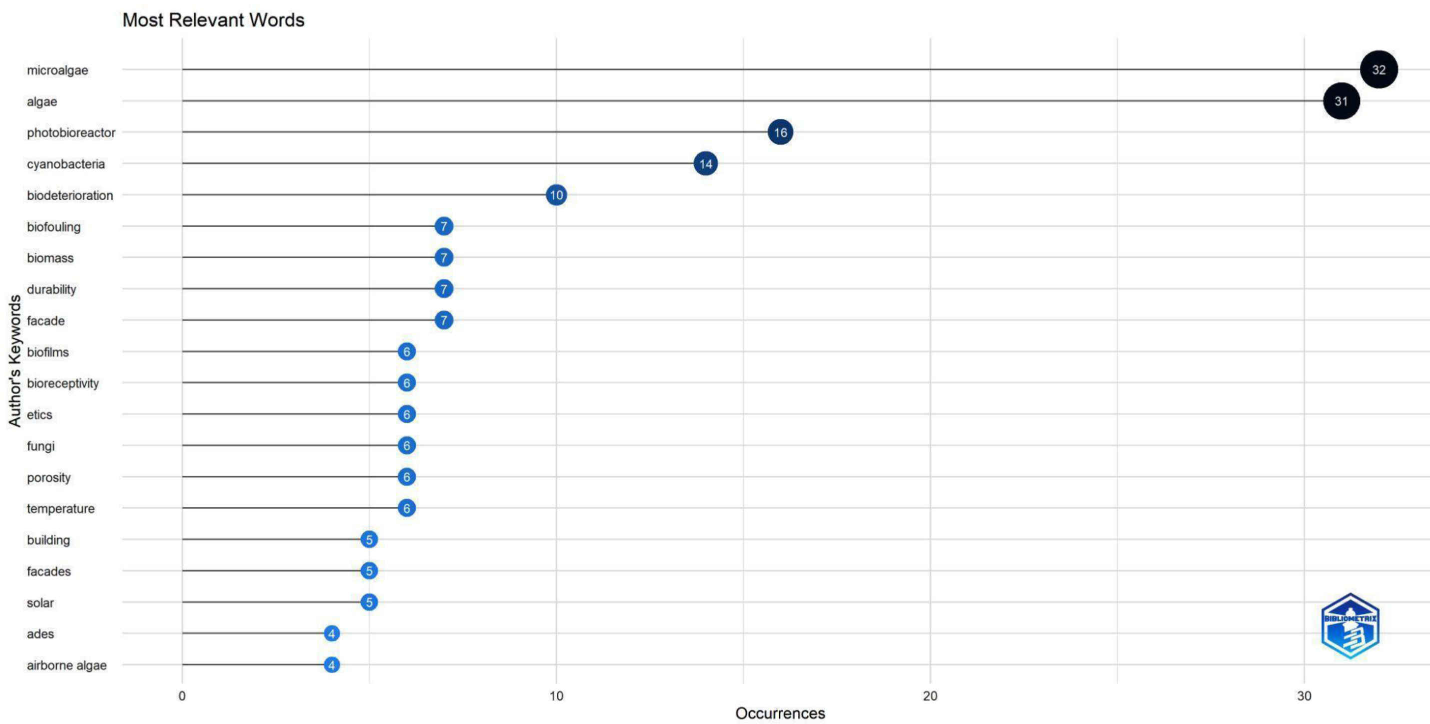


Figure 8. Most Frequent Words. Source: Prepared by the authors.

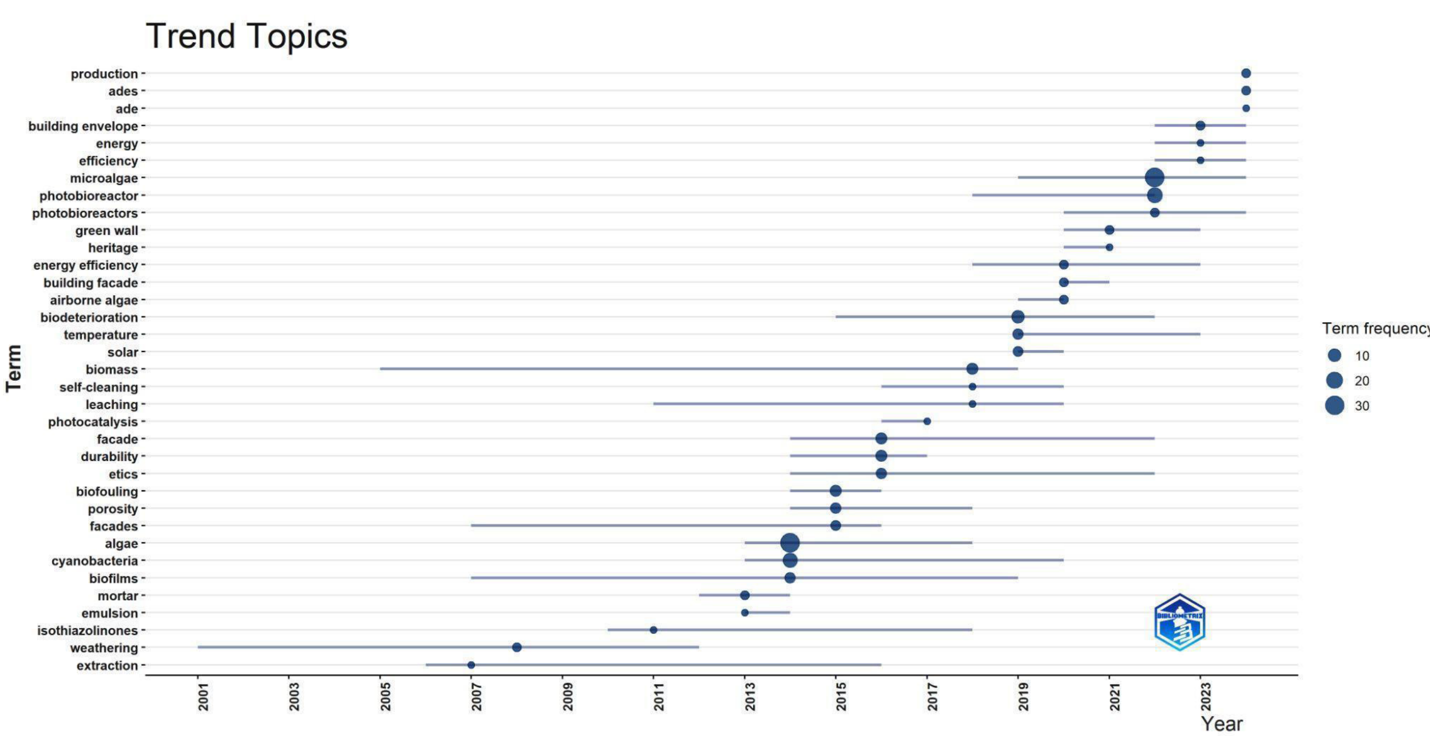


Figure 9. Trend Topics. Source: Prepared by the authors.

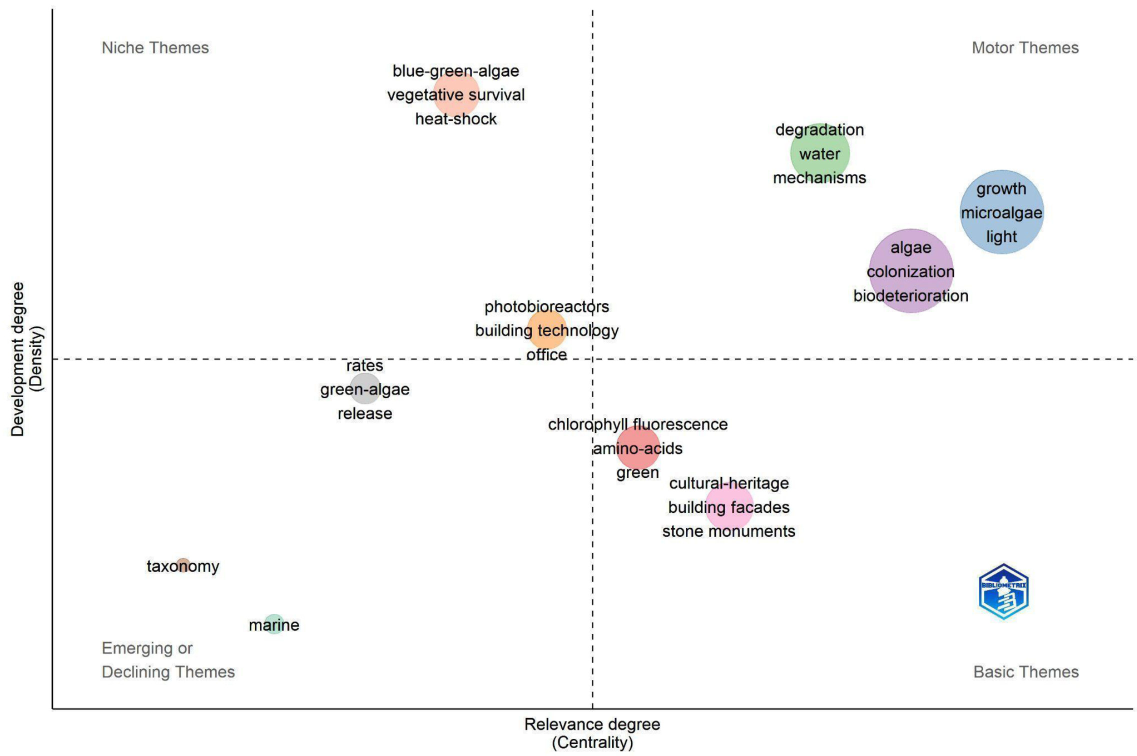


Figure 10. Thematic Map. Source: Prepared by the authors.

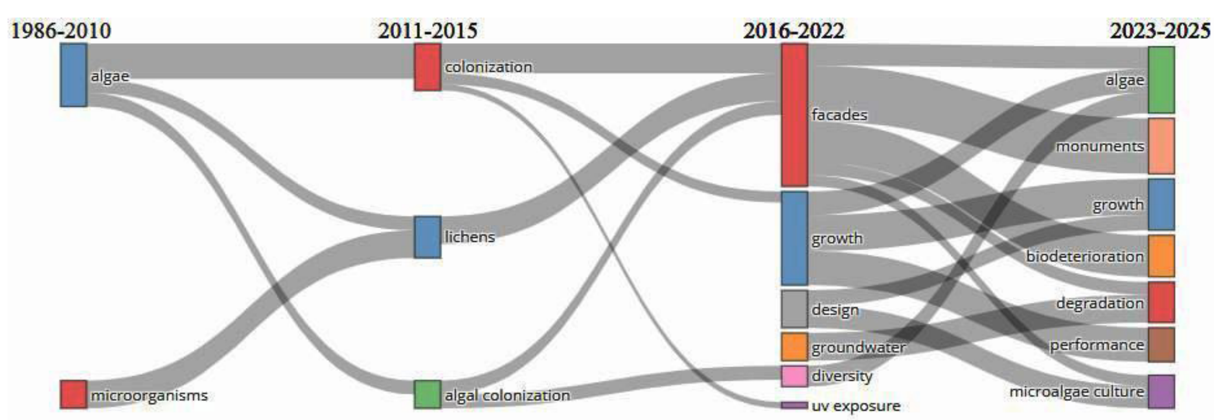


Figure 11. Thematic Evolution. Source: Prepared by the authors.

such as "microalgae", "photobioreactor", and "energy efficiency" reveals that this field has begun to attract more attention in the context of sustainability and energy production. In particular, the term "microalgae" is used with high frequency between 2018 and 2023, indicating that these living organisms stand out for their functions, such as biofuel production and carbon absorption, in façade applications. In addition, terms such as "building envelope", "green wall", 'durability' and "self-cleaning" emphasize that algae can offer not only biological but also structural and aesthetic contributions in facade systems. The distribution of terms along the time axis indicates that this topic has gained an interdisciplinary dimension and is now being addressed in an integrated manner, encompassing energy efficiency, material durability, and environmental solutions.

The contextual focus and degree of development of scholarly research on the use of algae in façades are depicted in the thematic map in Figure 10. In the upper right corner, terms like "growth," "microalgae," and "light" stand out as "motor themes" with high centrality and density, suggesting that these subjects are both well-developed and essential to the field. Similarly, the highly central themes of "algae," "colonization," and "biodeterioration" indicate that biodeterioration and algae accumulation on façade surfaces are among the primary research topics. While "taxonomy" and "marine" in the lower left represent waning or underdeveloped themes with low centrality and intensity, terms like "blue-green-algae" and "heat-shock" in the upper left represent more specifically defined niche themes of particular interest. Terms like "building facades," "cultural heritage," and "stone monuments" are located in the lower central area and exhibit high centrality but low density, indicating that they are fundamental subjects with substantial room for expansion. While research on the use of algae in facades has advanced in the context of biological growth and degradation, this distribution suggests that more research is required for construction technologies and cultural heritage applications.

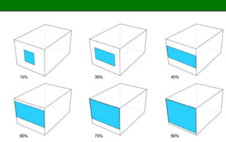
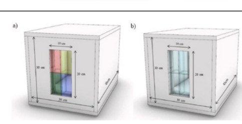
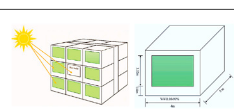
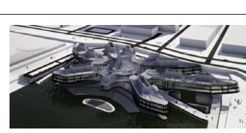
The Sankey diagram in Figure 11 illustrates the evolution of academic trends in using algae on facades over the years. Research on general biological terms, such as "algae" and "microorganisms," was more prevalent between 1986 and 2010. However, between 2011 and 2015, the focus shifted to studying biological settlement on building surfaces, using terms such as "colonization," "lichens," and "algal colonization." Research has undergone significant changes between 2016 and 2022, focusing on more specialized topics such as "facades," "growth," "design," "diversity," and "groundwater." This suggests that the relationship between algae and building envelopes is being studied in terms of both biological growth and design. With terms like "biodeterioration," "degradation," "performance," and "microalgae culture," which highlight the robustness and functionality of façade materials as well as the microalgae production processes, these themes have become even more complex in the most recent period, 2023–2025. This evolution demonstrates how the application of algae in facades has evolved into a multidisciplinary field of study that now encompasses sustainable design, materials engineering, and surface biology.

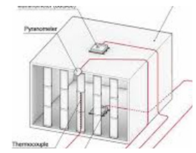
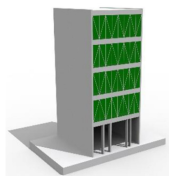
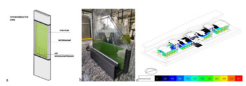
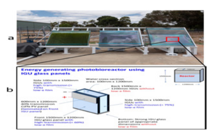
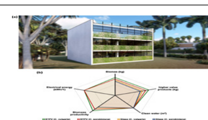
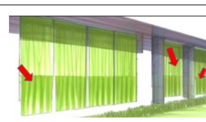
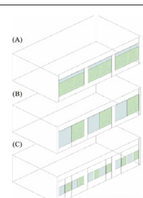
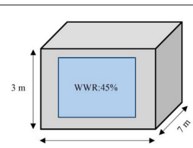
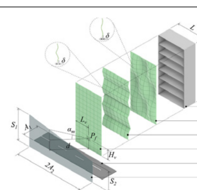
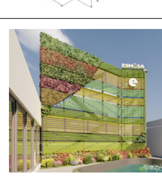
SYSTEMATIC REVIEW

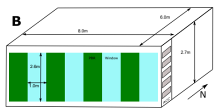
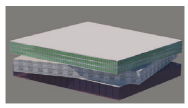
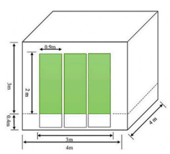
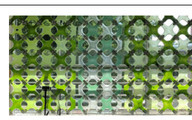
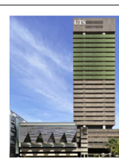
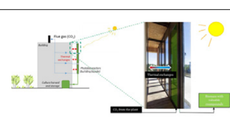
As part of the study, a comparative matrix for algal facade design, location, climate, photobioreactor type, algae type, and intended use on the facade was used to analyze the content of the articles scanned in WOS (Table 1). 26 publications that created façade suggestions for the use of algae were found among 217 studies. Examining these articles revealed that façade proposals were mainly created for the United States, Europe (including Germany, Spain, and France), and Iran. Different climate zones were represented, where Chlorella vulgaris algae were used as the algae species, and flat panel types were typically employed as photobioreactor types. According to studies, the primary goals of using algae on facades are energy efficiency, daylight control, aesthetic comfort, and biomass production.

The comparative matrix reveals common patterns across the reviewed designs. The predominant use of

Table 1. Algae-facade designs. Source: Prepared by the authors.

Source	Image	Place	Climate	Photobioreactor Type	Microalgae Species	Façade Function
Negev et al, 2019		Tel Aviv University, Israel	Mediterranean climate	Flat-panel PBR	Chlamydomonas reinhardtii ve Chlorella vulgaris	Energy efficiency, Shading and daylight control, Thermal comfort, Biomass production
Sarmadi & Mahdavinejad, 2023		Tehran, Iran	Cold semi-arid climate	Flat-panel PBR	Chlorella vulgaris	Visual comfort, Energy efficiency, Thermal comfort, Energy generation
Ahmadi et al., 2023		Isfahan, Iran	Hot and dry climate	Flat-panel PBR	Chaetoceros, Chlorella vulgaris, Haematococcus, pluvialis, Spirulina platris	Energy efficiency, Thermal comfort, Daylight control, CO_2 absorption
Talaei et al., 2021b		Meshed, Iran	Cold semi-arid climate	Flat-panel PBR	Chlamydomonas reinhardtii ve Chlorella vulgaris	Energy efficiency, Daylight control, Thermal comfort, Shading
Hasnan & Zaharin, 2020		Malaysia	Tropical climate	Flat-panel PBR	-	Energy efficiency, Thermal comfort, Daylight control, and Sustainability

Source	Image	Place	Climate	Photobioreactor Type	Microalgae Species	Façade Function
Woo et al., 2022		-	-	Flat-panel PBR	Chlorella sp.	Energy efficiency, Thermal comfort, Daylight control, CO_2 absorption
Rezazadeh et al., 2021		Tehran, Iran	Semi-arid climate	A closed-loop photobioreactor	-	Air quality improvement, Energy efficiency, and Sustainable building design
Talaei et al., 2021		Passo Fundo, Brazil	Temperate climate	Flat-panel PBR		Energy efficiency, Thermal comfort, Daylight control, CO_2 absorption
Nwoba et al., 2021		West Australia	Mediterranean climate	Flat-panel PBR	Nannochloropsis sp. (deniz mikroalg türü)	Biomass production, Electricity generation, Eliminating the need for cooling water, Energy efficiency
Gol et al., 2025		-	-	Closed system photobioreactor	Chlorella sorokiniana and Chlorella vulgaris	Electric power generation, Waste water treatment, Biodiesel production, Production of high-value bioproducts (lipids, lutein, chlorophyll a and b)
Elmalky & Araji, 2024a		Spain	Mediterranean climate	Tubular PBR	Chlorella vulgaris	Energy efficiency, Biomass production, Solar control, Regulation of heat gains, Carbon dioxide absorption
Metwally & Ibrahim, 2024		Hamburg, Germany	Temperate ocean climate	Flat-panel PBR	Chlorella vulgaris	Energy production, Sunlight filtering, Thermal insulation, Aesthetic contribution
Yaman et al., 2025		Central Europe	Continental climate	Flat-panel PBR	Scenedesmus obliquus	Energy efficiency, Indoor comfort, Minimizing environmental impact
Talaei & Sangin, 2024a		-	Mediterranean climate	Tubular PBR	Chlorella vulgaris	Regulating indoor temperature, daylight, and reducing energy consumption
Elmalky & Araji, 2024b		USA	Temperate climate	Flat-panel PBR	Chlorella vulgaris	Energy production, Passive solar control, reducing carbon footprint
Villalba et al., 2023		Southern Europe	Temperate climate	Flat-panel PBR & Cylindrical systems	Chlorella vulgaris and Spirulina platensis	Improving air quality, Carbon dioxide absorption, Biofuel production, Aesthetic contribution, and reducing the urban heat island effect

Source	Image	Place	Climate	Photobioreactor Type	Microalgae Species	Façade Function
Girard et al., 2023		Toulouse, Fransa	Temperate ocean climate	Flat-panel PBR	Chlorella vulgaris	Balancing heat gains, Regulating indoor temperature, CO_2 absorption, and daylight control
Vajdi & Aslani, 2023		Arizona, USA	Hot-semi-arid climate	Horizontal flat-panel	Nannochloropsis oculata	Energy production, Indoor temperature control, and daylight management
Todisco et al., 2022		Milan, Italy	Humid subtropical climate	Vertical flat-panel	Chlorella vulgaris	Filtering solar radiation, CO_2 absorption, and improving the energy performance of the building
Talaei et al., 2022		Seoul, South Korea	Humid continental climate	Flat-panel PBR	Chlorella vulgaris	Reducing energy consumption, optimizing indoor temperatures, controlling daylight, and contributing to environmental sustainability
Wu et al., 2022		-	Mediterranean climate	Modular panel	Chlorella vulgaris	Energy production, aesthetic integrity, exterior CO_2 absorption, and thermal insulation
Scherer et al., 2020		Ilmenau, Germany	Temperate continental climate	Multi-skin PBR	Cyanobacteria or Chlorophyta	Energy generation, lightening the building envelope, daylighting, CO_2 absorption, and aesthetic appearance
Biloria & Thakkar, 2020		Hamburg, Germany	Temperate ocean climate	Double-skin PBR	Chlorella vulgaris	Filtering sunlight, increasing indoor thermal comfort, contributing energy through biomass production, and reducing CO_2 emissions
Arbye et al., 2020		Indonesia	Tropical climate	Flat-panel PBR	Chlorella sp.	Improving air quality, providing shading, generating energy, providing thermal comfort, providing visual aesthetics, and sustainable biofuel production
Elrayies, 2018		-	-	Flat-panel and Tubular PBR	Chlorella vulgaris and Spirulina platensis	Energy generation, reduction of carbon emissions, improvement of indoor thermal comfort, control of daylighting, and aesthetic contribution
Pruvost et al., 2016		Barcelona, Spain	Mediterranean climate	Flat-panel PBR	Chlorella vulgaris	Contributing to the energy balance of the building, creating a renewable energy source with biomass production, increasing indoor thermal comfort, and solar control

Chlorella vulgaris and flat-panel photobioreactors across different climates suggests a functional and adaptable model for façade integration. Most case studies emphasize energy efficiency, daylight control, and thermal comfort, indicating a trend towards multifunctional façade systems. Despite the diversity in geographic locations, the recurrence of similar microalgae types and photobioreactor configurations signals a consensus on technical feasibility. These findings highlight opportunities for standardizing façade-integrated algae technologies and suggest the need for further studies on long-term performance, cost-effectiveness, and user acceptance (Table 1).

CONCLUSION

Using bibliometric techniques based on English-language articles published in the Web of Science database between 1986 and 2025, this study examined the literature on the application of microalgae in building facades. According to the results for 217 documents, the subject has garnered more attention recently and has demonstrated consistent scholarly advancement, with an annual growth rate of 5.48%. Notably, the observed 5.48% annual growth rate in publications aligns with broader trends in academic publishing. Therefore, this figure should be interpreted cautiously and not as a direct indicator of the topic's relative prominence. Moreover, the exclusive inclusion of English-language articles may have limited the scope of the review, potentially overlooking significant research published in other languages. These limitations introduce a degree of bias that must be acknowledged when interpreting the findings.

The 743 authors' contributions in these documents demonstrate how interdisciplinary research has shaped the field and how highly collaborative it is. Microalgae-based façade systems have evolved into a comprehensive research field that spans not only architecture and building sciences but also numerous other disciplines, including environmental engineering, biotechnology, and energy systems, as evidenced by the fact that the majority of examined publications are multi-authored and that the international collaboration rate is 23.5%. The average of 17.35 citations received by the documents indicates that the topic has a high level of academic impact and that the research has had a significant influence on the scientific community.

It is confirmed that studies on the use of algae on facades are addressed in terms of both sustainability and biological interaction by the inclusion of journals from various fields, including "Building and Environment," "International Biodeterioration & Biodegradation," and "Biofouling," among the journals with the highest number of publications within the analysis's scope. The contribution of microalgae to energy efficiency through photobioreactor systems is also highlighted in publications in energy-focused journals, such as "Algal Research" and "Renewable Energy."

The study also found that universities like Murdoch University in Australia and Università Politecnica delle Marche in Italy are leaders in the field. These centers are essential to international collaborations in terms of both scientific production and research infrastructure, as evidenced by their high publication numbers. Strong research networks supporting the potential of microalgae in frontline applications are also confirmed by the large number of publications and national and international collaborations in countries such as Germany, France, and Australia.

The conceptual network map and keyword analysis demonstrate that there are two primary axes along which the application of microalgae on façade surfaces is addressed: The first is damage prevention research, including material-based degradation, biofouling, biodeterioration, and bioreceptivity; the second is benefit-oriented applications, including energy production, sustainability, and photobioreactor systems. According to this comprehensive strategy, microalgae-based façade systems will be crucial to future energy efficiency, environmental performance, and urbanization policies. The use of microalgae in building facades has consequently developed into a vibrant field of study where new solutions that adhere to sustainability principles are being developed, interdisciplinary collaborations are increasing, and global interaction is expanding. Both academic production and applied architectural practices stand to benefit significantly from the future growth of this field and its integration with other disciplines.

AUTHOR CONTRIBUTION CRediT

Conceptualization, A.T & G.M.-A.; Data Curation, A.T & G.M.-A.; Formal Analysis, A.T & G.M.-A.; Funding Acquisition; Research, A.T & G.M.-A.; Methodology, A.T & G.M.-A.; Project Management, A.T & G.M.-A.; Resources, A.T & G.M.-A.; Software, A.T & G.M.-A.; Supervision, A.T & G.M.-A.; Validation, A.T & G.M.-A.; Visualization, A.T & G.M.-A.; Writing - review and editing, A.T & G.M.-A.

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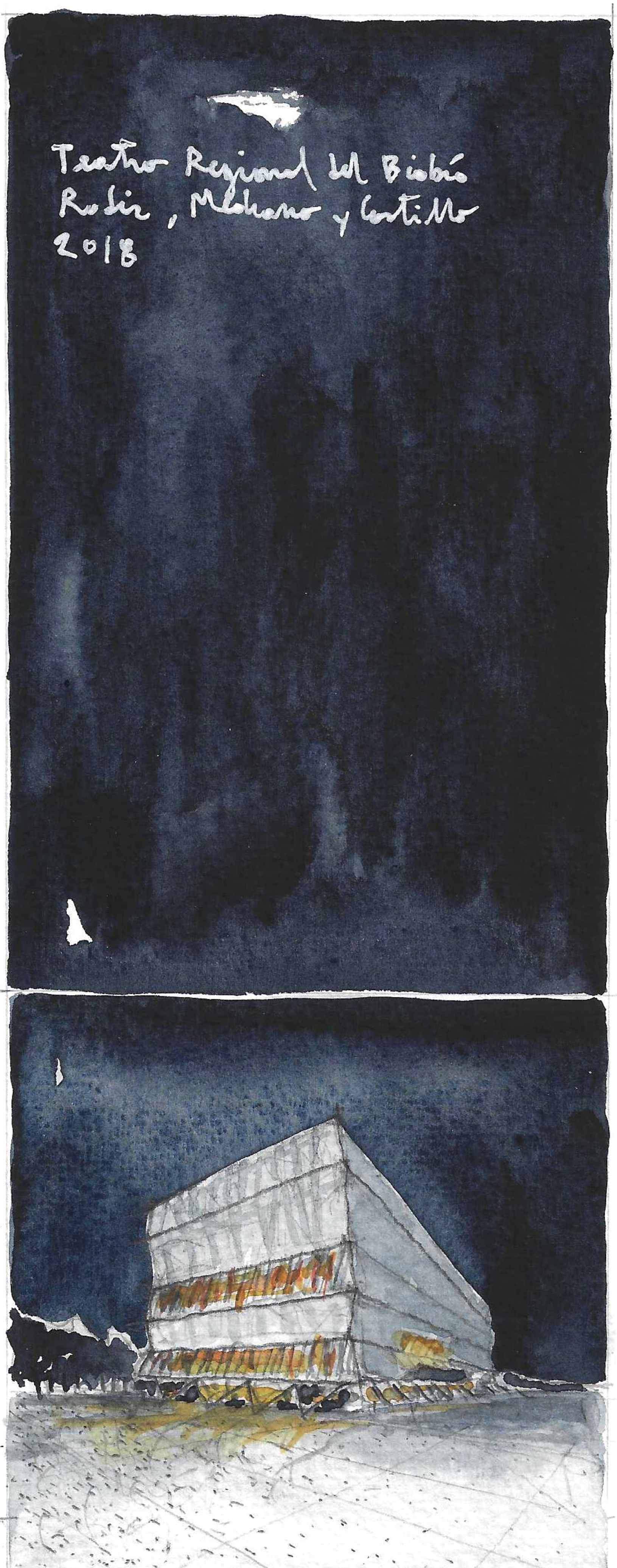

Objeto singular Concepción