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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

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,

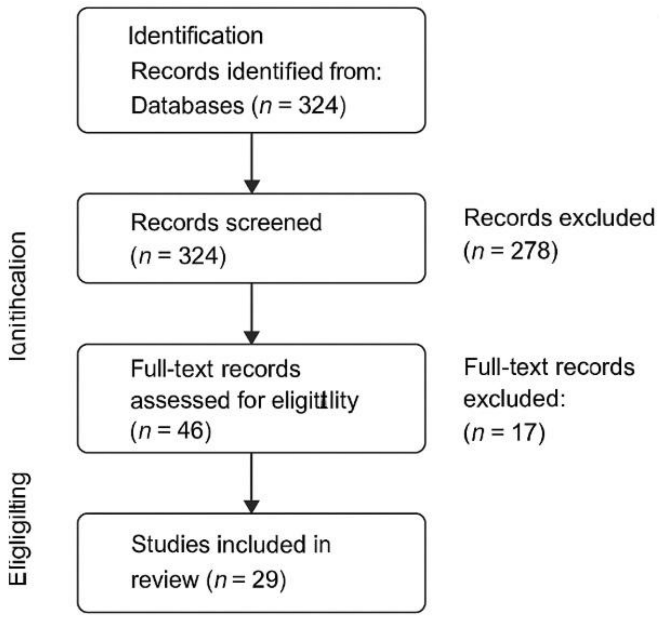

Figure 1. PRISMA flow diagram of the study. Source: Prepared by the authors.

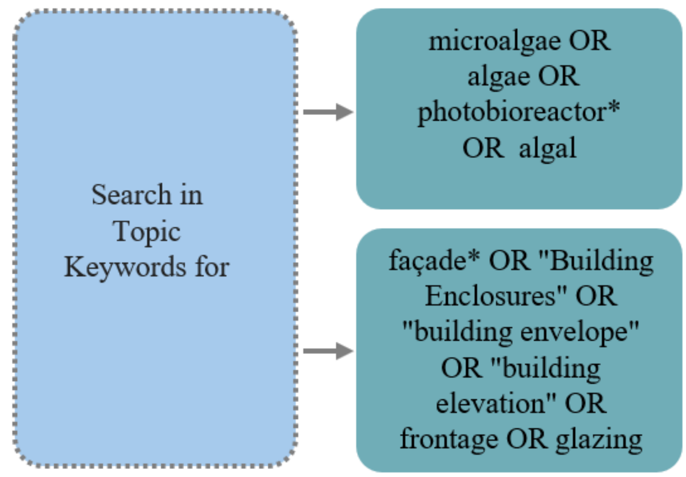

Figure 2. Search in the Web of Science Database. Source: Prepared by the authors.

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.

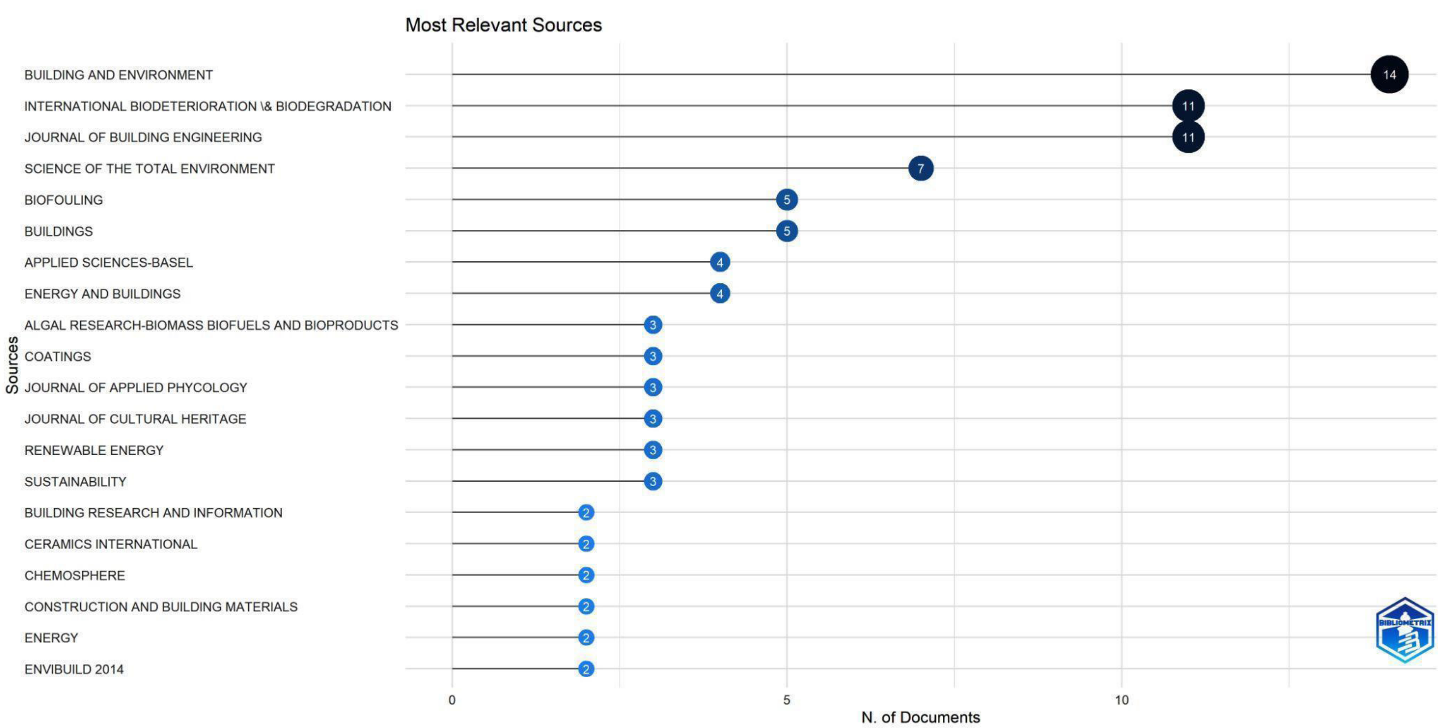

Figure 4. Most Relevant Sources. Source: Prepared by the authors.

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

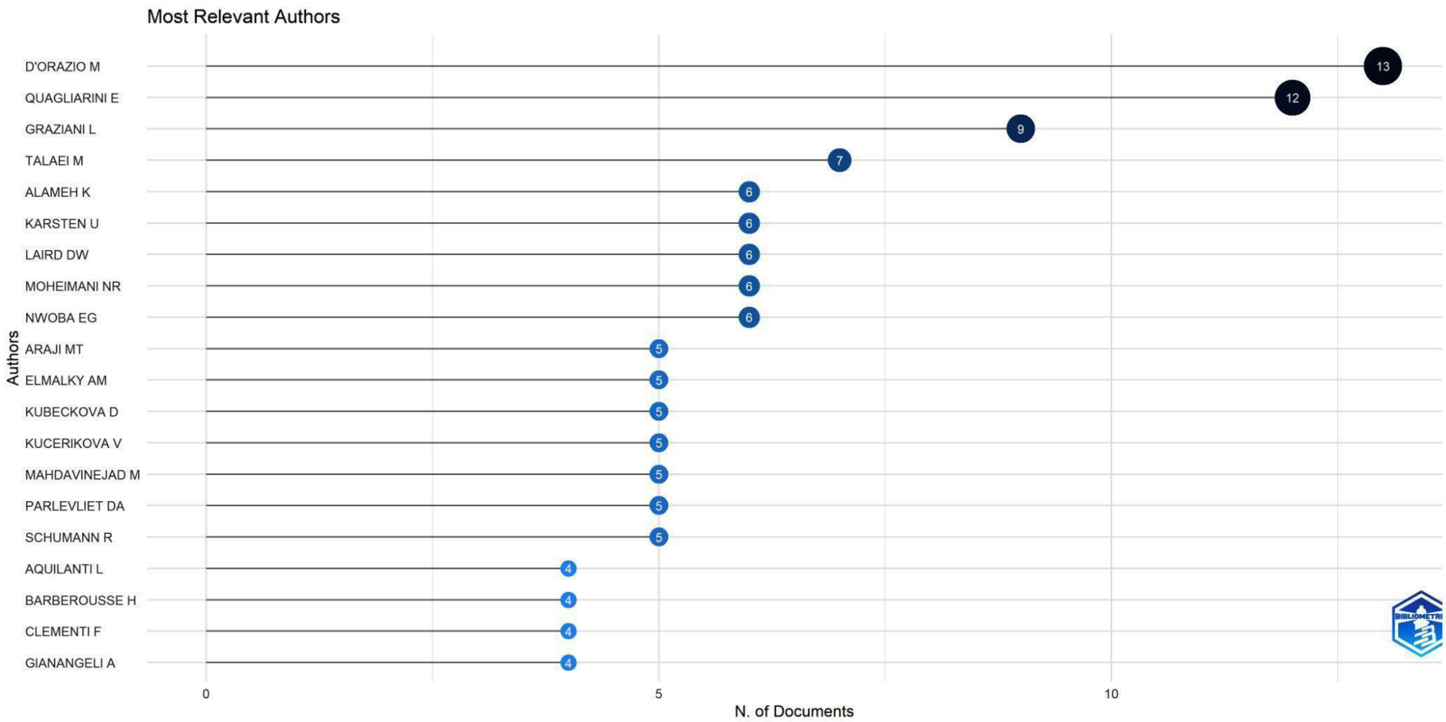

Figure 5. Most Relevant Authors. Source: Prepared by the authors.

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.

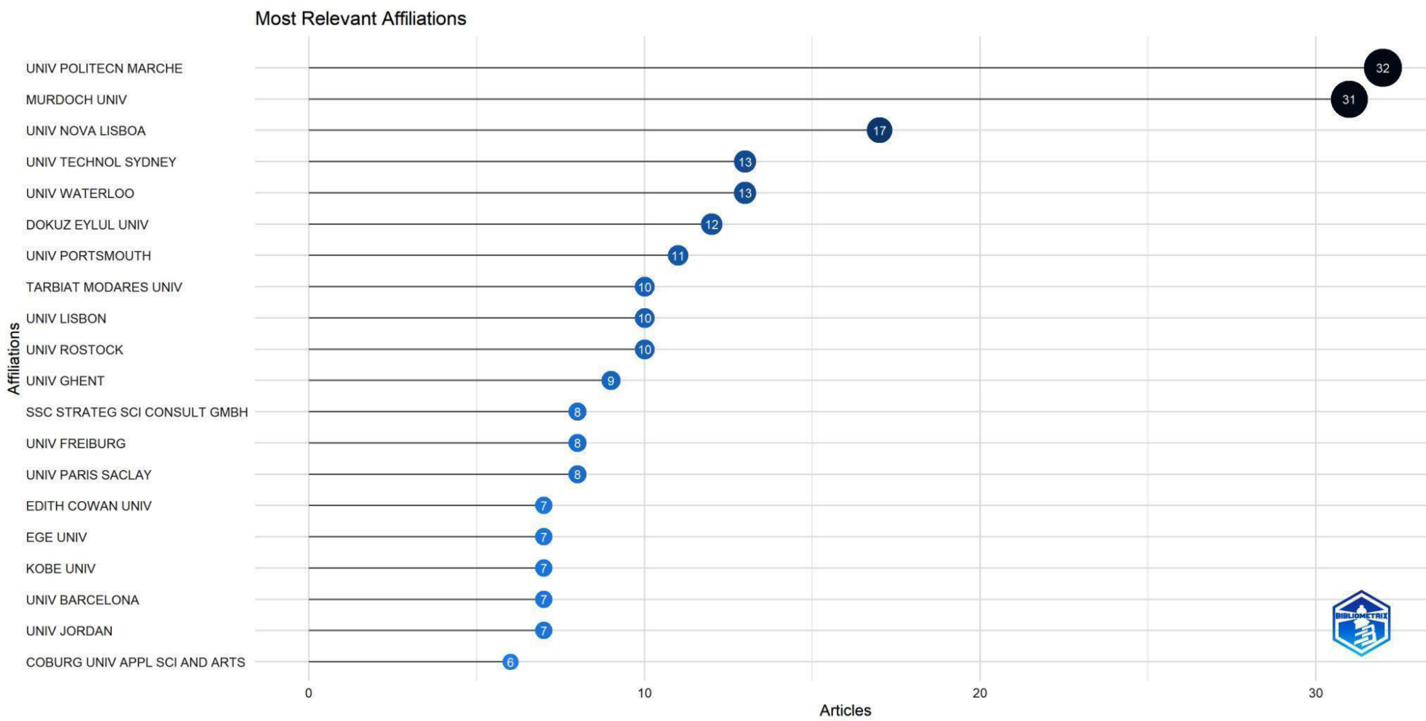

Figure 6. Most relevant affiliations. Source: Prepared by the authors.

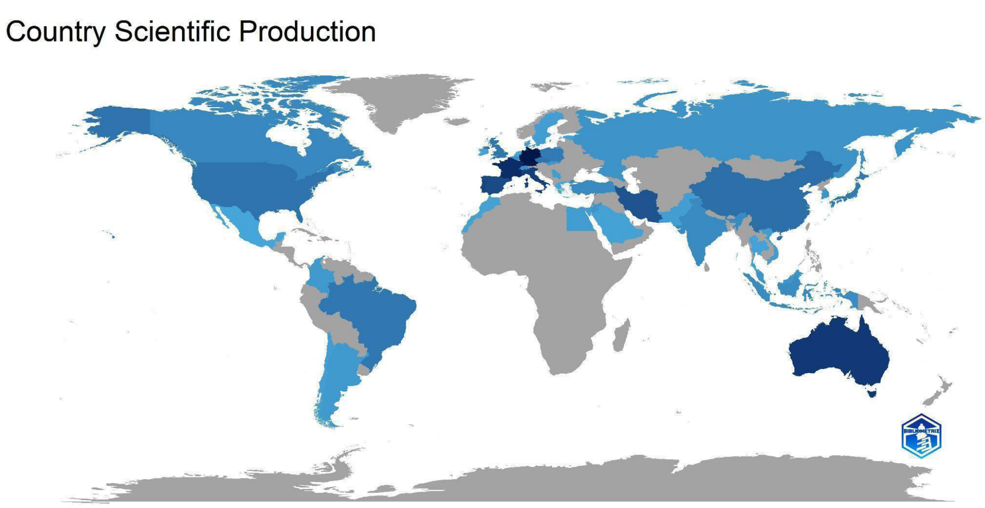

Figure 7. Countries' Scientific Production. Source: Prepared by the authors.

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

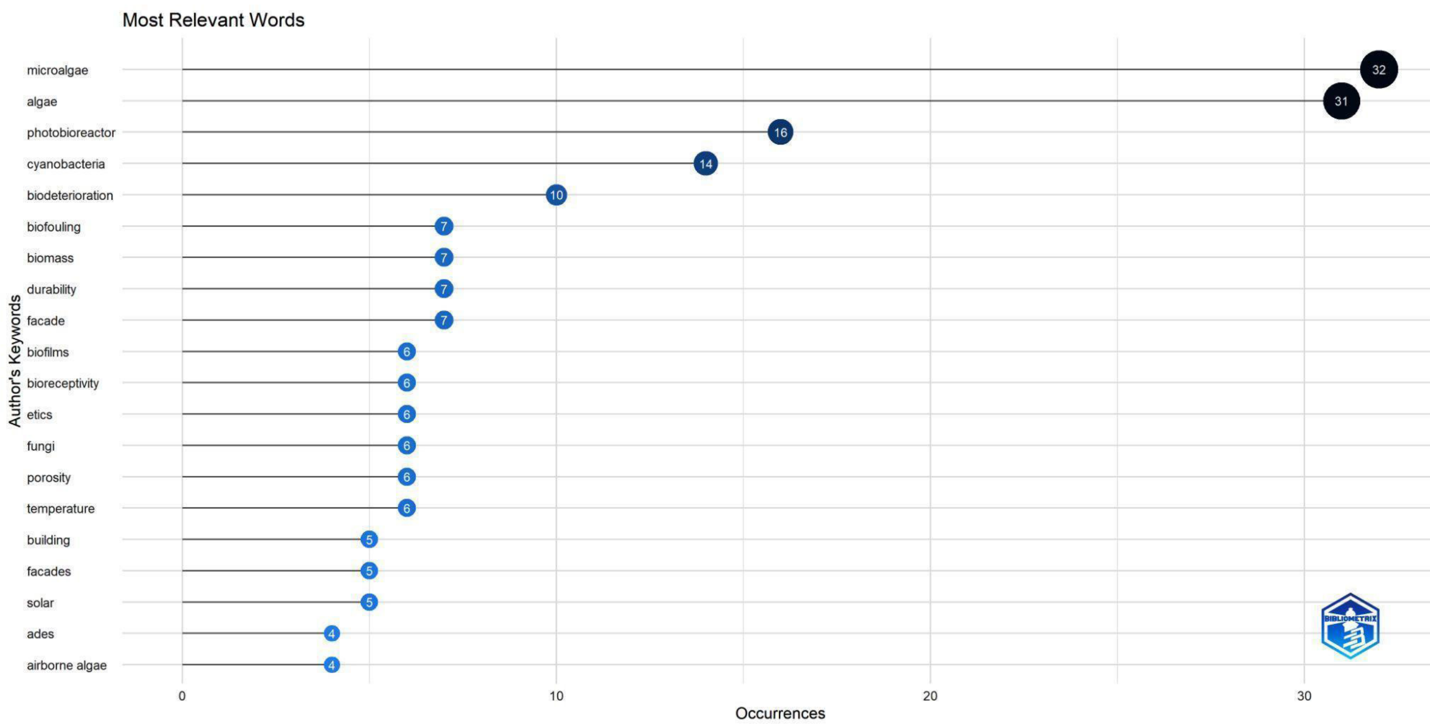

Figure 8. Most Frequent Words. Source: Prepared by the authors.

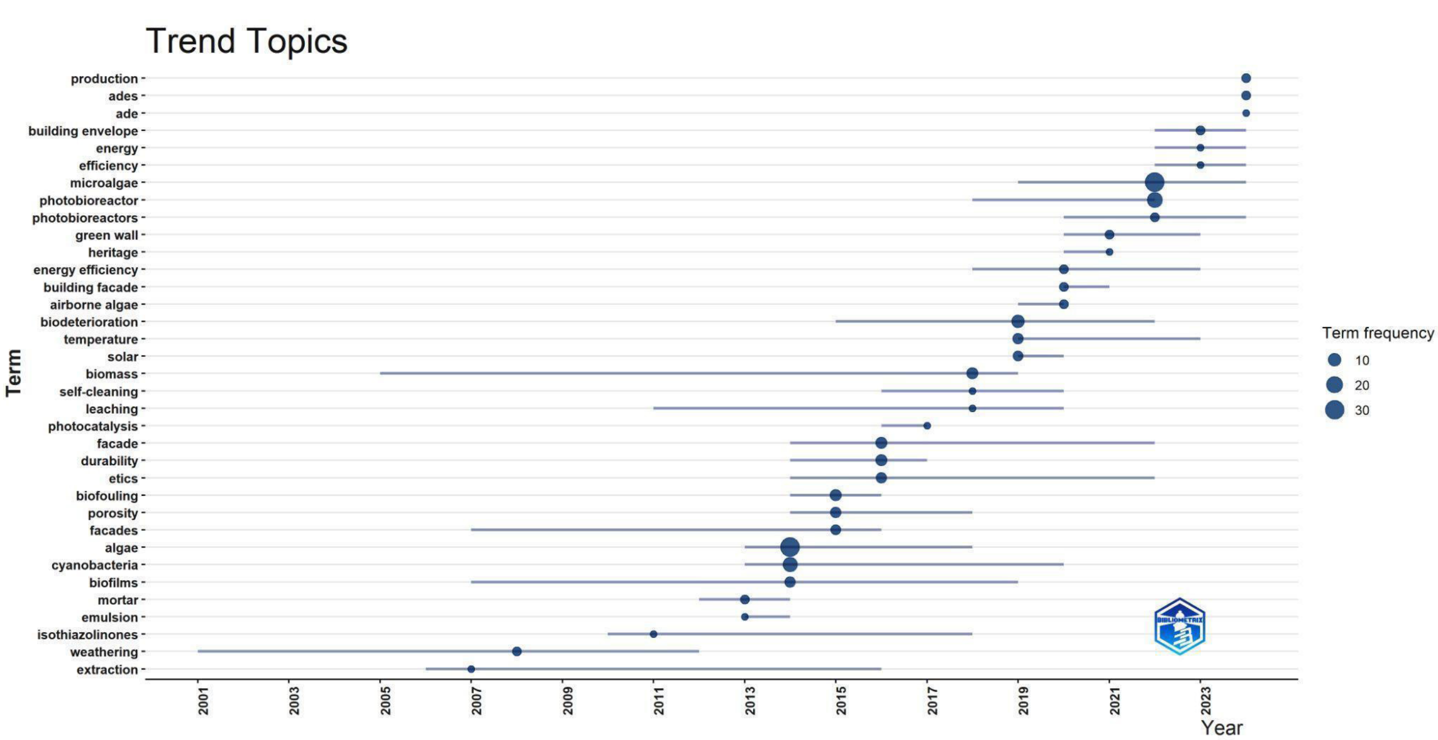

Figure 9. Trend Topics. Source: Prepared by the authors.

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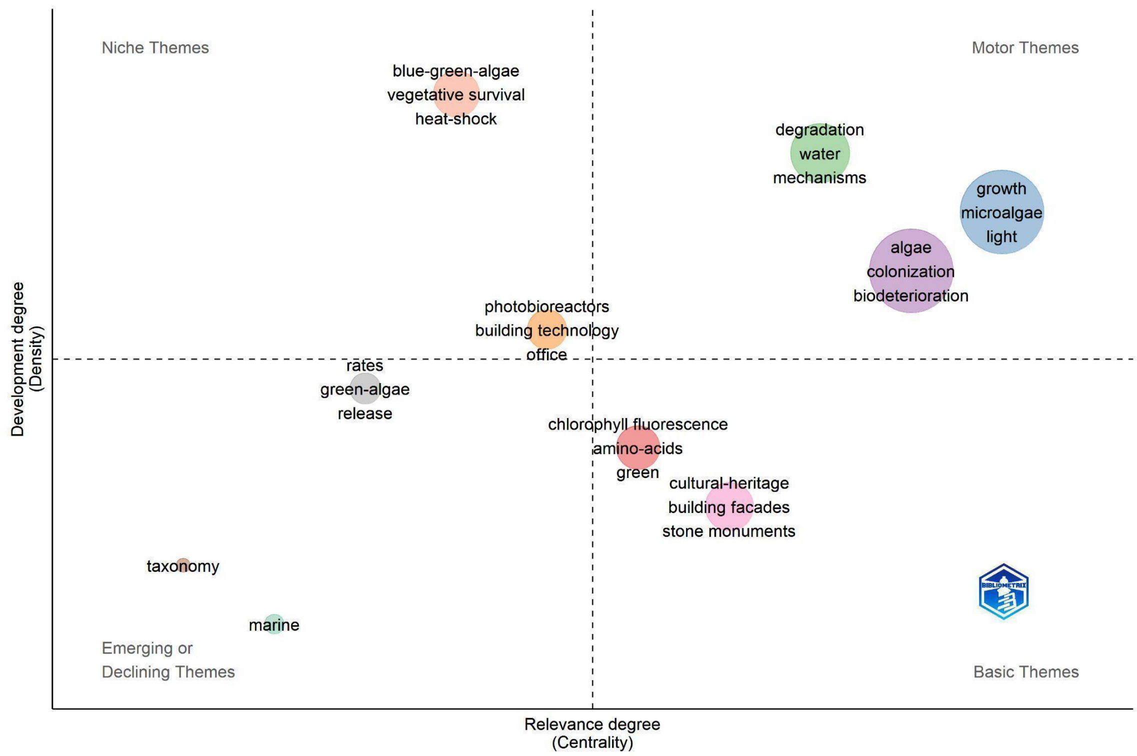


Figure 10. Thematic Map. Source: Prepared by the authors.

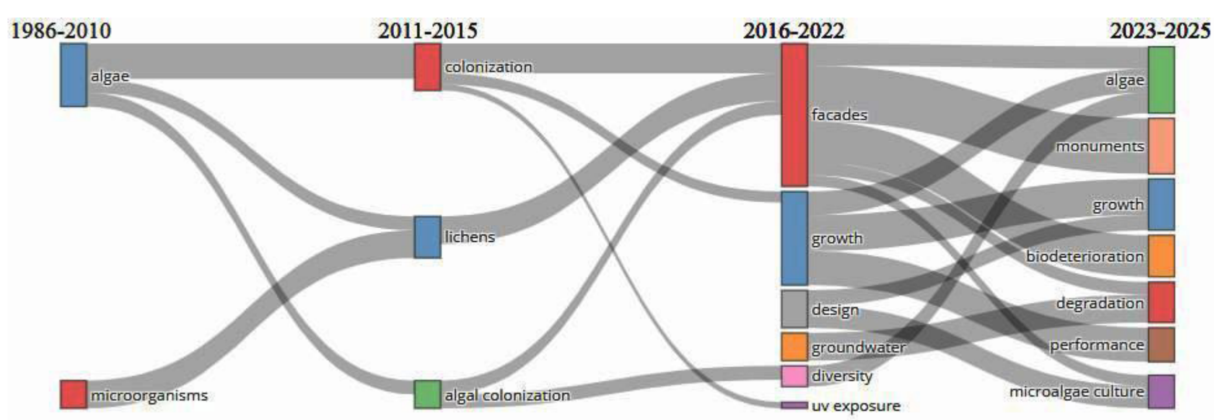


Figure 11. Thematic Evolution. Source: Prepared by the authors.

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.

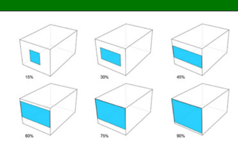
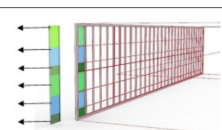
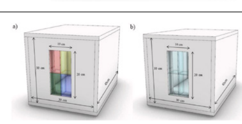
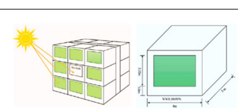
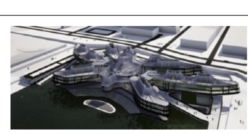
The Sankey diagram in Figure 11 illustrates the evolution of academic trends in using algae on facades over the years. Research on general biological terms, such as "algae" and "microorganisms," was more prevalent between 1986 and 2010. However, between 2011 and 2015, the focus shifted to studying biological 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

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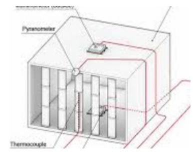
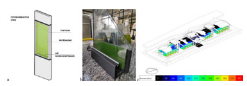
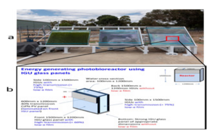
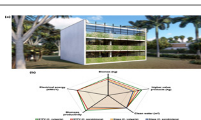
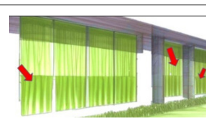
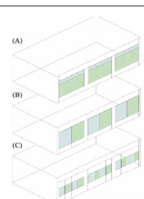
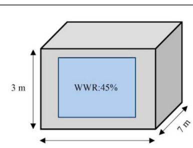
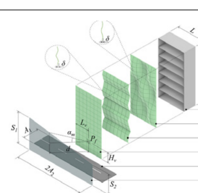
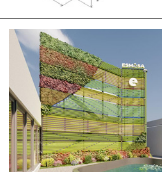
Source	Image	Place	Climate	Photobioreactor Type	Microalgae Species	Façade Function
Woo et al., 2022		-	-	Flat-panel PBR	Chlorella sp.	Energy efficiency, Thermal comfort, Daylight control, CO_2 absorption
Rezazadeh et al., 2021		Tehran, Iran	Semi-arid climate	A closed-loop photobioreactor	-	Air quality 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

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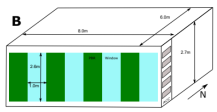
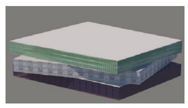
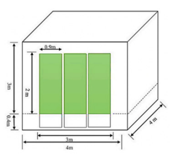
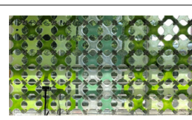
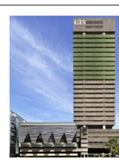
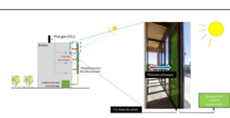
https://doi.org/10.22320/07190700.2025.15.01.10

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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