

Article

Harnessing AI and Sustainable Materials for Greener, Smarter Buildings: A Bibliometric Study

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Abstract

As global energy challenges intensify, reducing energy consumption in buildings is becoming a crucial economic and environmental priority. Despite extensive research on energy efficiency, a comprehensive synthesis that addresses emerging trends, eco-friendly insulation materials, and artificial intelligence (AI)-based methods remains limited. This study aims to bridge this gap through a bibliometric analysis of 2477 articles from the Scopus database, using the tools VOSviewer and Biblioshiny to explore several key questions: What are the dominant research trends? Who are the most influential contributors? And how are AI and sustainable insulation technologies evolving and converging to optimize energy performance? The analysis highlights major research themes, global collaboration networks, and two key strategies: eco-insulation materials, which help reduce environmental and technical costs, and AI-based solutions, which enable accurate energy predictions, real-time optimization, and material selection tailored to diverse climates and architectural contexts. Despite these advances, significant gaps remain in the development and characterization of eco-insulating materials. Future research should focus on integrating AI with sustainable insulation to enhance energy efficiency and minimize environmental impact, thereby paving the way for innovative, energy-resilient building solutions.

Keywords: building; bibliometric analysis; Scopus; energy efficiency; bio-sourced insulation materials; artificial intelligence



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1. Introduction

Climate change and the surge in global energy consumption present serious challenges for the building sector. According to the International Energy Agency (IEA) [1], buildings are responsible for approximately 40% of global energy use and generate 30% of greenhouse gas emissions. Addressing these challenges requires a critical focus on improving energy efficiency within the sector. Implementing strategies to optimize energy use not only reduces consumption and emissions significantly but also supports the sustainable management of our planet's limited resources. By prioritizing energy-efficient measures, the building industry can play a pivotal role in combating climate change and fostering environmental resilience.

In this particular context, the implementation of building insulation plays an essential role in reducing operational energy consumption, in particular to mitigate heat dissipation. Nevertheless, insulation also contributes significantly to greenhouse gas emissions and, consequently, to the ecological footprint of building components. A great deal of research has been carried out to reduce energy consumption. For example, Tislova Milena et al. [2] investigated the use of insulating materials ideal for improving the energy efficiency of structures, reducing expenditure on heating and cooling systems and improving overall thermal insulation for sustainable construction methodologies. Similarly, Alekhya Chetty et al. [3] examined the impact of thermal insulation on cooling and heating demands for building energy efficiency, focusing on material selection according to climate zones to achieve optimal performance.

The use of thermal insulation to reduce heat loss—and therefore energy consumption—is essential for improving energy efficiency. This argument gains credibility when eco-friendly materials are used to meet environmental standards. In a similar vein, Hanifi Binici et al. [4] investigated the creation of insulating composites using bio-based resources such as corn stalk particles, highlighting the potential of bio-based insulating materials to minimize energy expenditure in architectural structures. Similarly, Nadir Yildirim et al. [5] researched bio-based thermal insulation foam boards made from cellulosic nanomaterials, presenting a viable option for sustainable construction projects, despite the need to further improve marketing strategies due to their inferior mechanical properties.

The application of artificial intelligence (AI) facilitates the swift implementation of energy efficiency solutions across various types of buildings, yielding significant improvements in performance outcomes. For instance, Catalina et al. [6] developed a model to predict the monthly heating requirements of residential buildings. Their approach incorporated key variables such as building morphology, the U-value of the building envelope, the ratio of glazed area to floor area, building inertia, and climatic conditions, including ambient temperature and the designated heating set point. These factors serve as inputs for sophisticated regression models that provide accurate energy forecasts.

Similarly, Dong et al. [7] employed Support Vector Machines (SVMs) to predict the monthly electricity consumption of four buildings situated in a tropical region. This AI-based methodology demonstrated the effectiveness of machine learning techniques in modeling and anticipating energy use, thereby optimizing energy management strategies and enhancing building performance.

The package comprises three components, “improving the energy efficiency of buildings, use of bio-sourced insulating materials and use of artificial intelligence”, for which a bibliometric analysis was used. Bibliometrics is a quantitative approach used to evaluate, monitor, and study the scientific literature. According to researchers, bibliometrics can be divided into two main groups: those that focus on the distribution of publications and those that examine citation patterns. The first group carries out a quantitative analysis of documents, identifying three bibliometric principles, which are developed in the following sections.

The first principle, Lotka’s law (1926) [8], establishes a mathematical correlation between the productivity of authors and the frequency of their works. For example, if a hundred people produce one work, a quarter of them should produce two, one in nine will create three works, and so on. This principle, also known as Lotka’s inverse square law of productivity, describes a specific model of author productivity.

Zipf’s law (1933) [9] classifies words according to their frequency in documents, providing a model suitable for indexing purposes.

Bradford’s law (1934) provides a crucial theoretical framework for understanding publication dynamics within scientific journals, particularly in relation to the decline in

research output. This model, also referred to as the Pareto distribution, emphasizes the uneven distribution of research findings across journals. It illustrates that a small number of studies tend to accumulate a large share of recognition or citations, while the majority receive far less attention.

Bibliometrics, as described in reference [10], comprises three fundamental elements: bibliometrics for bibliometrics, bibliometrics for science (information science), and bibliometrics for science policy and management. The use of bibliometric analysis (BA) involves the quantitative assessment and examination of various specific metrics in the published literature in a given field, facilitating the creation of knowledge maps derived from large databases [11]. This method allows researchers to succinctly summarize publication details regarding the distribution of articles by author, institution, year, journal, and specialization, as well as collaborations between authors and organizations and keyword ratings [12]. BA (bibliometric analysis) is based on relevant data extracted from scientific publications and documents, including crucial information for source identification (journal/document, volume, page), author identification, institutional affiliations, references, document classification, titles, keywords, abstracts, and subject classification.

This work significantly contributes to the current body of research on building energy efficiency through a multifaceted approach. First, it provides a comprehensive literature review encompassing three critical dimensions: the impact of bio-based insulation on energy conservation, the application of artificial intelligence (AI) techniques for optimizing energy consumption, and the methods used to evaluate building energy performance.

Second, the research undertakes a detailed bibliometric analysis of 2477 articles published over a twelve-year span, utilizing data from the Scopus database. This analysis synthesizes existing research on building energy efficiency, offering a holistic overview of the field.

Third, the study employs advanced bibliometric tools, specifically an R-based bibliometric package (RStudio, version 2024.04.2.0) and VOSviewer software (version 1.6.20), to visualize and interpret the data effectively. These visualizations provide insights into the landscape of energy efficiency research, focusing on advancements in thermal insulation and AI technologies since 2011. By examining publication trends over time, the analysis reveals the total number of publications, aggregate citation counts, and average citations per paper and identifies the most influential sources, authors, institutions, and countries.

Fourth, the analysis explores bibliometric relationships, including bibliographic coupling among journals, authors, and countries, and the co-occurrence of keywords, which illuminate thematic progressions and emerging research trends. It also quantitatively assesses collaborative networks, offering a nuanced understanding of the connections between different researchers, journals, and regions.

Fifth, the study synthesizes these findings to identify existing research gaps and limitations in the current literature. It then outlines several promising directions for future exploration:

- Discovery of innovative eco-friendly insulation materials, which hold the potential to significantly enhance thermal performance and reduce energy consumption.
- Reduction in greenhouse gas emissions through the development and use of environmentally sustainable materials.
- Optimization of computational efficiency for predicting building energy consumption by refining AI algorithms, thereby increasing the accuracy of energy performance forecasts.

In summary, this study aligns with ongoing efforts to address contemporary energy challenges by exploring potential synergies between emerging technologies and sustainable practices. In the face of current climate issues, improving the energy efficiency of buildings has become a strategic priority. Two main drivers have emerged in this context: the

development of sustainable insulation materials and the growing application of artificial intelligence (AI) to optimize energy consumption. However, an integrated vision combining these two approaches remains underexplored in the literature. This study aims to provide a comprehensive bibliometric analysis of research conducted at the intersection of sustainable insulation materials and AI techniques applied to building energy efficiency, based on publications indexed in the Scopus database between 2011 and 2022. To achieve this objective, we seek to answer the following questions: What are the main publication trends in this field over the past twelve years? Which authors, institutions, countries, and journals are the most influential? What are the dominant and emerging themes related to AI and sustainable materials in the context of building energy performance? What types of scientific collaboration (both domestic and international) emerge from this literature? What research gaps can be identified to guide future studies? Finally, the study proposes a forward-looking integration of AI techniques with the use of eco-friendly insulation materials, suggesting that this combined approach could lead to substantial improvements in building energy efficiency.

2. Literature Review

Currently, it is vital to regulate energy consumption. This issue is particularly linked to the increase in energy consumption in buildings, due to the widespread use of heating, ventilation, and air conditioning (HVAC) systems. In response, the researchers focused their study on investigating the potential for energy savings in the building sector, widely recognized as one of the most energy-intensive sectors. Two main categories of research have been undertaken in this area. The first category focuses on research into new materials suitable for thermal insulation. The second category focuses on new methods for saving energy, in particular by exploring the field of artificial intelligence.

2.1. The Contribution of Bio-Based Materials to Energy Efficiency

The incorporation of natural and recycled materials in the construction sector can play a crucial role in initiatives to improve energy efficiency and promote sustainable development [13]. These plant-based materials offer the opportunity to add value to non-recyclable waste by utilizing agricultural or industrial residues such as stalks, husks, plant fibers, or wood shavings. These components, often considered unusable in other recycling streams, can be transformed into efficient insulating products. For example, straw or hemp, which are difficult to reintegrate into other production cycles, can be repurposed as insulation panels. This reuse not only reduces the amount of waste sent to landfills or incineration but also contributes to a circular economy. Thus, these materials actively promote sustainable resource management while minimizing the ecological footprint.

Today, researchers are increasingly interested in exploring the use of eco-friendly materials, whether natural or recycled, to assess their potential for reuse or recycling in the construction industry. In this context, Lifang Liu et al. [14] examined the development and prospects of bio-based insulation materials, highlighting their growing importance in energy-saving applications. Yunxian Yang et al. [15] demonstrated the improved thermal performance and fire resistance of bio-based retardants, such as corn marrow cellulose and alginate. Similarly, Hanifi Binici et al. [4] have explored the use of corn stalk particles in insulating composites to reduce energy costs. Juan Pablo Cárdenas-R et al. [16] studied the *Hydrangea macrophylla* polymer, demonstrating its potential as a bio-based insulation material. Similarly, Nadir Yildirim et al. [5] have developed thermal insulating foam panels from cellulosic nanomaterials, despite the need for improvements for better commercialization. Amel Limam et al. [17] have evaluated the potential of bio-based materials such as Aleppo pine wood and cork for building insulation.

With this in mind, Saghar Parikhah Zarmehr et al. [18] proposed bio-based polyurethane foam boards as a sustainable option for insulation. Francesco Barreca et al. [19] highlighted *Arundo donax* and gypsum boards using a natural wax oleogel to improve thermal performance in controlled environments. Alessio Tola et al. [20] highlighted the advantages of cork for passive climate control. Eshrar Latif et al. [21] provided information on the durability and thermal properties of bio-based insulation materials to reduce energy consumption. Katja Sterflinger et al. [22] observed that perlite is particularly suitable for thermal insulation due to its resistance to fungal growth. Mourad Chikhi et al. [23] have developed a biocomposite based on date palm fibers, improving thermal and mechanical properties. Asdrubali et al. [24] reviewed the use of natural resources for insulation, in particular date palm fibers, while Boumhaout et al. [25] showed that date palm fibers improve the thermal performance of mortar.

Dinh Linh Le et al. [26] studied circular bio-based building materials (CBBMs) such as hemp, cork, and straw, highlighting their ability to reduce the carbon footprint of buildings and facilitate a circular construction model. They also made recommendations for overcoming the challenges hindering their integration. Lise Mouton et al. [27] highlighted that bio-based materials such as wood, straw, and hemp have lower greenhouse gas emissions than conventional materials, despite the presence of environmental trade-offs. According to Daniela Florez et al. [28], it is common to overestimate the thermal conductivity of wood fiber panels, which requires adjustments to improve the accuracy of measurements. Güliz Oztürk et al. [29] have developed a wood–starch composite material incorporating MicroPCM to provide thermal storage, demonstrating improved thermal regulation and low thermal conductivity. Yuhao Dong et al. [30] presented SFGA foam, made from sucrose and SFG resin, as a promising alternative to tannin for insulation materials due to its thermal stability and biodegradability properties. In conclusion, Alina Galimshina et al. [31] highlighted that the integration of bio-based materials in building renovation can lead to the achievement of carbon neutrality while offering cost-effective and environmentally friendly solutions, as demonstrated by a case study carried out in Switzerland.

2.2. Contributions of AI Methods to Energy Efficiency

The integration of artificial intelligence (AI) techniques in the field of building energy efficiency has emerged as a crucial tool to optimize energy consumption and improve thermal comfort. Various applications (see Table 1), such as energy consumption forecasting, thermal comfort evaluation in subway compartments, monthly electricity consumption prediction, and the integration of phase-change materials (PCMs) into cement composites, demonstrate the significant impact of these technologies on energy management.

Machine learning algorithms, whether supervised—such as Support Vector Machines (SVMs), which determine an optimal hyperplane to separate classes in a multidimensional space; Artificial Neural Networks (ANNs) (see Figure 1), which replicate the functioning of the human brain through layers of neurons to process complex data; Random Forests (RFs) (see Figure 2), which combine multiple decision trees to reduce overfitting; or Extreme Gradient Boosting (XGBOOST), which builds trees sequentially to improve prediction accuracy—or those falling under unsupervised or reinforcement learning, offer powerful solutions to the challenges associated with analyzing complex datasets in the field of building energy efficiency. To enhance the performance of these models, the `RandomizedSearchCV` class from the `scikit-learn` library was used to optimize hyperparameters [32].

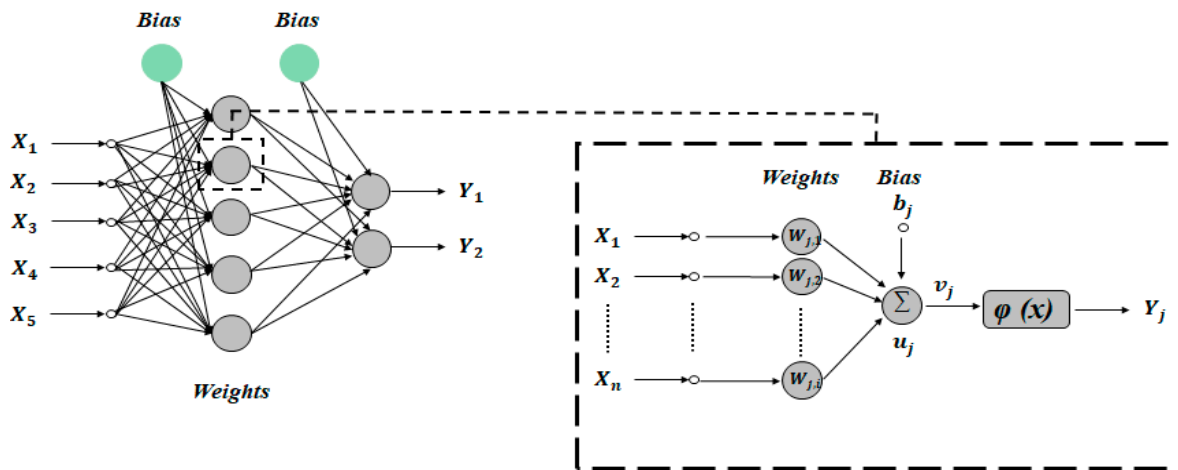


Figure 1. Architecture of the Artificial Neural Network model.

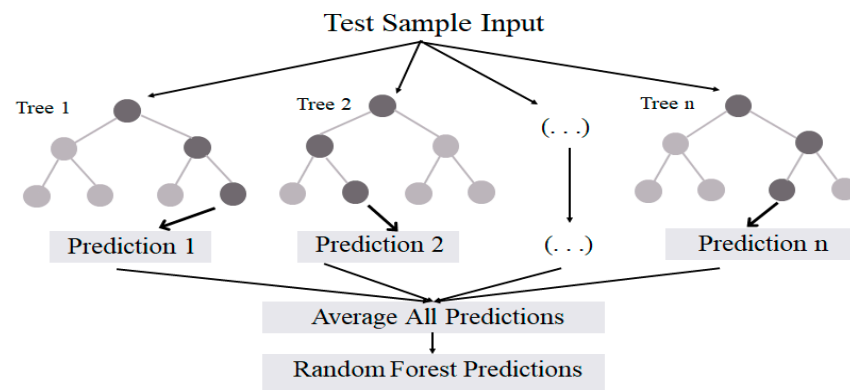


Figure 2. Streamlined Random Forest.

For the RF model, the optimized parameters include the number of trees ($n_{\text{estimators}}$), the maximum depth (max_depth), the minimum number of samples required to split a node (min_samples_split), and the minimum number of samples per leaf (min_samples_leaf). For the SVM, these include the kernel type (kernel), the regularization parameter (C), the kernel coefficient (gamma), and the degree of the polynomial kernel (degree). The optimized parameters for XGBOOST include the learning rate (learning_rate), number of trees ($n_{\text{estimators}}$), maximum depth (max_depth), and L2 regularization parameter (reg_lambda). Finally, for ANN, the considered hyperparameters are the number of hidden layers ($\text{hidden_layer_sizes}$), the activation function (activation), the solver for weight optimization (solver), and the learning rate (learning_rate).

The performance of these models is evaluated using four standard metrics [32]: Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and the Coefficient of Determination (R^2). These indicators assess the quality of predictions by measuring the difference between predicted values (y_{pred}) and actual values (y_{actual}) of the studied factors. The calculations are based on well-established statistical formulas, ensuring a reliable interpretation of model precision and robustness.

$$\text{RMSE}(y_{\text{act}}, y_{\text{pred}}) = \sqrt{\frac{\sum (y_{\text{act}} - y_{\text{pred}})^2}{n_{\text{samples}}}} \quad (1)$$

$$\text{MSE}(y_{\text{act}}, y_{\text{pred}}) = \frac{\sum (y_{\text{act}} - y_{\text{pred}})^2}{n_{\text{samples}}} \quad (2)$$

$$MAE(y_{act}, y_{pred}) = \frac{\sum |y_{act} - y_{pred}|}{n_{samples}} \quad (3)$$

$$R^2 = 1 - \frac{\sum (y_{act} - y_{pred})^2}{\sum (y_{act} - y_{act_mean})^2} \quad (4)$$

The use of these techniques not only facilitates the prediction of the thermal performance of buildings but also optimizes heating, ventilation, and air conditioning (HVAC) systems through advanced diagnostics. Furthermore, these approaches promote informed decision-making and pave the way for more sustainable and intelligent construction, addressing contemporary challenges related to energy consumption and environmental sustainability.

A number of studies have looked at the application of AI (artificial intelligence) in the field of energy efficiency in buildings. Tian Li et al. [33] proposed a new approach, MEBA (Monthly Energy Benchmarking Approach), which uses AI to assess energy consumption patterns and track bills. It covers two scenarios: predicting monthly consumption from partial data and estimating monthly loads from annual data. Similarly, Christian Gnekpe et al. [34] analyzed the effectiveness of energy renovations supported by the EU (European Union) to improve the energy performance (EP) of buildings. Of six machine learning algorithms tested, the Gradient Boosting model achieved the best accuracy at 84.34%. Key recommendations for improving post-renovation EP include the installation of modern heating systems, the use of high-performance insulation materials, and regular maintenance. In another study, Luong Duc Long et al. [35] proposed a new integrated model for the energy-efficient design of buildings from the earliest stages, without detailed plans. The model includes an energy performance simulator, a predictive model based on Gradient Boosting (with an R^2 of 0.994), and an optimization model using AI algorithms. The results show significant cost and energy savings, with examples of 7.52% and 8.48%, respectively, for a case study in Vietnam. This model provides a solid basis for design solutions and enables future objectives to be added. For example, Samee Ullah Khan et al. [36] proposed a hybrid AI-based framework to accurately predict energy consumption and production in Net Zero-Energy Buildings (NZEBs). The model uses advanced techniques such as ConvLSTM (Convolutional Long Short-Term Memory) and BDGRU (Bidirectional Gated Recurrent Unit) to extract spatio-temporal patterns and significantly reduce prediction errors, with MSEs (Mean Squared Errors) of 0.012 and 0.045 on hourly data, outperforming current state-of-the-art techniques.

Buildings consume around 40% of the world's energy, mainly to maintain indoor comfort. Traditional control methods are often inefficient and do not take comfort into account. With this in mind, Jack Ngarambe et al. [37] examined the use of AI and machine learning methods to optimize energy efficiency while improving thermal comfort and identified gaps in current research and avenues for the future. In the same context, Chih-Yen Chen et al. [38] presented an AI-based model to assess the impact of occupant density on energy consumption and CO₂ emissions in offices. Using EnergyPlus and real weather data, an LSTM (Long Short-Term Memory) model was developed to predict these factors. The results show that the model performs very well and can optimize energy consumption and CO₂ (carbon dioxide) emissions for various types of offices.

Raheemat O. Yussuf et al. [39] explored the application of AI to improve the energy efficiency of buildings across all phases of their life cycle, from design to renovation. They highlighted the use of AI to optimize design, decision-making, and energy monitoring, while identifying research needs to further integrate AI into the construction phase for more energy-efficient techniques. On the other hand, Kan Xuc et al. [40] showed that digitalization and AI are transforming building management, although the diversity of

data poses challenges for their interoperability. They proposed a semantic framework for integrating these data, simplifying the deployment of AI-based management applications. This framework has been successfully tested to predict cooling loads in three types of buildings, showing its potential for widespread adoption in the building sector.

Table 1. Summary of relevant studies.

Author	System Analyzed	ML Model	Remarks
H. Yan et al. [41]	Optimizing building performance	XGBOOST	XGBOOST demonstrated the best performance in transfer learning, with $R^2 = 0.95$, MAE = 1.17, and MSE = 4.56 for high-consumption buildings.
Li and Yao [42]	Prediction of heating and cooling loads for residential buildings	SVR and LR	SVR with a radial basis function kernel achieved the best performance, with a MAE of 4.40 and an RMSE of 6.28.
K. Huang et al. [43]	Passenger thermal comfort in subway compartments	LR, RF, SVM, DT	Random Forest outperformed others with an R^2 of 0.6607 for predicting passenger TSV values.
Karatasou et al. [44]	Hourly energy loads	ANN	Empirical results showed prediction accuracy comparable to the best documented in the existing literature.
Kajl et al. [45]	Energy consumption for buildings	ANN	Fuzzy logic was used for post-processing ANN results to adjust the influence of various building attributes on annual and monthly energy consumption.
Dong et al. [7]	Forecasting monthly electricity consumption	SVM	SVMs proved to be particularly effective in addressing this specific problem, with MSE values varying by building: Building A showed the highest MSE (0.73), while Building D recorded the lowest (0.14).
Marani and Nehadi [46]	Integration of phase-change materials in cement composites	RF, ETR, GBR, XGBOOST	A dataset of 154 cement mixtures with PCM was used, with Gradient Boosting showing the highest precision ($R^2 = 0.977$) and RMSE and AMAE values of 2.419 and 1.752, respectively.
Liang and Du [47]	Fault detection and diagnosis for HVAC systems using a combined physical model with SVM	SVM	A four-layer SVM classifier effectively identifies normal conditions and three possible faults, achieving up to 100% accuracy on both test sets, even with a limited number of training samples.
Luong Duc Long et al. [35]	Optimization of building energy design from early phases	Gradient Boosting	The study highlighted significant savings in both cost and energy consumption—7.52% and 8.48%, respectively, for Vietnam—with high predictive performance ($R^2 = 0.994$, RMSE = 1.19, MAE = 0.50).
Y. Boutahri et al. [48]	Prediction of thermal comfort levels and optimization of energy consumption in HVAC systems	SVM, ANN, XGBOOST, RF	The RF and XGBOOST algorithms demonstrated superior performance, achieving accuracies of 96.7% (MAE = 0.021, RMSE = 0.073) and 96.4% (MAE = 0.01, RMSE = 0.076), respectively. In contrast, the SVM performed less well, with an R^2 of 81.1% (MAE = 0.083, RMSE = 0.18).
Dnyandip K. Bhamare et al. [49]	Prediction of thermal performance of roofs with PCM integration	RF, XGBOOST, ETR, GBR, Catboost, ANN	The Gradient Boosting regression model outperforms other machine learning models in terms of performance, with an R^2 of 97.92, MAE of 0.23, and RMSE of 0.374.

These studies reveal notable variations in the performance of artificial intelligence (AI) models applied to energy consumption optimization, thermal comfort prediction, and HVAC system management. In terms of accuracy, Gradient Boosting models (notably XGBOOST and Gradient Boosting Regression) and Random Forest (RF) stand out for their exceptional performance, achieving accuracy rates of 96.7% to 97% in various contexts, such as energy load prediction and building thermal comfort optimization. These models, due to their ability to handle complex datasets and manage nonlinear relationships, have proven particularly effective for regression and optimization problems in multifactorial environments.

On the other hand, models like Support Vector Machines (SVMs) have demonstrated remarkable efficiency in specific cases requiring binary or multi-class classification, such as fault detection in HVAC systems and electricity consumption prediction. While SVM excels in situations with relatively small or noisy datasets, it may perform less effectively in tasks involving more complex relationships between variables.

Artificial Neural Networks (ANNs) have also shown competitive accuracy, particularly in energy load prediction and thermal comfort forecasting for passengers in public transportation. However, the addition of fuzzy logic to the ANN, as observed in the study by Kajl et al. [45], helps compensate for uncertainties related to environmental variables and building attributes, thereby offering better accuracy in contexts with uncertain data.

From a computational performance perspective, boosting models (XGBOOST and Gradient Boosting) and Random Forest are generally more resource-intensive. However, their ability to provide high-quality predictions justifies this computational investment in contexts where precision is crucial. In contrast, models like Support Vector Regression (SVR) and Neural Networks can offer better efficiency in terms of computational time while remaining competitive in less complex applications.

Finally, it is clear that the choice of model should be guided by the specific needs of the problem being addressed. For example, in applications requiring rapid and reliable fault detection in HVAC systems, SVM combined with physical models appears to be an effective solution. Conversely, for tasks related to building energy optimization or energy consumption forecasting in complex environments, boosting models and Random Forest are more appropriate, particularly due to their ability to handle large, heterogeneous datasets.

In conclusion, while each AI model has advantages and limitations depending on the application context, the findings from these studies highlight the importance of selecting the appropriate model based on the specific objectives of the project, the characteristics of the available data, and the computational constraints.

2.3. The Assessment of Building Energy Efficiency

Energy-efficient buildings, offering optimum thermal comfort and a low carbon footprint, are of crucial importance in today's fight against climate change and dwindling resources. Optimizing the energy efficiency of buildings can play a crucial role in meeting these criteria when implemented appropriately.

Consequently, this area of research has spawned numerous studies on various insulation strategies and materials. Geetanjali Kapoor et al. [50] proposed innovative solutions such as bi-layer insulation, polymer sandwich glass walls, and triple glazing with solar panels, showing energy efficiency gains in composite climates. Kadi Yasmina et al. [51] evaluated the impact of eco-friendly insulation materials and shading devices in reducing heating and cooling loads, while Shiyan Wang et al. [52] highlighted the significant improvements brought by prefabricated buildings to urban energy efficiency in China.

In the same context, Alekhya Chetty et al. [3] examined the impact of thermal insulation on heating and cooling loads, depending on climatic zones. Guillermo Escrivá-Escrivá et al. [53] proposed energy efficiency indices based on actual consumption and specific

building parameters. Ákos Lakatos et al. [54] discussed new insulation materials, such as aerogels and vacuum panels, to reduce energy losses. Anna Laura Pisello et al. [55] used thermal deviation indices to assess the summer and winter energy performance of buildings.

Similarly, Imhade P. Okokpujie et al. [56] studied thermal insulation materials for sustainable construction, while Aleksey Zhukov et al. [57] assessed the effectiveness of insulation materials such as foam glass and mineral fibers. Jiashuo Wang et al. [58] showed that radiative cooling and low-emissivity coatings can offer substantial energy savings. Spiru Paraschiv et al. [59] found that improved thermal insulation reduced the load on micro-cogenerator systems, while MES Hassan et al. [60] found a 38% reduction in electricity consumption thanks to adequate insulation in Khartoum.

In addition, Touraj Ashrafian [61] highlighted the impact of future weather forecasts on building performance, with varying implications for costs and energy consumption depending on climate. Siranush Egnatosyan et al. [62] optimized thermal insulation according to climatic conditions and costs, and A. P. Siciliano et al. [63] presented an insulation foam based on wood waste to improve energy efficiency. Anwar Khitab et al. [64] explored nanotechnology for thermal insulation, while Mahmoud Behzadi Hamooleh et al. [65] assessed the effectiveness of phase-change materials in various Iranian cities.

Sara Abd Alla et al. [66] highlighted the impact of insulation materials on heating and cooling loads, while Lizica Simona Paraschiv et al. [67] developed a web application to analyze optimal insulation thickness. Meanwhile, Eshrar Latif et al. [21] discussed material selection for low-energy buildings, and Hacer Mutlu Danaci et al. [68] compared the effectiveness of materials such as aerogel and rock wool. Similarly, Reyhan Kaya et al. [69] assessed the financial feasibility of thermal insulation in university buildings, and Weiwu Ma et al. [70] proposed energy efficiency indicators for combined cooling, heating and power generation systems. Durmuş Kaya et al. [71] noted that thermal insulation reduces cooling and heating loads, while Radwa Amr El-Awadly et al. [72] evaluated various insulation materials for their impact on the energy efficiency of residential buildings. Abdelali Agouzoul et al. [73] examined the improvement of energy efficiency through advanced control systems, and Dieu Tien Bui et al. [74] optimized heating and cooling load forecasts using genetic algorithms. Finally, I. Makrygiannis et al. [75] explored the impact of brick geometry and thermal coefficient on thermal insulation, while Muhammad Sajjad et al. [76] addressed efficient building design with advanced predictive models.

Summary of the Literature Review

The reviewed literature underscores the increasing urgency of energy optimization in the building sector, a domain that represents a substantial portion of global energy consumption and a critical area for environmental impact reduction. Two primary research trajectories have emerged as focal points in addressing this challenge: the utilization of eco-friendly, bio-based insulation materials and the deployment of artificial intelligence (AI) techniques for energy management.

A. Bio-Based Insulation Materials

One major research avenue emphasizes the integration of renewable, natural, and recycled materials, such as cork, wood, plant fibers, and natural polymers, to improve thermal insulation performance. These bio-based solutions leverage agricultural by-products and industrial residues, transforming otherwise non-recyclable waste into valuable insulating materials. Studies demonstrate their potential to contribute to a circular economy while significantly reducing the ecological footprint associated with traditional insulation methods. However, several challenges remain, including the need to enhance the thermal performance and fire resistance of these materials and to address issues related to scalabil-

ity and commercial viability. Additionally, researchers are exploring the development of hybrid insulation systems that combine the strengths of different bio-based substances to maximize efficiency.

B. Artificial Intelligence (AI) in Energy Management

The second research direction focuses on harnessing AI techniques to predict, optimize, and manage energy consumption in buildings dynamically. Methods such as Neural Networks, Support Vector Machines (SVMs), Gradient Boosting, and ensemble learning models have been widely adopted for tasks like energy consumption forecasting, optimizing HVAC (heating, ventilation, and air conditioning) systems, and enhancing overall building energy performance. AI algorithms have shown remarkable success in processing complex datasets, enabling real-time adjustments and informed decision-making, which are especially beneficial for achieving nearly zero-energy building (NZEB) standards. Moreover, these models improve prediction accuracy and operational efficiency, allowing for advanced control strategies that reduce energy wastage and enhance thermal comfort for occupants.

C. Integrative Approaches and Future Prospects

Emerging research highlights the synergistic potential of combining bio-based insulation with AI-driven energy management strategies. This integrated approach not only enhances the energy performance of buildings but also contributes to reducing their carbon footprint, creating a more sustainable and resilient built environment. However, the literature indicates that further investigation is necessary to fully realize this potential. Specifically, there is a pressing need to develop new eco-friendly materials with improved performance characteristics and to refine AI models for faster and more accurate energy predictions.

D. Research Gaps and Future Directions

Despite the advancements in both fields, significant research gaps persist. For bio-based materials, there is a need for extensive performance testing under diverse climatic conditions and for innovations that ensure durability and cost-effectiveness at scale. In the realm of AI, refining algorithms to handle diverse data inputs and optimizing computational efficiency remain critical challenges. Future research should also explore the long-term environmental impact of these combined solutions and develop frameworks for widespread implementation.

The confluence of bio-based insulation technologies and AI-driven energy optimization represents a transformative opportunity to advance building energy efficiency. Continued interdisciplinary research and innovation are essential to address the identified gaps and drive the adoption of these promising technologies on a global scale.

3. Bibliometric Analysis

3.1. Methodology

This study employed bibliometric methods to examine the scientific literature on optimizing building energy performance through the use of bio-based insulating materials and the integration of artificial intelligence (AI) technologies. The primary search terms included “buildings”, “energy efficiency”, “artificial intelligence”, and “ecological materials”. Quantitative analysis techniques were applied to assess the breadth of research conducted in this domain and to identify gaps in existing research frameworks. To complement the quantitative approach, text mining was conducted to extract thematic areas, key terms, and the most influential authors and contributing countries. All bibliographic data were

sourced from the Scopus database. The bibliometric methodology followed in this study is structured into two main phases, data collection and data analysis, as illustrated in Figure 3.

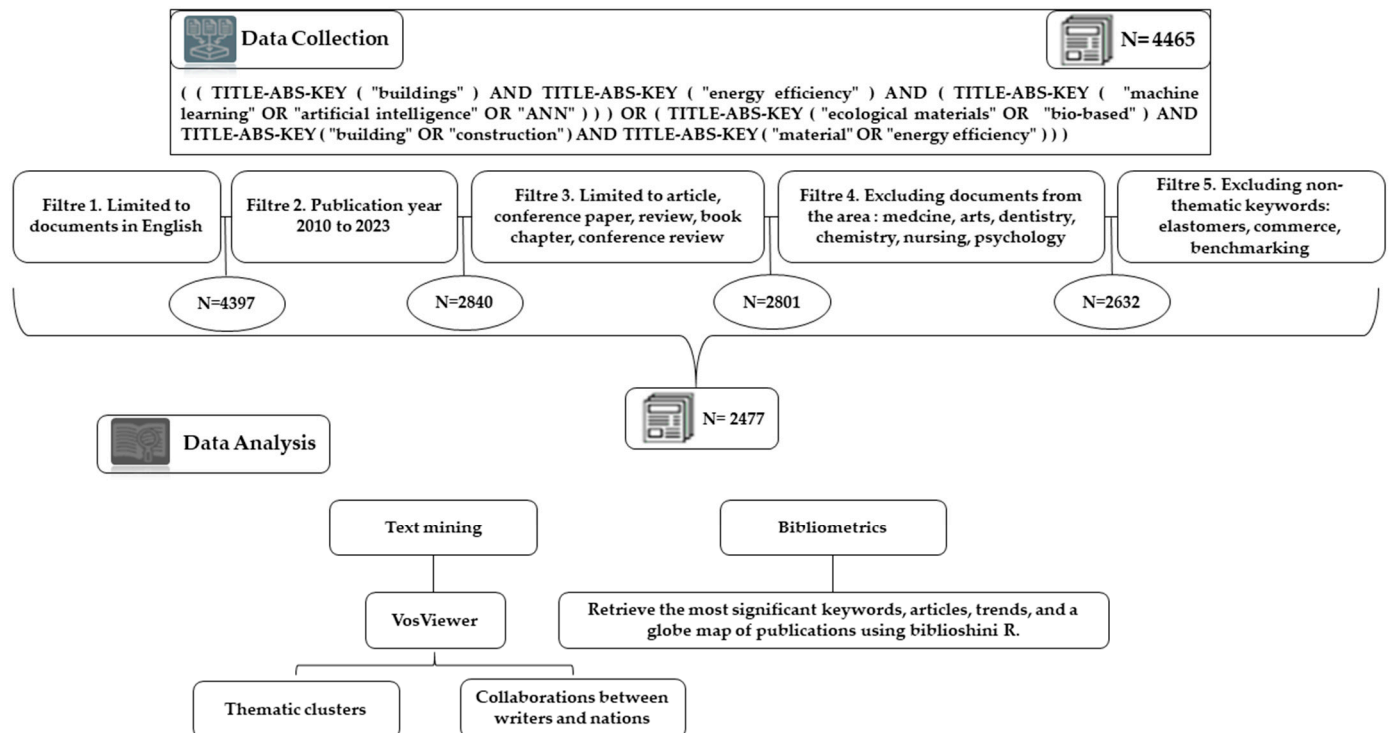


Figure 3. Examination of consolidated data conducted in the study.

3.1.1. Publication Search

In the context of this bibliometric study, the selection of the database represents a critical step to ensure the robustness of the results and the reliability of the analysis. Several databases are commonly used in the scientific literature, including Scopus, Web of Science (WOS), and Google Scholar [77]. Although Google Scholar provides extensive coverage—encompassing articles, conference proceedings, theses, preprints, institutional repositories, and patents—its lack of editorial control and the heterogeneous nature of its sources limit its suitability for rigorous bibliometric analysis. The difficulty of exporting standardized metadata and the inability to apply precise filters pose significant methodological challenges.

Web of Science, initially developed by Thomson Reuters, is well known for its rigorous standards and reliable citation indicators. However, while its coverage is of high quality, it tends to focus more heavily on specific scientific domains such as medicine, pharmacy, or the natural sciences. This focus can introduce considerable noise in interdisciplinary studies such as the present one, which lies at the intersection of building engineering, ecological materials, and artificial intelligence.

By contrast, Scopus, developed by Elsevier, stands out due to its broad thematic coverage, frequent updates, and precise metadata structure. It supports advanced search functions through the combination of specific fields (title, abstract, keywords, source, etc.) and offers refined filtering options based on language, publication type, subject area, and time period. These features enable the extraction of highly targeted and relevant documents. Moreover, Scopus is compatible with powerful bibliometric analysis tools such as VOSviewer [78,79], facilitating the exploration of co-occurrence networks, citation patterns, authorship, and institutional collaboration.

Given these methodological advantages—including metadata quality, query flexibility, refined filtering, and tool compatibility—Scopus was selected as the exclusive data source

for this bibliometric study. This decision aims to ensure the coherence, scientific relevance, and analytical reliability of the corpus in line with the objectives of the research.

3.1.2. Data Gathering

The data used in this study were extracted from the Scopus database, known for its extensive coverage of scientific publications and its compatibility with bibliometric analysis tools such as VOSviewer. A rigorous methodology was implemented to construct a relevant search equation, based on the identification of keywords that accurately reflect the thematic scope of the study. This process was preceded by an exploratory literature review, focusing on both the use of eco-friendly insulating materials and the applications of artificial intelligence (AI) in building energy optimization.

The selected terms were combined using the Boolean operators AND and OR to formulate an effective query targeting research at the intersection of energy efficiency, sustainable materials, and intelligent technologies. The applied search equation was as follows:

[(“buildings”) AND (“energy efficiency”) AND ((“machine learning” OR “artificial intelligence” OR “ANN”) OR ((“eco-friendly” OR “bio-based”) AND (“building” OR “construction”) AND (“material” OR “energy efficiency”)))]].

The Boolean query strategy adopted in this study made it possible to include not only research focused on bio-based materials and that on artificial intelligence in energy optimization, but also—and most importantly—studies that combine both approaches. These latter works represent an emerging synergy in which AI models (such as ANN, Random Forest, or SVM) are directly applied to the analysis, simulation, or optimization of ecological materials. This approach ensures comprehensive thematic coverage and justifies the combined analysis of both research axes in our study.

This initial search yielded a total of 4465 documents. To ensure scientific quality, thematic relevance, and coherence of the corpus, several successive filters were applied. The first filtering step concerned language: only documents written in English were retained, reducing the dataset to 4397 publications. This choice is justified by the dominance of English in international scientific production, ensuring better comparability across studies and the linguistic consistency required for bibliometric analysis tools.

Next, a time filter was applied to include only documents published between 2011 and 2022. This period was chosen as it corresponds to a phase of significant growth in research related to AI in the building sector and sustainable materials, allowing the study to capture emerging trends while excluding outdated work.

A third filter was applied based on document type: only peer-reviewed journal articles, conference proceedings, academic book chapters, review papers, and conference reports were retained. These formats typically adhere to a rigorous structure, undergo peer review, and present exploitable results for bibliometric analysis. Editorials, letters, and short reports, which are generally less structured and less methodologically detailed, were excluded. At this stage, the refined corpus comprised 2801 publications.

To further narrow the analysis to topics directly related to the research objectives, thematic filtering was then performed. Despite the presence of overlapping keywords, some documents fell within unrelated disciplines such as medicine, psychology, the arts, or chemistry. These publications, although technically included by the initial query, had no direct link to building energy performance or the use of sustainable materials and were therefore excluded, reducing the corpus to 2632 documents.

Finally, a last stage of keyword cleaning was carried out. Terms such as “benchmarking”, “commerce”, or “elastomers”, which often appear in publications unrelated to the

core topic (e.g., in human resources or marketing), were identified and removed. This process helped eliminate documents that, although captured by the initial query, did not meaningfully contribute to the research problem. After this comprehensive filtering, the final corpus consisted of 2477 documents, as shown in Figure 3.

The inclusion criteria for this study thus comprised the following: publication in English, a publication date between 2011 and 2022, document types subject to peer review, and an explicit link to one or more of the following areas: eco-friendly insulating materials in buildings, the use of AI for modeling or energy prediction, and improvements in energy performance. Conversely, documents written in other languages, lacking scientific validation, originating from unrelated disciplines, or containing misaligned keywords were systematically excluded from the analysis corpus.

3.1.3. Data Management and Statistical Assessment

To analyze the selected publications, two complementary tools were used: Biblioshiny (the graphical interface of the Bibliometrix package in R) (RStudio, version 2024.04.2.0) and VOSviewer (version 1.6.20). These tools were chosen for their robustness, open-source accessibility, and ability to generate advanced visualizations from bibliographic metadata.

Biblioshiny was selected for its user-friendly interface and direct compatibility with Scopus data. It allows for a comprehensive exploration of bibliometric indicators such as author productivity, journal impact, geographical distribution, and collaboration networks. The data were first converted into a compatible format using Biblioshiny and then used to generate tables and graphs, which were further analyzed using Microsoft Excel. This process made it possible to structure the information around key aspects such as productivity, scientific influence, and institutional collaboration.

In addition, VOSviewer was used for its ability to efficiently visualize co-occurrence networks of keywords, co-authors, and co-citations. The textual analysis focused on author keywords and indexed keywords, applying a minimum occurrence threshold (e.g., at least five mentions) to ensure the relevance of the results. The generated maps helped identify semantic proximity between concepts and thematic clusters within the dataset. These visualizations highlighted research dynamics, emerging trends, and interdisciplinary connections.

The combined use of these two tools enabled both a quantitative analysis of the publications and a semantic visualization of conceptual relationships, providing a structured overview of the scientific landscape studied.

3.2. Bibliometric Results

The results of the bibliometric analysis are presented in the following section in order to evaluate our initial research questions. After applying selective filtering on the search query in the Scopus database, a total of 2477 publications were identified, covering the following keywords: buildings, energy efficiency, bio-source material, and artificial intelligence. We begin by presenting the descriptive analysis and the co-citation network based on all the articles. We then present a summary of the results obtained for the various sub-groups.

3.2.1. Descriptive Data Analysis

The study focused on a twelve-year period, from 2011 to 2022. The categories of documents specifically selected include articles and book chapters, and the topics covered are related to the research objective, particularly in the fields of engineering and energy, as illustrated in Figure 4.

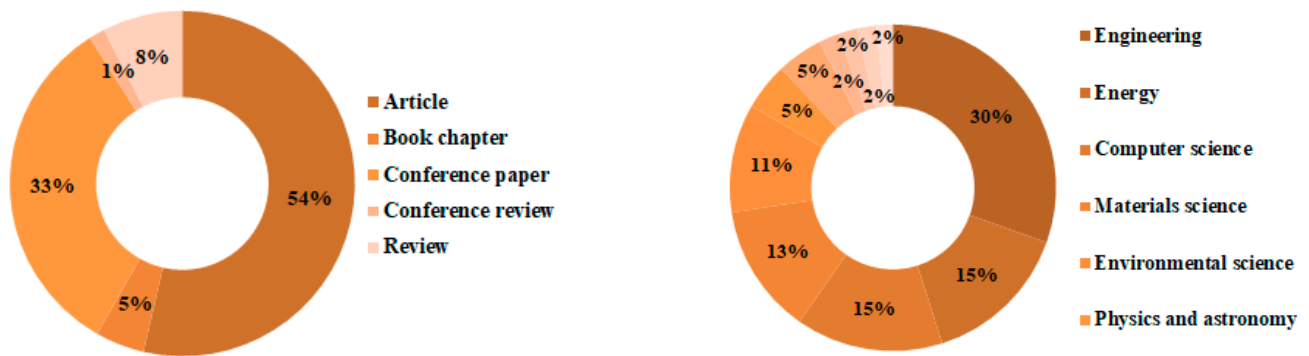


Figure 4. Conclusions of the bibliometric study.

3.2.2. Volume of Scientific Publications

Figure 5 illustrates the evolution of energy efficiency publications in terms of total number of publications, total citations, and average citations. We can see that the growth in publications has remained constant, increasing from 37 to 125 publications in the first 6 years, before rising significantly from 176 to 522 publications in the last 6 years. In addition, there has been a significant increase in the total number of citations over the years, reaching 2458 citations in 2021. However, a careful analysis of publications' average citations reveals a slight but steady increase over the years, culminating in 2018 with the highest score recorded that year.

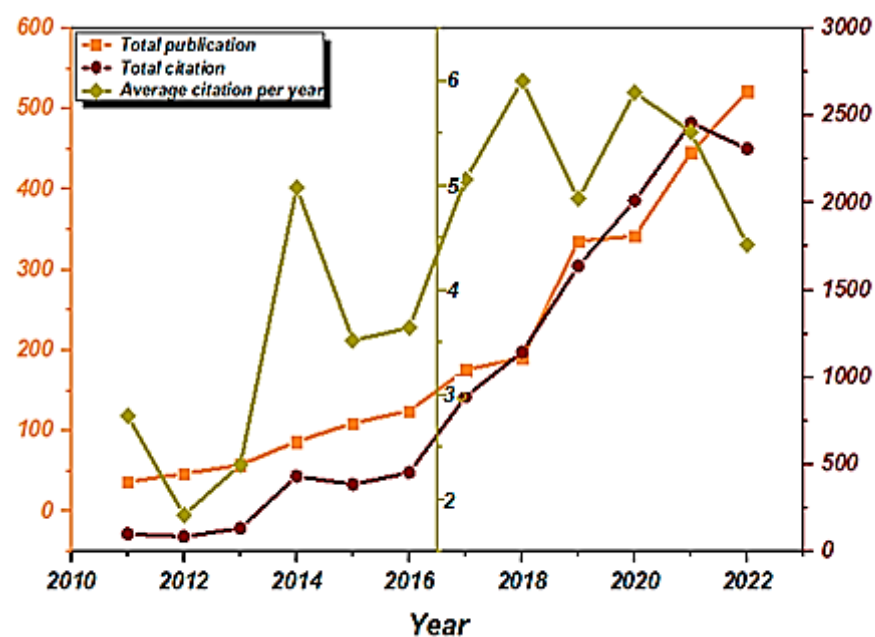


Figure 5. Trends in publications, total citations, and average annual citations in research.

A plausible explanation for these trends lies in the increasing environmental concerns and the rising energy demands of the construction industry, coupled with a burgeoning interest in artificial intelligence technologies. During the 2000s, a paradigm shift occurred in the understanding of regulatory mechanisms and the global implications of energy efficiency. This shift underscores the importance of energy efficiency in shaping the evolution of energy policies and regulations worldwide.

In the early 2000s, many countries prioritized sustainable energy development, setting ambitious goals to reduce environmental impact and optimize energy use. Since 2015, there has been a marked increase in the number of academic publications focusing on energy efficiency, reflecting the field's growing significance.

The slight decline in scientific output in 2021 could be interpreted in light of the disruptions caused by the COVID-19 pandemic, which temporarily slowed down academic activities. That said, this drop does not appear to undermine the overall upward trend observed over the past decade. On the contrary, it highlights the importance of sustained and resilient investment in energy research, particularly in emerging fields such as the integration of AI with sustainable insulation materials.

3.2.3. Publications Categorized by Countries, Sources, Affiliations, Authors, and Keywords

i. *Most influential sources and authors*

Table 2 presents the top 10 journals and authors ranked by the number of publications and citations. The results also highlight key bibliometric indicators: the H-index, G-index, and M-index of these prolific sources and authors.

Table 2. Top 10 journals ranked by publications and impact.

Journal	Publications	Citations	H-Index	G-Index	M-Index
Energy and Buildings	104	7672	49	86	3.5
Applied Energy	53	5420	38	53	3.17
Building and Environment	63	2818	31	52	2.82
Construction and Building Materials	77	2547	29	47	2.23
Journal of Cleaner Production	36	2053	26	36	2.36
Energies	72	1461	21	35	1.5
Renewable and Sustainable Energy Reviews	21	3544	21	21	2.1
Journal of Building Engineering	46	1346	20	35	2.22
Energy	30	1584	19	30	1.9
Polymers	36	2175	19	36	1.73

H-index: Number of publications (H) with at least H citations each. **G-index:** Weighted index favoring highly cited articles. **M-index:** H-index divided by the number of years since the first publication.

The H-index serves as a measure of both productivity and scholarly impact. Specifically, a researcher or publication with an H-index of N has authored N papers, each of which has been cited at least N times [80]. The G-index, while similar to the H-index, provides a broader assessment by considering the total number of citations received across all publications, thereby offering a more comprehensive evaluation of overall research influence [81]. In contrast, the M-index is calculated as the ratio of the total number of citations to the number of publications [82], offering an average measure of citations per work.

Together, these indicators provide valuable insights into the productivity and impact of academic sources and authors, as illustrated in Table 2. They enable a nuanced understanding of the research landscape and help identify influential contributors in the field.

The top 10 journals account for 22% of all publications examined in this study. The data in the table reveal that Energy and Buildings stands out as the journal with the highest number of articles published (104) and the highest number of total citations (7672). In addition, it has the highest H coefficient (49) and the highest G coefficient (86) among energy efficiency references. It is then followed by the Journal of Applied Energy, which includes 53 articles and has received 5420 citations, with H and G ratings of 38 and 53, respectively.

Table 3 illustrates the ten most prolific authors in terms of number of publications, as shown in the bottom panel. It appears that Moon Jin Woo is the most productive author in the field of energy efficiency, publishing 15 papers and receiving 337 citations. With an H-index of 12 and a G-index of 15, this journal occupies the top position in terms of impact. Guillaume Habert has published 16 articles and holds the record for the highest number of citations, totaling 670 in this field. His influence is also significant, given his H-index of

10 and G-index of 16, ranking him among the top 8 authors on the list. Table 2 provides a detailed analysis of citations from the top ten journals and authors and their influence.

Table 3. Top 10 authors ranked by productivity and impact.

Author	Publications	Citations	H-Index	G-Index	M-Index
Moon Jin Woo	15	337	12	15	0.92
Magniont Camille	15	580	11	15	1.1
Collet Florence	14	614	10	14	0.83
Habert Guillaume	16	670	10	16	1.11
Lawrence Mike	10	297	10	10	0.83
Walker Pete	13	353	10	13	0.83
Laborel-Préneron Aurélie	12	427	9	12	0.9
Langlet T.	13	414	9	13	0.9
Lanos Christophe	12	398	9	12	0.75
Pretot S.	12	538	9	12	0.75

H-index: Researcher has published H papers with $\geq H$ citations. **G-index:** Gives more weight to highly cited work. **M-index:** H-index divided by number of active publishing years.

Beyond these descriptive results, several significant implications emerge. On one hand, they guide researchers toward the most influential journals for publishing their work in order to increase visibility. On the other hand, they help identify key opinion leaders in the field, potentially leading to future scientific collaborations. Moreover, the high citation rate of journals positioned at the intersection of energy, materials, and artificial intelligence reflects a growing need for interdisciplinarity, which is now essential for addressing contemporary environmental challenges.

Ultimately, this bibliometric study reveals that academic influence is not solely dependent on the quantity of publications, but also on strategic alignment with global priorities such as carbon reduction, energy efficiency improvement, and the integration of AI into sustainable materials. These insights represent valuable directions to guide future research toward topics with strong scientific and societal impact.

ii. *Top contributing countries*

The geographical analysis of scientific production, beyond a mere enumeration of publications by country, highlights regional trends that reflect strategic priorities and varying technological capacities in the field of building energy efficiency. This distribution is illustrated in Figure 6, where countries that have contributed are highlighted in blue, while those that have not participated in this emerging area of research appear in grey.

France, China, and the United States stand out as the leading contributors in terms of publications. This prominent position can be understood as the outcome of ambitious energy strategies, supported by investments in research and development as well as robust academic infrastructure. Not only have these nations implemented advanced thermal regulations (such as France's RE 2020), but they are also actively engaged in global environmental treaties, which promotes research aligned with global climate goals. The growing volume of research in these regions demonstrates a clear intent to explore the synergy between artificial intelligence and bio-based materials to develop sustainable solutions tailored to the challenges of the energy transition.

Although their scientific output is lower, Italy and the United Kingdom also make a noteworthy contribution. This may be attributed to a growing awareness of the environmental impact of the building sector in these countries, combined with increasing interest in energy efficiency through interdisciplinary approaches. Their involvement also signals a broader European trend favoring collaborative research on green technologies.

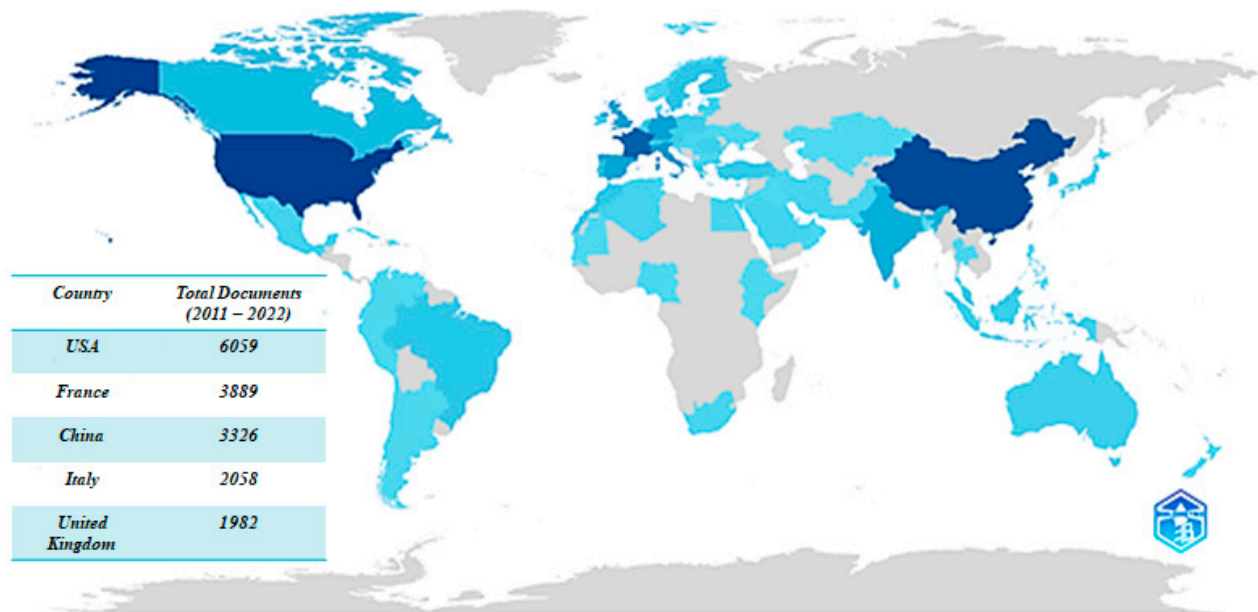


Figure 6. Heat map of countries based on the number of publications (from dark blue for the most publishing countries to very light blue for the least contributors), along with a list of the 10 most active countries.

However, countries such as Brazil, Canada, and Morocco—despite their potential in natural resources that could serve as sustainable insulating materials—remain under-represented. This under-representation may be linked to structural barriers such as limited funding for environmental research or a lack of well-organized specialized scientific networks.

These findings point to two key considerations: on the one hand, the need to strengthen international synergies to unify research efforts, especially in regions that are still under-developed in this field; on the other hand, the essential role of political and institutional support in steering research toward strategic topics such as the integration of AI with sustainable materials. Such an approach is critical to reducing disparities in global scientific participation and fostering fairer, more effective innovation in the fight against climate change.

Figure 7 highlights the number of citations received per country, highlighting a direct relationship between each nation's academic productivity in terms of publications and the number of citations received. The USA, France, and China stand out for their high output of papers on building energy efficiency and also lead the way in terms of citations received. This finding highlights the fact that the proliferation of scientific contributions leads to greater visibility within the academic community, resulting in an increase in the number of citations.

A more in-depth analysis, based on proportions, highlights significant disparities in academic impact between different countries. For example, China holds a 23.1% share of all citations received, followed by the USA with 22.9% and France with 12.2%. Together, these three nations account for 58.3% of all citations worldwide. This highlights a significant concentration of academic influence in a small number of countries in the field of building energy efficiency, with an emphasis on green insulation and the integration of artificial intelligence. The distribution of citations highlights the leading role of certain countries in the production of knowledge relevant to the global scientific community, highlighting the importance of the quality and relevance of the research generated. The leadership of China, the USA, and France, in particular, highlights the importance and richness of their contributions, arousing keen interest among researchers and practitioners in the field. This fosters a scientific exchange that transcends national borders.

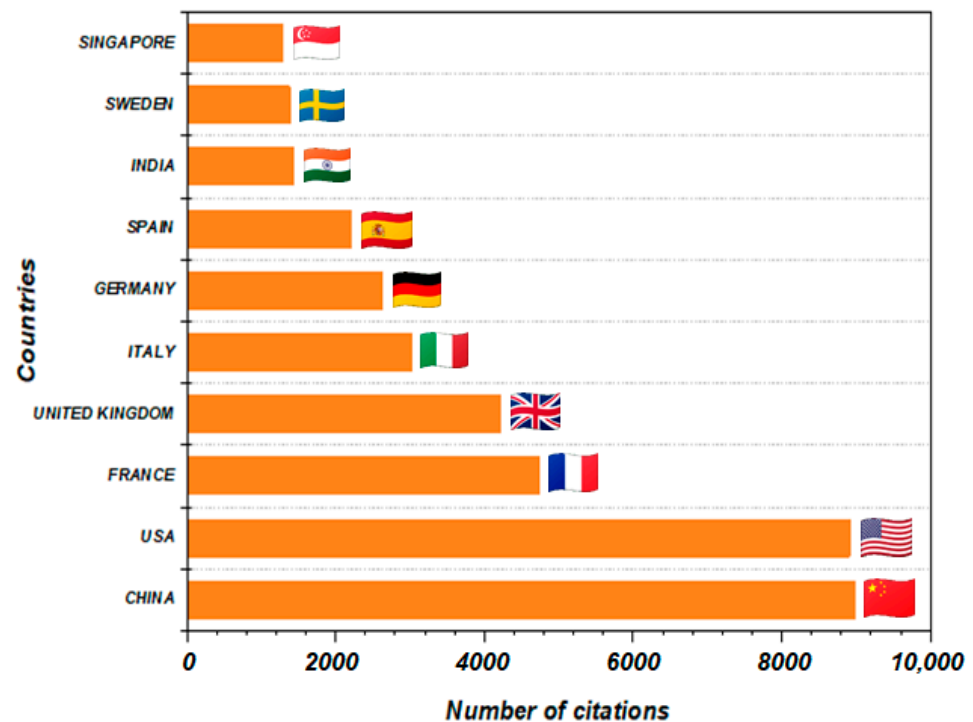


Figure 7. Distribution of citations by country.

iii. Scientific production by source

Figure 8 highlights the most influential scientific journals in the field of building energy efficiency. Beyond a simple ranking, it shows how research is structured around specific priorities. Journals such as *Energy and Buildings* or *Construction and Building Materials* are not only popular; they play a key role in spreading specialized studies on energy consumption, sustainable materials, and the use of artificial intelligence. This reflects a strategic choice by researchers who aim to publish in reputable journals that reach both the academic world and industry professionals.

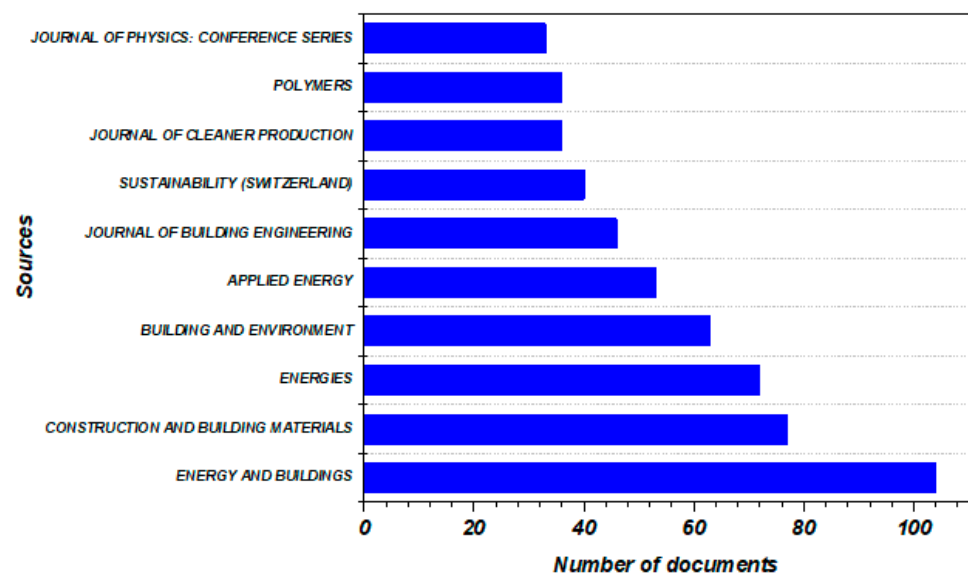


Figure 8. Most important sources.

The success of *Energy and Buildings*, which alone features 104 publications, underlines its central role in the scientific debate. It has become a reference point that brings together studies from different fields, indicating a strong trend toward interdisciplinary

approaches. For example, it includes research combining thermal insulation issues with AI tools, showing a clear drive for innovation at the crossroads of technologies.

Other journals, such as Sustainability or Journal of Cleaner Production, show that research is no longer limited to technical solutions. It is expanding toward broader reflections on environmental impacts, ecological transition, and even the social role of sustainable buildings. These publications promote a more comprehensive vision, where energy efficiency is seen as part of a wider set of sustainable development concerns.

Finally, the diversity of journals highlights the deeply interdisciplinary nature of this research field. Published articles cover engineering, environmental science, artificial intelligence, and architecture. This richness helps better address current challenges by combining various areas of expertise. As a result, these journals are not just publication platforms; they also help shape the scientific debate and put forth practical solutions for a more sustainable future.

iv. Scientific contribution by affiliation

The data indicate that the top five institutions associated with the authors are the University of Bath (72 papers), the University of Toulouse (72 papers), RWTH Aachen University (61 papers), Riga Technical University (57 papers) and Nanjing Forestry University (53 papers). However, in this study, the predominant affiliated entities are universities and research institutes. This suggests that these institutions allocate resources to research and development (R&D) and implement actions to encourage energy efficiency research.

Figure 9 highlights the importance of universities and research institutes in applied research and technology development, underlining their essential contribution to understanding the collaborations that influence energy efficiency research. For example, the top 4 European universities and the Chinese universities ranked 5th, 6th, and 8th are among the most influential institutions, demonstrating a strong commitment to building energy efficiency research. This is in response to growing energy demand and the harmful effects of organic and inorganic insulation materials on the environment.

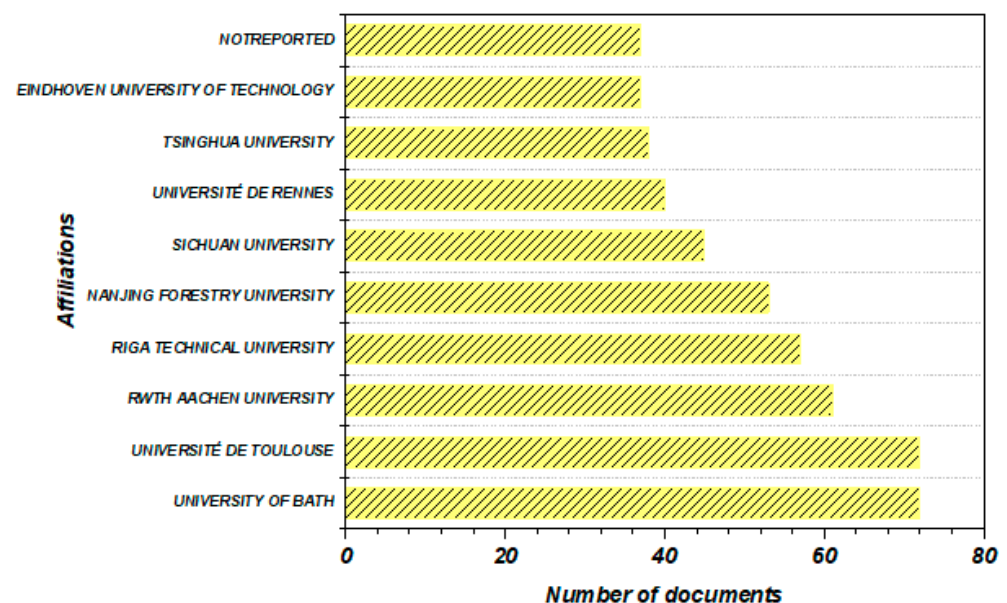


Figure 9. Most significant affiliations.

This dynamic is driven by the continuous increase in energy demand and a growing awareness of the environmental impacts associated with construction materials. The most productive institutions in this field go beyond purely academic objectives; they are fully engaged in technological innovation that addresses broader societal challenges. Their

scientific output helps shape public policy, influence professional practices, and support the development of standards for sustainable construction.

The findings thus highlight a research landscape organized around major academic hubs. These centers of excellence play a key role in accelerating the transition toward high-performance buildings by promoting interdisciplinary approaches and advanced technological solutions.

v. *Scientific publications by author*

The field under study includes a total of 8070 authors, among whom 121 have publications as sole authors. Of these, 25.68% are involved in international collaborations, with an average of 4.21 co-authors per publication. This co-authorship dynamic highlights the growing importance of global research networks in developing innovative solutions for building energy efficiency.

Figure 10 highlights the most prolific researchers. H. Guillaume stands out with 16 publications, followed closely by M. Camille and M. Jin Woo, each with 15 articles. Other researchers follow with between 11 and 14 publications. This distribution indicates a small group of highly active authors who play a key role in driving the scientific output in this area.

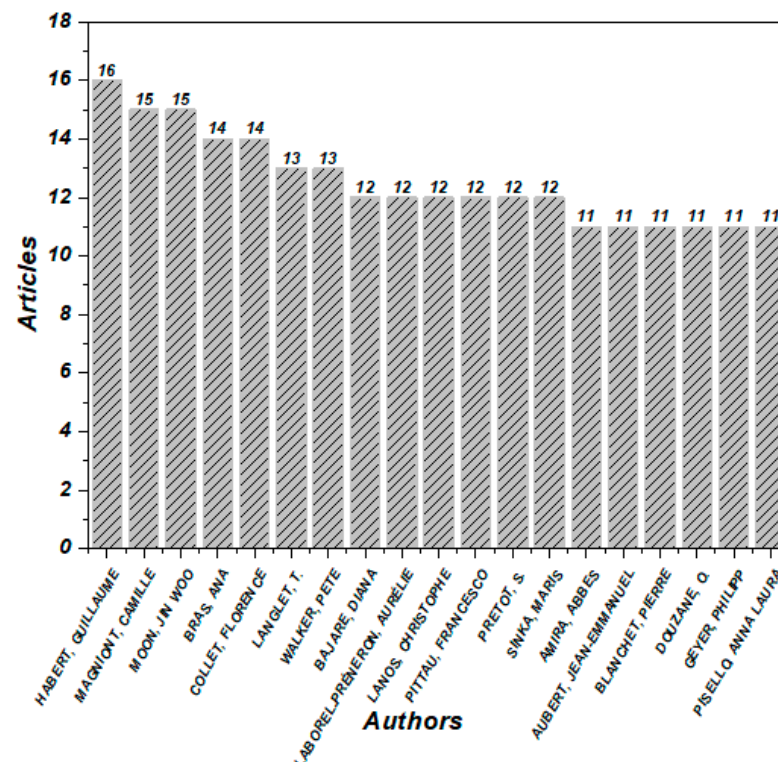


Figure 10. The most productive authors.

However, high productivity does not necessarily equate to high scientific impact. For this reason, the h-index (see Table 3) is used to better assess the significance of contributions. This index evaluates both the consistency and influence of publications based on the number of citations received. In this analysis, the overall h-index of each author is calculated based on all their published articles, with particular attention given to those included in the sample studied.

Although H. Guillaume is the most prolific author, his overall h-index stands at 10, with a total of 670 citations for the articles in the sample. His recent work addresses contemporary issues related to the environmental impact of buildings, notably through articles

such as “Embodied GHG Emissions of Buildings—The Hidden Challenge for Effective Climate Change Mitigation” [83] and “LCA and BIM: Visualization of Environmental Potentials in Building Construction at Early Design Stages” [84]. These publications reflect a focus on integrating life cycle assessment and digital tools to reduce the carbon footprint of buildings.

On the other hand, M. Camille has the highest h-index (11), with a total of 580 citations, reflecting significant impact despite slightly lower productivity. His research focuses on the use of bio-based materials in construction, directly addressing issues of sustainability and ecological transition. Works such as “Plant Aggregates and Fibers in Earth Construction Materials: A Review” [85] and “Hygrothermal Properties of Earth Bricks” [86] contribute to redefining building practices by promoting natural, low-impact materials.

These findings provide insights not only into the profiles of influential researchers but also into the key scientific trends shaping the field of energy efficiency. They reveal a structured research landscape centered around emerging themes—such as sustainable materials, environmental assessment, and BIM integration—that align with current priorities in the energy transition.

vi. *The attributes of keywords*

Keywords are of paramount importance when searching for information, having a significant impact on the relevance of results in a given field. It is therefore essential to know how to choose the most relevant keywords for each situation. Keywords can come from a variety of sources, including author-selected keywords and “Keywords Plus” keywords. Authors select keywords directly, taking into account their relevance after summarizing their articles. “Keywords Plus”, on the other hand, are automatically created by algorithms integrated into bibliographic software, which identify the terms and expressions most commonly used in the titles of cited references.

In this research work, preference is given to “author keywords” over “Keywords Plus”, as the former are considered to be more representative of article content [87].

Figure 11 presents a word cloud that visually highlights the most commonly used terms in publications related to building energy efficiency. The size of each term reflects its frequency of occurrence, with “energy efficiency” occupying a central and prominent position. Other frequently associated terms include “energy consumption”, “artificial intelligence”, “machine learning”, “buildings”, “bio-based”, and “bio-based materials”.



Figure 11. Term cloud of publications.

Figure 12 complements this analysis by illustrating the quantitative distribution of author-selected keywords. “Energy efficiency” stands out as the dominant keyword (15%), followed by “energy consumption” (6%), “machine learning” (5%), “artificial intelligence” (4%), then “buildings” and “bio-based” (3% each), and finally “bio-based materials” (2%). This ranking helps identify the major research trends in the field.

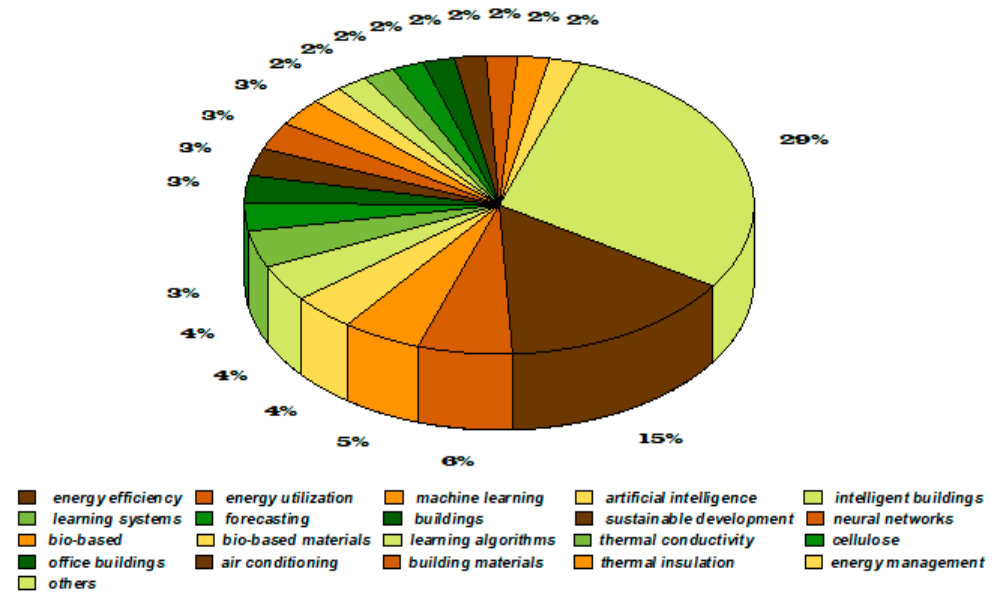


Figure 12. Top 20 most frequently used keywords by percentage.

Beyond simple frequency, these keywords reflect a strategic orientation of research toward technological innovation and eco-design. The emergence of terms related to artificial intelligence and machine learning indicates growing interest in predictive approaches and intelligent systems for energy optimization. At the same time, the significant presence of keywords such as “bio-based” and “bio-based materials” highlights increasing awareness of environmental concerns and the importance of renewable resources in sustainable building design.

These findings reveal a clear convergence between digital technologies and sustainability in recent research. This dual focus suggests that the future of energy performance lies in hybrid solutions that combine advanced technologies with natural materials. Keyword analysis thus provides insight not only into the most prominent topics but also into the potential drivers for addressing the challenges of energy transition in the building sector.

3.2.4. The Thematic Evolution of Research

The thematic evolution highlights the many connections and intense exchanges of ideas that have taken place over time. The graph shows the close links between themes over the years. Some topics were identified at the outset of the study, while others have emerged more recently. For example, in the period from 2018 to 2022, topics such as energy consumption and green insulation attracted a great deal of interest in studies of building energy efficiency. However, recent topics have surfaced, focusing mainly on techniques for quantifying energy performance, in particular artificial intelligence.

Figure 13 presents a tripartite Sankey diagram illustrating the relationships between the ten most frequently used keywords (left), the authors’ countries (center), and the scientific journals (right). This visual mapping offers a comprehensive overview of the thematic and geographical distribution of academic research related to building energy efficiency.

The diagram highlights several key patterns. The United States emerges as a central contributor, with strong associations to a diverse set of keywords including machine learning, energy efficiency, artificial intelligence, and smart buildings. This reflects a broad and strategic engagement with both technological innovation and sustainable practices. Major outlets for these contributions include Energy and Buildings, Construction and Building Materials, and Building and Environment.

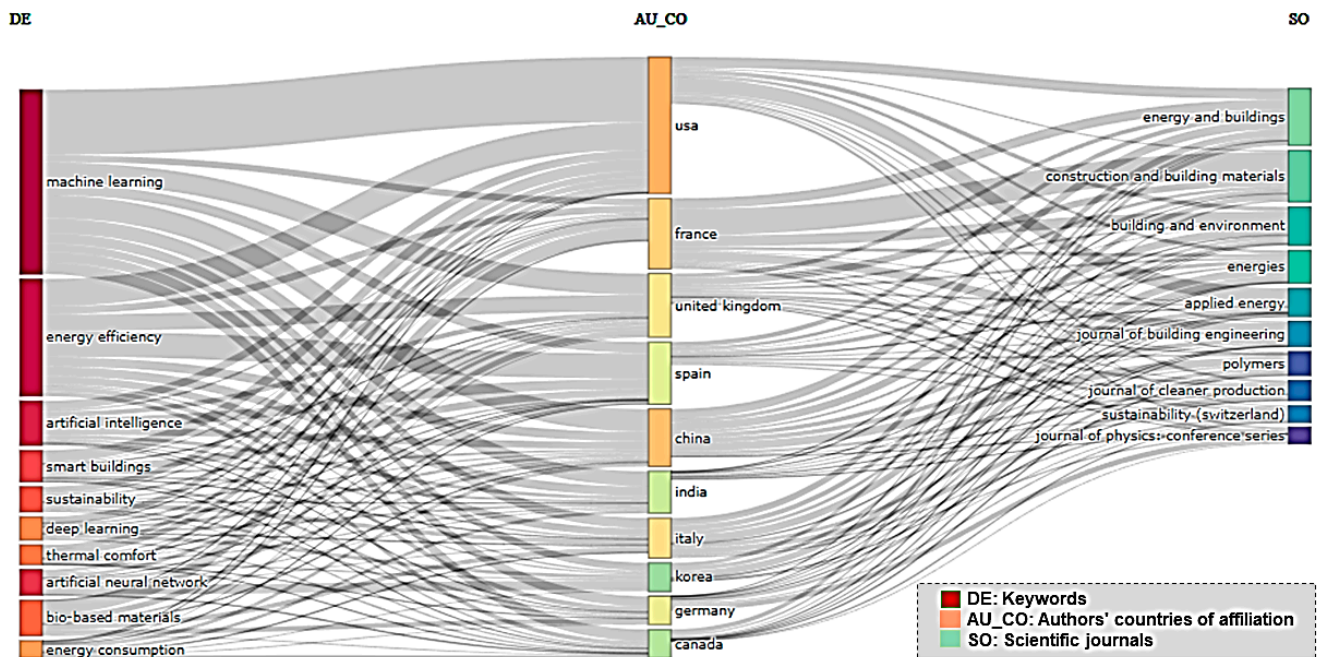


Figure 13. Three-field analysis of research on energy efficiency, bio-based materials and AI.

European countries such as France, the United Kingdom, and Spain show a marked interest in themes like bio-based materials, thermal comfort, and sustainability, suggesting a research focus on ecological design and low-impact materials. France, in particular, demonstrates a pronounced alignment with bio-based construction approaches.

China also stands out with a strong publication output, especially in the areas of artificial intelligence and energy consumption, reinforcing its growing role in applied energy research. These contributions are frequently disseminated through leading international journals.

Emerging research activity is observed in countries like India, South Korea, and Canada, with notable linkages to deep learning and sustainability. This indicates an expanding global interest in data-driven and environmentally responsible solutions.

In addition to the dominant journals, publications such as *Applied Energy*, *Journal of Cleaner Production*, *Polymers*, *Journal of Building Engineering*, and *Sustainability* (Switzerland) provide specialized platforms for research on innovative materials, energy optimization, and environmental assessment. Their increasing relevance underscores the multidisciplinary nature of this field.

Overall, the diagram reveals a dual trajectory in current research: the adoption of advanced digital technologies (e.g., AI, Neural Networks, deep learning) alongside a rising focus on sustainable practices (e.g., bio-based materials, thermal comfort). This convergence suggests that future advancements in building energy efficiency will be driven by the integration of smart technologies and environmentally conscious design.

3.2.5. Cluster Analysis: Bibliographic Coupling of Journals, Countries, and Keyword Co-Occurrence, and Author Co-Citation

The concept of “bibliographic coupling” refers to the way in which objects are linked to each other, based on the number of references they share in common. The frequency with which a document is cited reinforces the connection with it. Bibliographic linking highlights the similarity of content between documents, sources, authors, organizations, and countries. Unlike the approach based on co-citation analysis, which focuses on jointly cited documents, this research restricts its scope to the analysis of bibliographic coupling due to the use of a consolidated database, enabling the identification of occurrences where

In sum, this analysis reveals a dual dynamic in the field: on one hand, a strong focus on advanced technologies (AI, machine learning), and on the other, a rising concern for environmental impact and sustainable materials. The convergence of these two areas appears to be a major direction for future innovations in building energy efficiency.

Figure 15 highlights the structure of international collaborations in the field of energy efficiency through a mapping of bibliographic linkages between countries. Five major collaboration clusters have been identified. The United States, at the center of the red cluster, emerges as a major hub of scientific production, closely connected to countries such as Canada and Brazil. India leads the green cluster, which includes countries like Malaysia and Australia. France, for its part, forms a distinct purple cluster, illustrating its leadership within the European research space, alongside countries such as Italy (blue cluster) and Greece (yellow cluster).

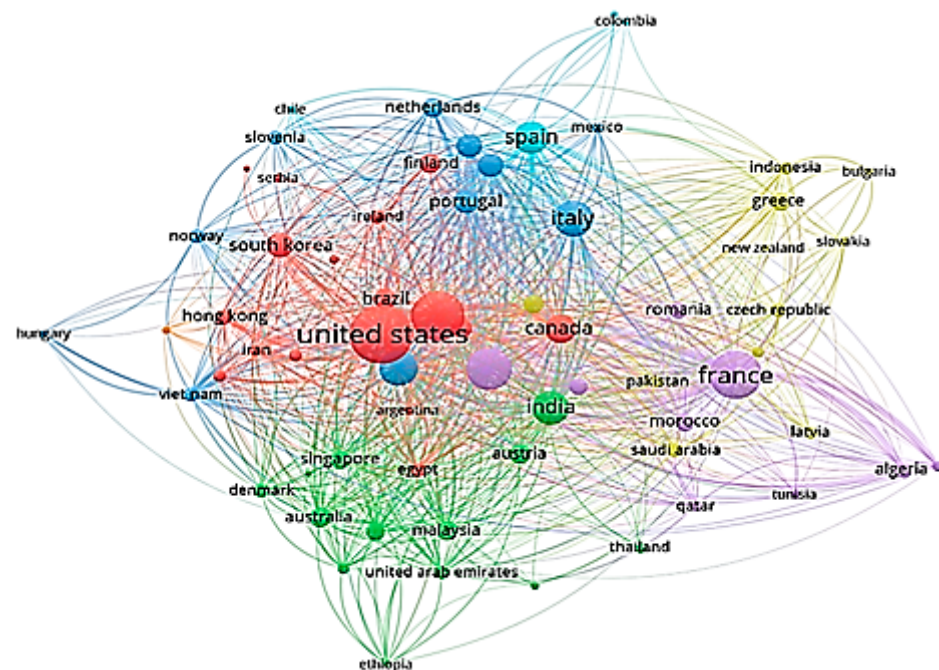


Figure 15. Bibliographic coupling analysis of countries.

Beyond a simple visualization, the analysis of network dynamics reveals significant implications for the development of the field. On the one hand, the concentration of exchanges around specific countries underlines existing imbalances in global scientific production, which may influence research directions, particularly regarding the integration of artificial intelligence and bio-based materials. On the other hand, the relative fragmentation between clusters suggests that the full potential for knowledge sharing and interdisciplinary innovation has yet to be realized.

In this context, strengthening international collaboration appears to be a strategic avenue to foster shared innovation. In particular, cooperation between technologically advanced countries (such as the USA or France) and emerging or developing nations (such as India or Brazil) could accelerate the diffusion of sustainable solutions adapted to a variety of climatic, economic, and regulatory contexts. These findings emphasize the importance of promoting a more collaborative scientific governance, especially through international initiatives focused on building energy efficiency.

The keyword co-occurrence analysis (Figure 16) provides a deeper insight into how research topics related to building energy efficiency are organized and interconnected. By grouping more than 68 terms into four main clusters, the key trends shaping this evolving field are highlighted. The green and red clusters contain the most frequently associated keywords, notably “energy efficiency”, “artificial intelligence”, and “bio-based materials”. Their frequent co-occurrence suggests that researchers are increasingly integrating digital

technologies with sustainable approaches to enhance building performance. This reflects a growing focus on solutions that combine innovation with environmental responsibility.

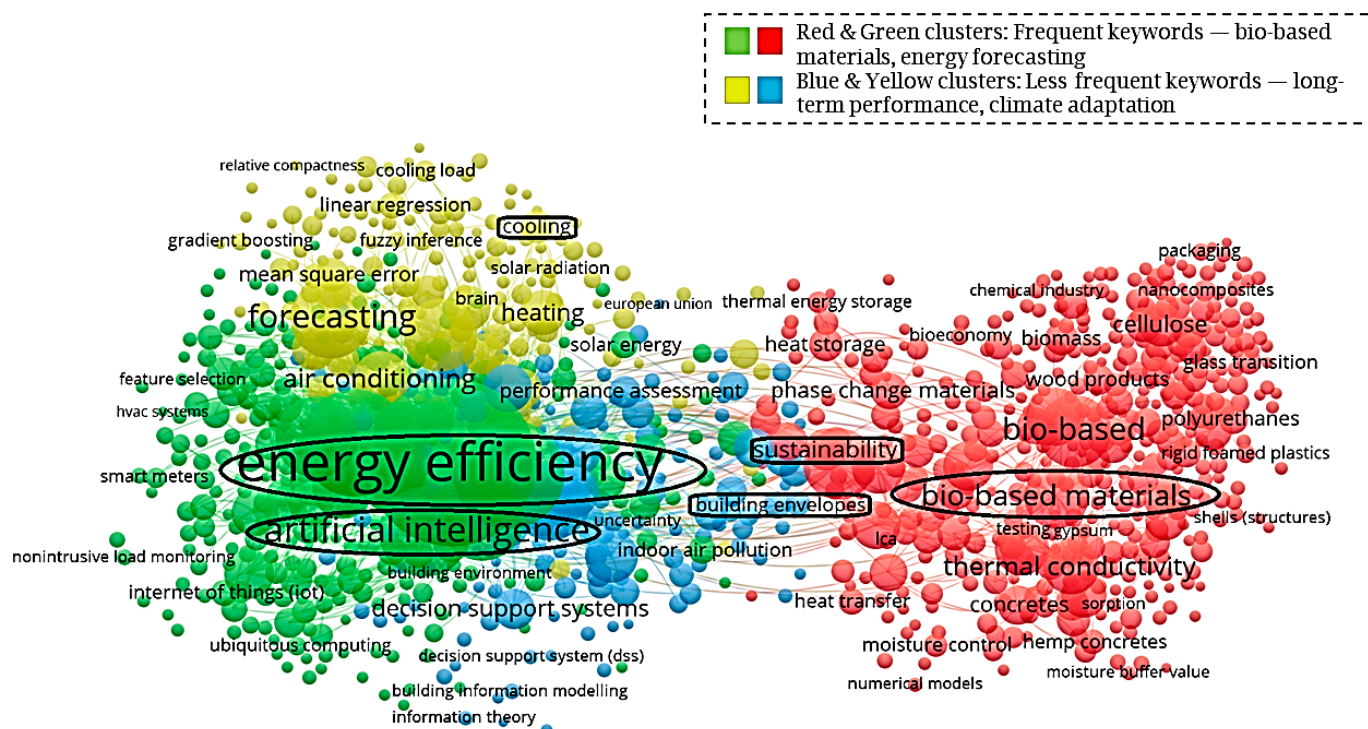


Figure 16. Co-occurrence of key terms.

In the field of AI, commonly used models include Artificial Neural Networks (ANNs), Random Forest, Support Vector Machines (SVMs), and XGBoost, which are widely applied for predicting energy consumption, thermal optimization, and climate scenario modeling in buildings. On the materials side, bio-based materials such as hempcrete, cellulose insulation, or mycelium-based composites offer competitive thermal performance, good durability, and moisture regulation, while having a reduced environmental impact compared to traditional construction materials.

Several recent studies concretely demonstrate the synergy between sustainable materials and artificial intelligence. For instance, some research integrates plastic and ceramic waste into mortars optimized using Artificial Neural Networks (ANNs), showing notable performance gains [88]. Others utilize bio-based phase-change materials (PCMs), whose thermal behavior is modeled using AI approaches such as LSTM, achieving exceptional prediction accuracy ($R^2 = 0.99$) [89]. Finally, some studies combine intelligent decision-making models (QPFRS, clustering, PROMETHEE) to select the best materials for sustainable urban projects. These examples confirm that AI can not only simulate or predict, but also guide sustainable choices in construction [90].

Furthermore, terms such as “foresight”, “sustainability”, and “thermal conductivity” reflect a broader interest in long-term performance, material behavior, and climate adaptation. Thus, this mapping not only highlights dominant themes but also points to new research directions, particularly the promising intersection between AI and eco-friendly materials. It emphasizes the importance of strengthened interdisciplinary collaboration to foster innovation and address current climate and energy challenges.

Figure 17 presents the results of the author co-citation network analysis, revealing five distinct clusters, each distinguished by a different color. The co-citation analysis sheds light on the collaborative dynamics and thematic focus areas within the field.

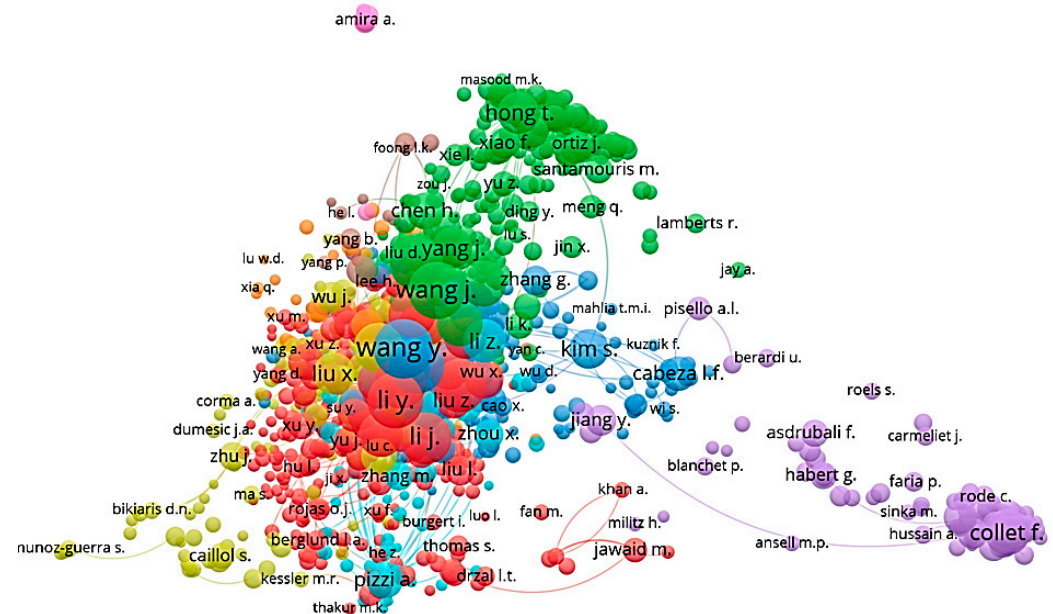


Figure 17. Co-citation network of authors.

The red cluster, dominated by authors such as “Li Y.” and “Liu Z.”, indicates a substantial interconnection among these researchers, suggesting a significant focus on energy-related studies. The prominence of these authors is reflected in the large size of their nodes, signifying their considerable influence and impact.

The green cluster, featuring prominent authors like “Hong T.” and “Ortiz J.”, exhibits close collaboration and frequent mutual citations, predominantly within the domains of artificial intelligence and emerging technologies. This cluster underscores the integration of AI advancements into energy efficiency research.

The blue cluster, led by researchers such as “Kim S.” and “Wu W.D.”, stands out as a specialized research area centered on the characterization of ecological and innovative materials. Despite its distinct focus, this cluster maintains connections to other research areas, reflecting interdisciplinary linkages.

The purple cluster, anchored by “Collet F.” and “Habert G.”, indicates strong collaboration, likely in the field of thermal insulation. This cluster highlights a network of researchers dedicated to advancing insulation technologies and sustainable building practices.

Finally, the yellow cluster, which includes authors such as “Caillol S.” and “Berglund L.A.”, appears to represent a less central subfield or a research area with fewer integrations into the broader network. The relatively smaller size and density of this cluster suggest that it may contribute niche insights or emerging research themes.

Thus, beyond a simple mapping of author relationships, the analysis of node size and connection strength reveals key centers of expertise and fundamental collaboration dynamics within the field. The most prominent authors are not merely influential figures; their central position in the network suggests active involvement in knowledge dissemination, the emergence of interdisciplinary topics—particularly related to artificial intelligence, advanced materials, and sustainability—and the structuring of scientific communities. These findings highlight the critical role of collaborative networks in driving innovation and promoting convergence between technological and ecological approaches in building energy efficiency research.

➤ Interpretative Discussion of Clustered Results

The clustering and co-occurrence analyses conducted in this study highlight key research dynamics in the field of building energy efficiency. They reveal a growing conver-

gence between artificial intelligence and bio-based materials, reflecting both technological and environmental priorities. At the same time, clusters of journals, countries, and authors demonstrate well-structured research communities focused on specific themes—such as sustainable materials, energy modeling, and environmental performance—but also suggest some fragmentation.

These findings emphasize the emergence of interdisciplinary approaches and the importance of strengthening international collaboration. The analysis provides a clearer understanding of the field's structure and helps guide future research toward better integration of technological and ecological knowledge.

4. Research Gap and Problem Statement

Despite the apparent robustness of the results, the bibliometric analysis presented raises several methodological and interpretative limitations that reduce the overall scope of the findings. The exclusive use of the Scopus database, while advantageous for its rich metadata and broad thematic coverage, introduces a representational bias by excluding other databases such as Web of Science or Dimensions, which may contain publications from complementary disciplines or under-represented regions. This choice notably affects the geographical and interdisciplinary diversity of the dataset, limiting the inclusion of contributions from emerging contexts. Similarly, the rigorous filtering process based on language, document type, and subject area, although methodologically consistent, tends to exclude hybrid or cross-disciplinary work, which is essential in a field that links architecture, engineering, sustainable materials, and social sciences. The keyword-based search strategy represents another limitation, as it may overlook relevant studies expressed differently. A semantic or similarity-based search approach would have allowed for more comprehensive coverage. Tools like VOSviewer and Bibliometrix offer structured mapping of collaboration and co-occurrence networks, but they remain focused on quantitative and descriptive data, lacking qualitative insight into citation dynamics or scientific collaboration.

In terms of results, the study highlights a steady increase in publication volume between 2011 and 2022, reflecting growing interest in topics related to sustainability and artificial intelligence. However, this growth is analyzed purely in quantitative terms, without consideration for the scientific quality or actual impact of the work, limiting interpretation. The analysis of sources shows a dominance of technical journals such as *Energy and Buildings* or *Applied Energy*, with fewer contributions from journals focused on sustainable architecture or design, pointing to a lack of interdisciplinarity. The geographical distribution of publications reveals a concentration in Global North countries, with Southern countries—despite their richness in bio-based resources and innovation potential—remaining under-represented. This inequality, linked to structural factors such as funding access, or language of publication, is not sufficiently addressed. Additionally, the analysis of institutional affiliations highlights the central role of universities and research centers but overlooks the contributions of the private sector or cross-sector laboratories, which are nevertheless key players in applied technological development. Lastly, while the keyword analysis is visually rich, it would benefit from a diachronic perspective to track the emergence and decline of research themes over time.

Overall, the proposed analysis provides a relevant informational foundation but remains improvable. A broader inclusion of diverse sources, better consideration of qualitative and interdisciplinary dynamics, and a deeper exploration of international collaboration and industrial application issues would enhance the depth and relevance of the conclusions.

5. Conclusions

This study aimed to examine the evolution of research on the integration of artificial intelligence (AI) and bio-based materials in optimizing the energy performance of buildings, through a bibliometric and textual analysis of scientific publications from the past twelve years.

To this end, data from the Scopus database were analyzed using two complementary tools: Biblioshiny, chosen for its user-friendly interface and advanced bibliometric indicators, and VOSviewer, employed for its ability to visualize co-occurrence and collaboration networks. This methodological approach enabled the mapping of publication dynamics, the identification of key contributors, and the visualization of the field's core thematic areas.

The results show a steady growth in the number of publications, particularly since 2014, with an average annual growth rate of 25.2%. This reflects a growing interest in energy optimization through sustainable and digital approaches. The main research trends revolve around keywords such as energy efficiency, artificial intelligence, machine learning, bio-based materials, and thermal insulation. France, China, and the United States rank among the most prolific countries, while researchers like H. Guillaume and M. Camille stand out in terms of productivity and impact. Leading journals such as *Energy and Buildings* and *Applied Energy* account for a significant portion of the output. In terms of scientific collaboration, the analysis reveals dynamic transnational networks, although these are predominantly concentrated in the Global North. In contrast, Global South countries—despite their wealth in bio-based resources—remain under-represented in this research area.

Although this bibliometric analysis provides a structured overview of current trends, certain methodological limitations should be acknowledged. The exclusive use of the Scopus database, while ensuring data consistency, may have limited geographic and disciplinary diversity. Furthermore, the primarily quantitative approach does not assess the scientific quality or practical applicability of the studies reviewed.

Nevertheless, these limitations open up relevant future research avenues. It would be beneficial to complement this analysis with more refined semantic or qualitative approaches, to include additional databases, and to pay greater attention to publications from under-represented regions. Strengthening the connection between theoretical research and practical implementation would also be valuable, for instance through case studies, the development of prototypes, or real-world testing.

Finally, this study offers clear practical implications for researchers, architects, urban planners, and policymakers. It provides a useful map of existing knowledge, highlights underexplored areas, and guides future efforts toward solutions that combine high energy performance, algorithmic intelligence, and environmental sustainability.

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