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RESEARCH ARTICLE

Internet of Things (IoT) and smart building technologies: A bibliometric analysis from the perspective of energy efficiency and sustainability

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ABSTRACT

Recent urban population growth and environmental degradation have made the integration of digital technologies into the construction sector inevitable, particularly for energy efficiency and sustainability. In this regard, IoT-enabled smart building systems offer innovative solutions to enhance building performance and promote sustainable urban development. This study explores how IoT-integrated smart building systems have evolved in scholarly literature, focusing on energy-efficient and sustainable practices while analyzing structural, thematic, and collaborative dynamics. The aim is to provide a comprehensive bibliometric analysis of the intersection between IoT and smart building technologies based on publications from 2012 to 2025, with the data for 2025 being partial and covering only the first four months of the year. To this end, 233 relevant documents retrieved from the Web of Science and Scopus databases were analyzed using the Bibliometrix package in R Studio, incorporating diverse bibliometric indicators.

Findings reveal a steady increase in academic output, though recent publications exhibit relatively low citation impact. China and Spain lead in publication volume, whereas the United Kingdom and Pakistan distinguish themselves through extensive international collaboration. Keyword and thematic analyses reveal a strong emphasis on digitalization, energy management, user experience, and the integration of artificial intelligence technologies. These results suggest a paradigmatic shift from traditional automation-based frameworks toward cognitive systems capable of learning from environmental data and making autonomous decisions.

Overall, the study highlights the increasing maturity of the research field and underscores its interdisciplinary structure and innovation potential. Future research is recommended to focus on enhancing research capacity in underrepresented regions and on the integration of human-centered design with AI-driven energy optimization systems.

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INTRODUCTION

The integration of Internet of Things (IoT) technology into smart building systems holds significant potential for achieving sustainability and energy efficiency goals. Automated and location-based energy control systems, implemented through the capabilities offered by IoT-based architectural frameworks, enable multi-scale energy proportionality, allowing for substantial energy savings in buildings [1]. These technologies effectively optimize building performance through real-time data monitoring, intelligent automation processes, and data-driven decision-making mechanisms, potentially reducing energy consumption by up to 30% and operational costs by up to 20% [2]. Furthermore, the integration of IoT systems with artificial intelligence (AI) algorithms enhances not only energy management but also indoor environmental quality and resource optimization, thereby further improving efficiency in these areas [3]. However, the widespread and effective implementation of these technologies still faces several structural barriers. High initial investment costs, concerns regarding data privacy and cybersecurity, and the need for qualified technical expertise to operate and maintain these systems are among the primary limitations [2, 4]. Despite these challenges, the integration of IoT technology into green building design and sustainable urban development processes is seen not only as a transformative innovation for the construction sector but also as a promising approach to achieving environmental sustainability goals [3, 4].

Recent research on IoT-enabled smart buildings for sustainability centers around several critical themes. Energy

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management and efficiency stand out as primary areas of focus, with IoT technologies playing a significant role in monitoring, automation, and the integration of renewable energy systems. The concept of smart cities and sustainable urban development also features prominently, highlighting the contribution of IoT in fostering environmentally responsible urban infrastructures [5, 6]. Additionally, the convergence of IoT with complementary technologies such as artificial intelligence, blockchain, and digital twins is emphasized for its potential to enhance sustainability efforts [7]. Efficient resource utilization, including water conservation and waste minimization, constitutes another major research trajectory [3, 6]. A noteworthy emerging topic is the sustainability of the IoT devices themselves, with recent studies proposing sustainable asset management strategies for these systems within buildings [7]. Furthermore, issues related to security, privacy, and data analytics are acknowledged as essential areas for future investigation [3, 5].

Scientometrics, a subfield of information science, applies bibliometric techniques to investigate the dissemination, evolution, and influence of scientific knowledge, thereby examining how ideas emerge, spread, and shape scholarly communities. Bibliometrics, broadly defined as the statistical analysis of scientific publications such as books and journal articles through indicators including citation frequencies and publication trends, constitutes a computer-assisted review method that systematically encompasses the full body of literature within a given domain to identify core studies, influential authors, and their interconnections [8]. It evaluates features such as authorship, keywords, methodologies, and citation patterns to derive analytical insights [9], while data mapping techniques enable the visualization of intellectual structures and the dynamic development of research areas [10]. Citation analysis further contributes to assessing the scientific quality and impact of publications. Distinct from meta-analysis, which focuses on effect sizes and inconsistencies in findings, bibliometric analysis quantifies the scope and evolution of research output, while sharing certain methodological features with content analysis in its consolidation of data under concepts and themes for interpretative purposes [11, 12]. By employing statistical and mathematical approaches, bibliometric studies provide valuable insights into the development of disciplines and support the evaluation of the performance of authors, institutions, and countries, as well as the intellectual evolution of research fields [13, 14, 15]. Widely adopted across disciplines, this methodological framework allows for the systematic categorization and interpretation of large datasets, thereby improving transparency and enabling more comprehensive scientific assessments [17].

This methodological framework is particularly appropriate for examining the convergence of IoT and smart building technologies. Given the inherently interdisciplinary nature of these domains, which encompass computer science, engineering, architecture, and sustainability conventional narrative reviews often prove insufficient to capture their intricate intellectual structures. Bibliometric analysis, by employing techniques such as citation mapping, keyword co-occurrence, and collaboration network analysis, facilitates the systematic visualization of these dynamics. Such an approach not only quantifies the existing body of knowledge but also elucidates the evolutionary trajectories of research themes including energy efficiency, digitalization, and cognitive systems. Consequently, bibliometric analysis provides critical insights into the paradigmatic transitions that are shaping the development of smart and energy-efficient buildings.

In recent years, bibliometric analysis has attracted increasing attention due to its ability to examine scientific literature in a systematic, transparent, and consistent manner. This method is based on the application of quantitative analysis techniques to bibliometric data [13]. With the support of advanced scientific databases, researchers are able to access large volumes of data. For instance, platforms such as Web of Science (WOS), Scopus, PubMed, and ProQuest offer data suitable for various research fields in different formats. In parallel with the content provided by these databases, various software tools have been developed to support bibliometric analysis processes. Tools such as R Studio Biblioshiny, VOSviewer, CiteSpace, and SciMAT are widely used for bibliometric and network-based analyses. The primary reasons researchers turn to such analytical methods are to reveal the general structure of the existing literature, identify research gaps, develop new research areas, and evaluate the positioning of academic contributions [8, 16].

This study aims to provide a comprehensive bibliometric analysis of the intersection between IoT technologies and smart building systems within the context of energy efficiency and sustainability. Against the backdrop of increasing global urbanization and environmental degradation, the integration of digital technologies into the built environment has become a critical research domain. Smart buildings, empowered by IoT-enabled systems, offer innovative solutions for optimizing energy performance, improving building management, and contributing to sustainable urban development. Within this framework, the present research seeks to map the intellectual structure, scientific evolution, and emerging thematic trends of the scholarly literature in this interdisciplinary field. The scope of the study encompasses peer-reviewed academic publications retrieved from the WoS and Scopus databases, covering the time span from 2012 to 2025. Search strategies were systematically constructed using well-defined keyword combinations to capture literature that simultaneously addresses smart building technologies, IoT-based systems, and energy or sustainability performance parameters. The analysis considered only documents written in English and categorized as either research or review articles, as English functions as the principal language of scholarly communication, thereby ensuring methodological rigor, cross-study comparability, and broad accessibility of the dataset. Following the elimination of duplicate records via Microsoft Excel, a refined dataset consisting of 233 unique publications was obtained. The resulting bibliographic data were analyzed using the Bibliometrix package developed for R Studio, which enabled the visualization and quantitative evaluation of the research field through multiple bibliometric indicators and mapping techniques.

The core objective of this research is to reveal the development dynamics of scientific production in the area where IoT and smart buildings intersect, with a focus on energy-efficient and sustainable building practices. Specifically, the study examines publication trends over time, identifies leading contributors in terms of authors, institutions, and countries, and explores collaboration patterns and co-authorship networks. Additionally, the study assesses the conceptual structure of the field through co-word and thematic mapping and determine the research fronts and intellectual roots of the discipline. Through Multiple Correspondence Analysis (MCA), thematic clusters and co-occurrence patterns are visualized, offering insight

into how key concepts evolve and interrelate within the literature. Moreover, the study is guided by a set of interrelated research questions that probe the characteristics, dynamics, and structure of the field. These questions include how the research output has evolved over time; which entities have been most influential in shaping the discourse; what collaboration structures exist across geographical lines; which themes have emerged as dominant or peripheral; and what intellectual trends can be observed in relation to IoT applications in sustainable and energy-efficient buildings. The analysis also aims to identify underexplored areas and research gaps that could guide future investigations. By elucidating these dimensions, the study not only synthesizes the current state of knowledge but also provides a strategic foundation for further academic inquiry and practical innovation in smart building design and energy management systems.

MATERIALS AND METHODS

In this study, a bibliometric analysis approach was employed to reveal the scientific development trends in the field of the IoT and smart building technologies within the context of energy efficiency and sustainability. The data for the study were derived from two internationally recognized and widely used academic databases: Web of Science (WoS) and Scopus. The data retrieval process was conducted through the implementation of comprehensive keyword strings reflecting the conceptual framework of the study. In the WoS database, the following query was used: TS=("Smart Building" OR "Smart Buildings" OR "Smart Building Technologies" OR "Building Automation Systems" OR "Building Management Systems") AND TS=("IoT" OR "Internet of Things") AND TS=("Energy Efficiency" OR "Building Performance Monitoring" OR "Sustainable Building Design"). Meanwhile, for Scopus, the search string was formulated as: TITLE-ABS-KEY("Smart Building" OR "Smart Buildings" OR "Smart Building Technologies" OR "Building Automation Systems" OR "Building Management Systems") AND TITLE-ABS-KEY("IoT" OR "Internet of Things") AND TITLE-ABS-KEY("Energy Efficiency" OR "Building Performance" OR "Sustainable Building Design"). In both databases, the search was limited to English-language publications, including both original research articles and review papers.

As a result of the search, 227 publications were identified from WoS and 465 from Scopus. These records were compared and merged using Microsoft Excel, during which 91 duplicate entries were identified and removed. From the initial 601 records, non-English articles and those outside the scope of research and review articles (n=344) were excluded, yielding a dataset of 257 unique publications. Furthermore, 24 publications were eliminated due to the unavailability of full-texts, abstracts, or keywords, resulting in a final dataset of 233 publications included in the bibliometric analysis (Figure 1). The analytical process was conducted using the Bibliometrix package integrated into the R Studio software environment. The analysis included various bibliometric indicators such as annual scientific production, citation trends, prolific countries and authors, thematic mapping, multiple correspondence analysis, keyword frequency and co-occurrence, and collaboration network analysis. Publications included in this research span the years 2012 to 2025, with records for 2025 being limited to the first quarter of the year. The findings, interpreted through visual representations such as graphs and diagrams, provide a comprehensive overview of current research trends in the field and offer insights into its future research potential. In order to ensure methodological rigor and transparency in the data selection process, a PRISMA-style flow diagram was employed to document and visually represent the stages of publication identification, screening, eligibility assessment, and final inclusion. The application of this diagrammatic protocol enhances the reproducibility of the study and contributes to the methodological robustness of the bibliometric framework.

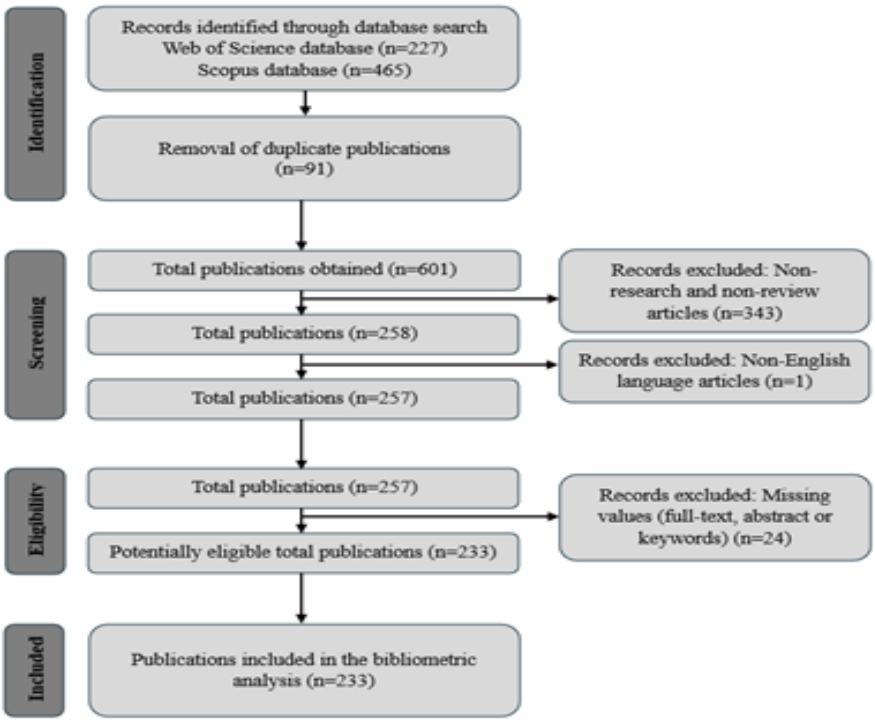

Figure 1. PRISMA flow diagram for data selection, identification, and filtering process

In order to ensure methodological rigor and transparency in the data selection process, a PRISMA flow diagram was employed to document and visually represent the stages of publication identification, screening, eligibility assessment, and final inclusion. The application of this diagrammatic protocol enhances the reproducibility of the study and contributes to the methodological robustness of the bibliometric framework (Figure 1).

Among the primary reasons for choosing the R programming language in this study are its ability to perform data analysis processes more quickly and efficiently, its powerful visualization tools that enhance data interpretability, and its wide range of functional features for analytical purposes. Additionally, the Biblioshiny platform, which is based on R, contributes to meeting the current demands of the analysis process through its user-friendly web interface and continuously updated structure. As an open-source and free software, R is widely preferred, particularly in academic settings. Another important factor influencing its selection, also demonstrated in this study, is its capacity to integrate data obtained from different databases, thereby enabling comprehensive and holistic analyses.

RESULTS AND DISCUSSION

This bibliometric analysis, covering the period from 2012 to 2025, was conducted based on a total of 233 publications, identifying 946 distinct contributing authors (Figure 1). The annual growth rate of publications was calculated as 18.41%, indicating a substantial and consistent increase in academic interest and productivity within the field. This upward trend underscores the growing significance and research momentum surrounding smart building technologies and IoT in the context of energy efficiency and sustainability. The analysis also revealed that 128 distinct sources were cited across the dataset. With an average publication age of 3.71 years, it is evident that literature is largely composed of recent studies, highlighting the contemporary relevance of the field. The average number of citations per publication stands at 28.68, suggesting a strong academic impact and frequent citation of the studies in this domain. Regarding authorship patterns, the data point to a strong emphasis on collaborative research. On average, each publication involved 4.52 authors, and the proportion of international co-authorship was measured at 24.03%. These figures reflect the highly interdisciplinary and transnational nature of the field. Conversely, the number of single-author publications was limited to only 11, indicating that individual scholarly contributions remain relatively rare in this research area (Figure 2).

In conclusion, the bibliometric indicators highlight a field characterized by increasing scholarly productivity, a robust culture of collaboration, and significant citation impact. These findings offer valuable insights for researchers engaged in smart building and IoT-related studies, particularly in terms of identifying collaboration opportunities and developing effective publication strategies.

As illustrated in Figure 3, which presents the scientific output by year, the number of publications began at relatively low levels in 2012 but has shown a consistent upward trend over time. Notably, there was a significant acceleration after 2018, culminating in a peak in 2023 and 2024, with 42 publications produced annually. This trend indicates a growing interest and increasing research activity in the relevant field in recent years. However, a noticeable decline is observed in 2025. This decrease may be attributed to the timing of data collection, which occurred early in the year. Therefore, it is likely that the data for 2025 is incomplete, as the year had not concluded at the time of analysis. Such temporary drops are commonly observed in similar bibliometric analyses when the full year's output has yet to be realized.

Overall, the general trend reveals a robust growth in scientific production, clearly indicating that the field is gaining increasing recognition within the scientific community and demonstrating a rising research potential.



Figure 2. General information about bibliometric analysis

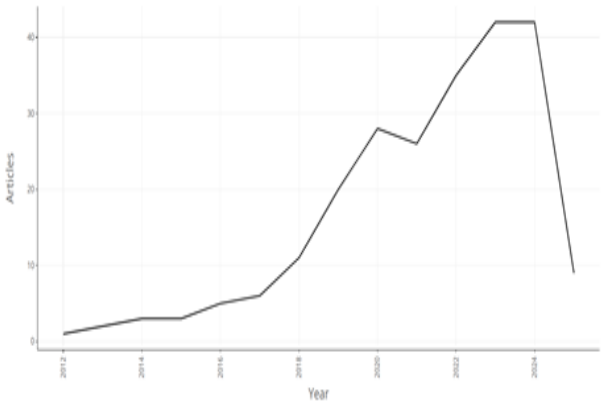

Figure 3. Annual scientific production

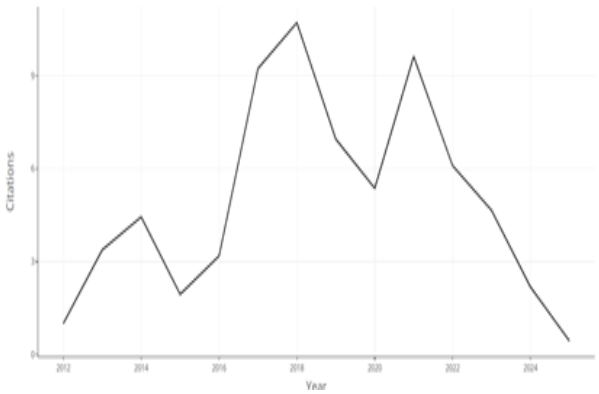

Figure 4. Annual scientific production

Figure 4 illustrates the variation in the average number of citations per publication across the years. In 2012, the average citation count was notably low; however, it followed a fluctuating trajectory and peaked in 2018 with a remarkable increase to 11 citations per publication. This surge indicates that the studies published during that period gained greater

visibility and were more effectively utilized within the academic community. Following 2019, a general downward trend in citation counts can be observed. Although there was a brief increase in 2021, this decline accelerated again from 2022 onward, with the average citation value approaching nearly zero by 2025. One of the primary reasons for this sharp drop is the incomplete nature of the 2025 data. Since citations accumulate over time, it is common for recently published studies not to have received a sufficient number of citations within the same year.

Moreover, despite the publication output reaching its highest levels in 2023 and 2024, the average citation counts remained relatively low during these years. This suggests that the works published during this period have yet to generate the expected citation impact. Such a phenomenon may be attributed not only to the inherently time-dependent nature of citations but also to the fact that a quantitative increase in output does not necessarily translate directly into qualitative influence. In addition, the persistently modest citation levels in recent years may also reflect a growing body of repetitive or incremental studies that build upon existing frameworks without introducing significant conceptual or methodological advances. This trend underscores the importance of pursuing innovative and interdisciplinary approaches in order to sustain the field's academic relevance and enhance its long-term impact.

Based on the data obtained in this study, China ranks first with 22 publications, and the majority of researchers from this country appear to engage predominantly in Single-Country Publications (SCP), indicating a strong tendency toward domestic collaboration (Figure 5). Similarly, Spain also exhibits a high number of publications; however, it maintains a relatively more balanced profile in terms of international collaboration. India ranks third in publication volume, yet the vast majority of its outputs are also classified as SCP, suggesting that academic production in these countries is largely driven by national research efforts.

In analyzing patterns of international collaboration, the rate of Multiple-Country Publications (MCP) was used as a key indicator. Several countries stand out in this regard. For example, the United Kingdom demonstrates a high MCP rate of 57.1%, while Spain leads quantitatively with 7 MCP publications. These findings suggest that the research ecosystems in these countries are highly integrated with global networks and that collaborative efforts play a significant role in shaping their scientific output. Notably, 75% of Pakistan's contributions fall under the MCP category, indicating a publishing strategy that is heavily reliant on participation in international projects. Some countries, however, demonstrate a more balanced structure in terms of collaboration. For instance, Greece and Brazil have achieved a noteworthy equilibrium between SCP and MCP outputs, with approximately half of their publications involving international collaboration. This balance suggests that these countries possess robust national research infrastructures while also maintaining active engagement with the global scientific community. Such a structure may play a crucial role in supporting long-term academic productivity and sustainability. In contrast, countries such as France, Poland, and Finland follow a publication strategy that is predominantly SCP-based. The tendency of researchers in these nations to publish primarily within national frameworks may be interpreted in multiple ways. On one hand, it reflects a sufficient level of national research capacity; on the other, it may indicate a limited degree of integration with international research networks. Therefore, it would be strategically beneficial for such profiles to develop mechanisms that foster greater international collaboration, potentially enhancing their scientific visibility and impact.

In summary, while countries leading in publication volume gain prominence through their quantitative output, others distinguish themselves through higher levels of international collaboration. It is a well-established fact in the literature that publications resulting from international partnerships tend to receive more citations. Accordingly, collaborations with countries that have high MCP rates offer the potential not only to increase the number of publications but also to enhance their visibility and scholarly impact. Thus, analyzing both the quantitative and collaborative dimensions of publication patterns provides valuable insights for strategic research planning in the field.

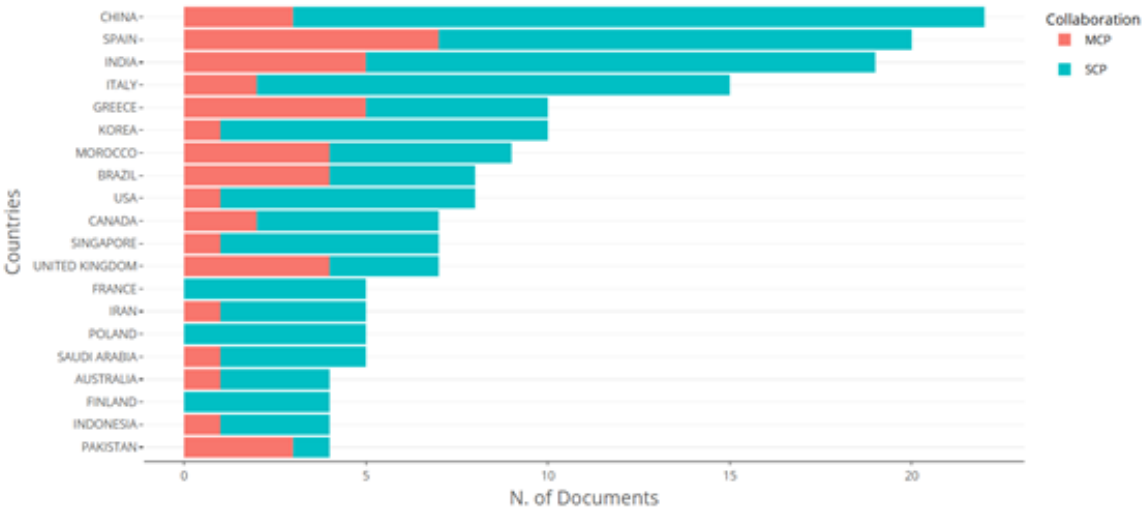

Figure 5. Corresponding author's countries

Figure 6 presents the distribution of publication volume by country within the analyzed literature. China emerges as the leading contributor with a total of 62 publications. This scientific dominance is closely associated with the country's recent investments in R&D, the strengthening of university-industry collaborations, and the implementation of incentive-based publication policies. China is followed by Spain (54), Italy (48), India (42), and the United States (42), all of which possess robust research infrastructures and have demonstrated both quantitative and qualitative strength in the field.

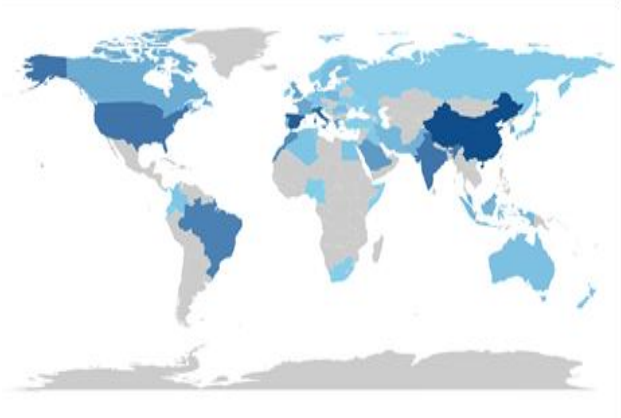

Figure 6. Corresponding author's countries

Countries highlighted in darker blue on the map represent those with higher contributions to literature. Most of these countries not only rank within the top ten in terms of publication volume but as previously discussed, some also demonstrate high levels of international collaboration. For example, while India and China show strong publication numbers, their outputs are predominantly based on domestic collaboration. In contrast, countries like Morocco and Pakistan rely heavily on international partnerships for their scientific production. The United States (42 publications) and Brazil (36 publications) are particularly notable among countries in the Americas. The U.S.'s contribution can be attributed to its well-established research institutions and global collaborative networks, whereas Brazil's rising presence is associated with its growing focus on topics such as environmental sustainability and the use of natural resources. European countries, in general, make widespread but balanced contributions to literature. Nations such as Italy, Spain, the United Kingdom, France, and Greece are active in both single-country and multi-country publications. This trend may be explained by the European Union's Horizon and similar framework programs that foster international research collaboration. In the Middle East and North Africa (MENA) region, countries such as Morocco (30 publications), Saudi Arabia (24), Iran (11), and Qatar (11) demonstrate significant levels of scientific output. In most of these cases, publications are predominantly the result of international collaborations, suggesting that local research efforts are often supported by external funding sources. Contributions from this region frequently center around themes such as environmental concerns, climate change mitigation, energy efficiency, and sustainable building systems. In contrast, the African continent is represented with lighter tones on the map, indicating a lower level of scientific production. Although countries like South Africa, Nigeria, Cameroon, and Egypt contribute to some extent, the overall publication intensity across the continent remains low. This situation may be attributed to infrastructural limitations, restricted funding opportunities, and imbalances in research capacity.

Finally, it is noteworthy that Türkiye appears in the analysis with only one publication. The country's limited visibility in this field may stem from a lack of academic interest in the specific topic or from the dispersion of relevant research across different thematic domains. This observation highlights the need to strengthen national research capacity in areas such as sustainability, digitalization, and smart architectural applications.

Word cloud analysis is a key bibliometric method that visually emphasizes recurring keywords based on their frequency across the analyzed literature. In Figure 7, the terms shown in the largest font sizes represent the most frequently occurring and thematically central concepts. Within this context, "internet" (33 occurrences) stands out as the most prominent keyword, underscoring a strong research focus on the integration of digitalization and information technologies into building systems. The term "smart buildings" (18 occurrences) highlights the importance of digitalization and automation in the built environment. This concept is closely related to other frequently used keywords such as "IoT" "management" and "systems". The terms "IoT" (16) and "things" (14) specifically reflect the transformation of buildings into intelligent systems through sensor networks, connected devices, and real-time data exchange. The recurrence of keywords such as "design" (16) and "management" (16) indicates that the technological transformation of building systems is not limited to technical dimensions but also encompasses strategic, functional, and user-centered aspects. These terms emphasize the need to reconfigure the built environment in both aesthetic and functional terms. In relation to sustainability, terms like "energy" (14), "energy efficiency" (12), and "energy consumption" (3) signal a strong emphasis on energy-related themes such as efficiency, resource optimization, and environmental performance. These findings reveal that energy considerations form a significant part of the discourse surrounding smart building research. Other frequently occurring terms include "systems" (15), "consumption" (14), "thermal comfort" (9), "prediction" (8), "big data" (7), and "performance" (7). These keywords suggest a research emphasis on data analytics, occupant comfort, and predictive performance modeling, core elements in the development of intelligent building systems. The presence of terms like "big data" and "prediction" also highlights the growing importance of AI-supported decision-making mechanisms. In addition to these high-frequency terms, several lower-frequency but thematically significant keywords contribute to the diversity of the research landscape. Terms such as "BIM" (3), "architecture" (5), "simulation" (5), "optimization" (5), and "artificial intelligence" (4) underscore the critical role of digital design, information modeling, and advanced simulation techniques in enhancing building performance.

In conclusion, the word cloud visualization reveals that digitalization, energy efficiency, management processes, and user experience are central themes in the current literature. These focal areas are largely addressed through data-driven technologies (e.g., IoT, artificial intelligence, big data) and system-oriented approaches (e.g., smart systems, modeling, control), which collectively define the evolving paradigm of intelligent building research.



Figure 7. WordCloud analysis

Keyword network analysis provides critical insights into thematic concentrations, interdisciplinary interactions, and conceptual focal points within a research domain. In the present analysis, the terms "internet", "technologies" and "things" occupy central positions in the network, underscoring the digital and interconnected nature of the research field. This suggests that IoT-based infrastructures play a pivotal role in shaping scholarly discourse in this area.

Branching out from this core are several distinct thematic clusters, each representing specific research directions. The blue cluster, which includes keywords such as "architecture", "generation", "automation", "edge" and "fog" reflects studies focused on optimizing computing resources through distributed architectures like edge and fog computing. This cluster is typically associated with investigations into data processing infrastructure and computational efficiency. The red cluster encompasses terms like "smart buildings", "consumption", "occupancy", "demand response", "framework" and "construction". This grouping reflects a strong focus on building automation systems, energy management strategies, and practical implementations of smart building technologies. It highlights the applied dimensions of smart infrastructure in the built environment. The green cluster, featuring terms such as "IoT", "design", "energy-efficiency", "artificial intelligence" and "thermal comfort" represents research centered on user comfort, operational efficiency, and AI-driven decision support systems. These studies integrate technological innovation with human-centered design principles and sustainable outcomes. The purple cluster, which includes "performance", "optimization" and "predictive control" is primarily oriented towards engineering solutions aimed at enhancing energy consumption efficiency and optimizing system responses through model-based predictive control strategies. This group reflects a data-intensive and algorithmic approach to energy performance management.

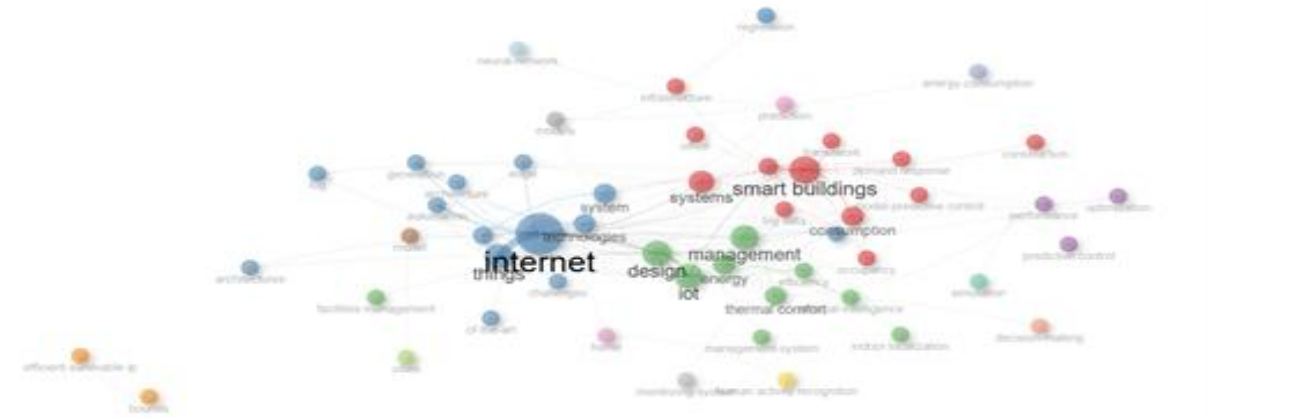

Figure 8. Keyword co-occurrence network

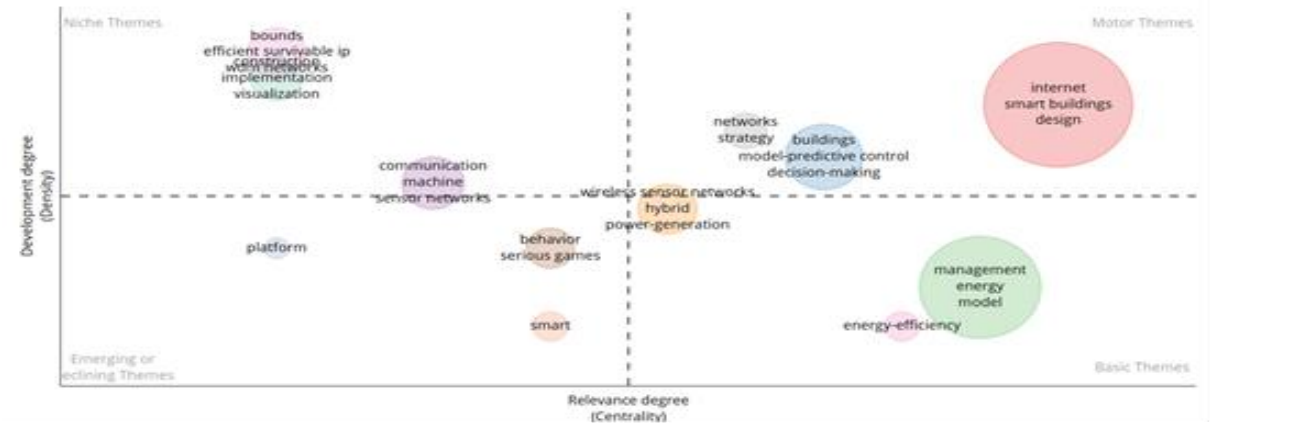

Figure 9. Thematic Map Analysis

The strong interconnections among these clusters point to a robust interdisciplinary integration and the adoption of holistic system approaches within the research field. The analysis indicates that the evolution of the domain is not only thematic but also structural, as it reveals increasingly complex and layered collaborations between concepts, technologies, and disciplines. These insights underscore the growing maturity and depth of the field, as reflected in Figure 8.

Thematic maps are two-dimensional visual tools that position key concepts within a given body of literature based on their level of development and relational centrality to other themes. Figure 9 offers a comprehensive analytical perspective by distinguishing between mature and central themes, emerging trends with potential for growth, isolated yet original research focuses, and declining or marginal topics within the field.

The X-axis represents the centrality or relevance degree of themes, which reflects their structural importance and interconnection with other themes. A movement towards the right on this axis indicates that the theme has become structurally integrated and forms a core part of the research domain. Conversely, the Y-axis corresponds to the density or development degree of the themes, signifying their internal maturity. A higher vertical position on this axis indicates a well-developed and methodologically coherent thematic structure. This dual-dimensional evaluation enables not only the identification of popular or central themes but also an understanding of which themes are conceptually mature or in need of further development.

The thematic map generated in this study categorizes the key concepts in the literature into four main quadrants based on their centrality and density:

- Motor Themes (Upper-right quadrant):

Themes such as “internet”, “smart buildings” and “design” are positioned in the upper-right quadrant, representing high development and high centrality. These are well-structured and strongly interconnected themes that constitute the theoretical and practical backbone of the field. Notably, the “internet” theme has a high Callon Centrality score of 7.706, indicating its strong relational network with other concepts and its central role in the literature.

- Basic Themes (Lower-right quadrant):

Themes like “management”, “energy”, “model,” and “energy-efficiency” fall under this category. Despite their high centrality, demonstrating foundational importance in the field, they exhibit relatively low-density scores, pointing to a need for deeper methodological refinement and theoretical expansion. For instance, the “management” cluster has a Callon Centrality value of 5.946 but a density score of only 45.128, suggesting that while management-related approaches are widely discussed, they have not yet achieved sufficient interdisciplinary integration or methodological sophistication.

- Niche Themes (Upper-left quadrant):

Themes such as “bounds”, “efficient survivable IP”, “construction”, “WOM networks”, “implementation” and “visualization” are placed in this quadrant. These themes are methodologically developed within specific research niches but have limited interaction with other themes, indicating a secondary role in shaping the broader literature. Their depth is often discipline-specific but lacks wider academic integration.

- Emerging or Declining Themes (Lower-left quadrant):

Themes like “platform”, “smart”, “behavior,” and “serious games” are located here, signifying either emerging areas of inquiry that have not yet fully matured or declining themes that are losing relevance in contemporary literature. Further analysis would be needed to determine the trajectory of these themes.

Overall, this thematic map clearly illustrates dominant research trends, the degree of methodological development, and potential areas for future exploration. The size of the bubbles represents the frequency and significance of the themes within the literature. Notably, “smart buildings” and “internet” appear as the most frequently studied and cited concepts, highlighting their prominence in the field.

In this study, a Multiple Correspondence Analysis (MCA) was conducted using the Bibliometrix package to uncover relationships among keywords. This analysis positions frequently co-occurring concepts from the publications on a two-dimensional plane, facilitating the identification of thematic clusters. The axes of the graph, Dim 1 (23.16%) and Dim 2 (16.85%), represent the principal components that explain 23.16% and 16.85% of the total variance, respectively. Together, these two dimensions account for approximately 40.01% of the total conceptual variation within the dataset. The visualization is based on the proximity of concepts, where terms frequently mentioned together in similar thematic contexts are placed closer on the plot. Conversely, more distant terms are indicative of distinct conceptual structures within the literature (Figure 10).

The MCA results reveal four major conceptual clusters that structure the prominent themes in the literature:

- Cluster A (Top-left quadrant):

This group highlights themes associated with renewable energy and digitalization, comprising keywords such as “renewable energy”, “digitalization”, “energy management”, “efficiency” and “energy”. It represents studies focused on improving the efficiency of energy systems through digital technologies (Fig 10).

- Cluster B (Top-right quadrant):

This cluster centers around smart cities and artificial intelligence-based systems, containing terms like “smart city”, “smart buildings”, “artificial intelligence”, “deep learning”, “transfer learning”, “sensor”, “systems”, “clustering” and “user-centric”. The keywords emphasize the development of AI-driven urban systems and user-oriented smart building technologies (Fig 10).

- Cluster C (Bottom-right quadrant):

This thematic group focuses on the IoT and smart home systems, including terms such as “internet of things..iot”, “wireless sensor networks”, “smart homes”, “things” and “internet”. It predominantly reflects literature on IoT-based home automation systems (Fig 10).

- Cluster D (Bottom-left quadrant):

This cluster includes concepts such as “building automation”, “internet” and “edge computing” representing approaches related to local data processing technologies and the enhancement of energy performance (Figure 10).

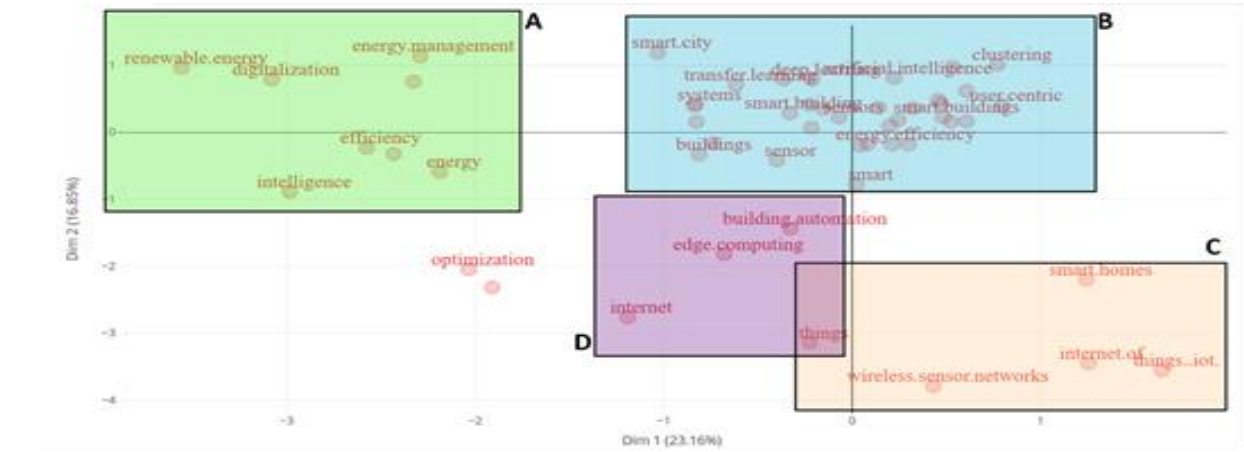

Figure 10. Conceptual map (Multiple Correspondence Analysis-MCA)

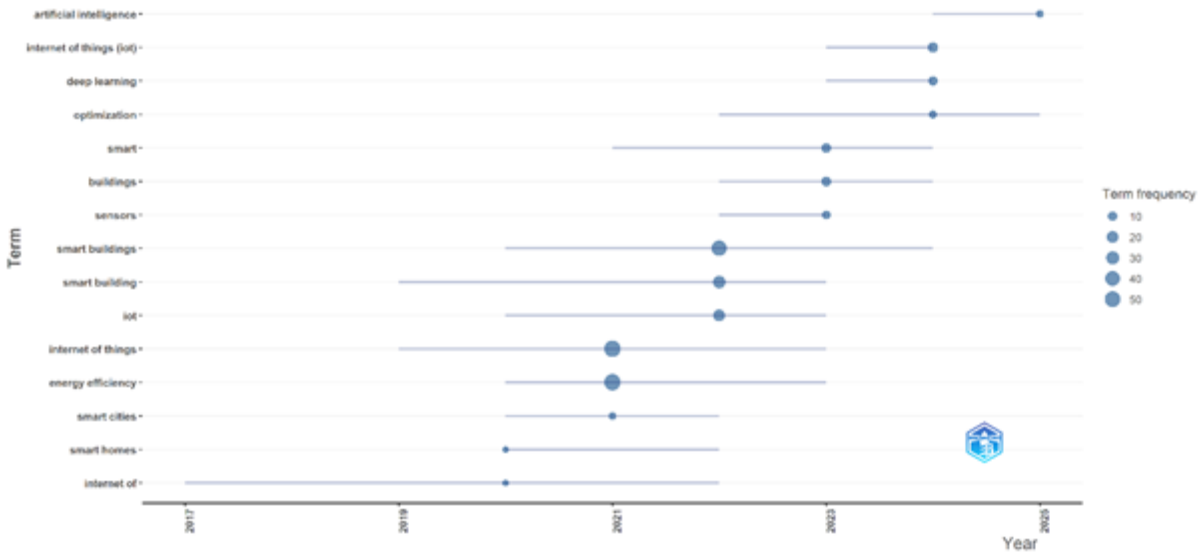

Figure 11. Trend data based on time series analysis

In addition to the defined clusters, several keywords occupy intermediate or peripheral positions on the map. These terms, situated either at the intersections of multiple clusters or in more isolated locations, are multifaceted and can be associated with both artificial intelligence and computing technologies as well as architecture and sustainability literature. This analysis offers insights into the thematic density, clustering patterns, and interdisciplinary connections within the research domain. Furthermore, it serves as a valuable tool for identifying potential research gaps that may guide future academic inquiry.

Trend data derived from time-series analysis reveals the evolutionary trajectory of research domains centered on smart buildings and energy efficiency. According to both graphical and tabular evidence, the literature between 2017 and 2020 predominantly emphasized core concepts such as “internet of things”, “smart homes” and “energy efficiency”. These terms signify the foundational phase in which digital infrastructures began to integrate with smart building technologies, marking the initial adaptation of IoT systems within the built environment. The period from 2021 to 2023 reflects a noticeable expansion in scope, with increasing prevalence of terms such as “smart buildings”, “buildings”, “sensors”, “smart cities” and “IoT”. During this stage, the smart building paradigm evolved beyond the scale of individual structures to encompass holistic urban planning approaches. In particular, the integration of IoT-supported infrastructures with energy efficiency and building performance measurement systems indicates the emergence of more comprehensive and interconnected frameworks. This phase underscores a transition toward systemic thinking in the management of energy performance across multiple spatial scales. In the most recent period, encompassing 2023 to 2025, a marked shift in research focus becomes apparent, as advanced technological concepts like “artificial intelligence”, “deep learning” and “optimization” gain significant prominence (Figure 11). The rising prominence of these terms suggests a reconceptualization of building management systems, not merely as automated, reactive platforms, but as intelligent, adaptive systems capable of learning and self-optimization. Particularly in studies published after 2024, there is growing emphasis on AI-driven energy modeling algorithms and optimization techniques as central components of sustainable building operations.

Considering these developments, the concept of sustainable smart buildings is being redefined: they are no longer viewed solely as automation-based systems but as cognitive entities capable of analyzing environmental data, learning from it, and making autonomous decisions accordingly. This transition indicates a paradigmatic shift from reactive to proactive

management approaches, offering not only enhanced energy performance but also the simultaneous improvement of occupant comfort and environmental sustainability.

CONCLUSION

This bibliometric analysis has offered a comprehensive overview of the intellectual landscape surrounding the integration of IoT technologies and smart building systems in the context of energy efficiency and sustainability. The results indicate a research domain that is not only growing rapidly in terms of publication output but also evolving structurally and thematically through interdisciplinary convergence and technological complexity. While the increase in publication volume, especially in 2023 and 2024, reflects the heightened global interest in this field, relatively low citation averages in recent years underscore the temporal lag in academic impact and suggest the need for deeper qualitative engagement.

The analysis revealed a dual-layered dynamic in global research activity: countries such as China and Spain lead quantitatively due to robust research infrastructures and strategic national policies, whereas others gain scholarly visibility through high levels of international collaboration. This highlights the critical role of transnational partnerships in amplifying both research quality and citation performance. For underrepresented countries such as Türkiye, the findings point to strategic opportunities for growth through targeted investments in interdisciplinary research and international cooperation. The thematic clustering and keyword analyses emphasize that smart building research is transitioning from traditional automation frameworks to more cognitive, data-driven paradigms. Core themes such as digitalization, energy optimization, and user-centered management are increasingly being addressed through advanced technologies including artificial intelligence, big data analytics, and integrated control systems. This shift signifies a move toward proactive, adaptive, and environmentally responsive building ecosystems capable of autonomous decision-making and continuous learning.

Furthermore, the strong conceptual interlinkages and methodological diversity observed across thematic clusters affirm the field's maturity and its potential for sustained innovation. The mapping of research trends and identification of peripheral yet emerging themes provide a valuable foundation for guiding future inquiries, particularly in the integration of architectural theory, computational design, and environmental science. In sum, this study not only charts the scientific evolution of smart building and IoT-related research but also provides actionable insights for scholars, practitioners, and policymakers aiming to foster energy-efficient and sustainable urban futures through digital innovation. For architects and engineers, the findings underscore the necessity of embracing data-driven design methodologies and systematically integrating advanced digital technologies into building systems to optimize energy performance and operational efficiency. For policymakers, the results point to the strategic importance of fostering interdisciplinary collaboration and prioritizing investments in digital infrastructure and governance frameworks as essential levers for advancing sustainable urban transformation.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

USE OF AI FOR WRITING ASSISTANCE

The authors declare that the generative AI tool OpenAI ChatGPT (March 2025 version) was used to enhance readability, improve language clarity and grammar, format the text, and assist in translating the manuscript into English. All content was thoroughly reviewed and approved by the authors, who assume full responsibility for the final version of the work.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1]. J. Pan, R. Jain, S. Paul, T. Vu, A. Saifullah, and M. Sha, "An Internet of Things framework for smart energy in buildings: Designs, prototype, and experiments," *IEEE Internet of Things Journal*, Vol. 2 (6), pp. 527-537, 2015.

[2]. M. Poyyamozhi, B. Murugesan, N. Rajamanickam, M. Shorfuzzaman, and Y. Aboelmagd, "IoT—A Promising Solution to Energy Management in Smart Buildings: A Systematic Review, Applications, Barriers, and Future Scope," *Buildings*, Vol. 14 (11), pp. 3446, 2024.

[3]. Y. Wang and L. Liu, "Research on sustainable green building space design model integrating IoT technology," *PLOS ONE*, Vol. 19 (4), 2024.

[4]. A. A. Umoh, C. N. Nwasike, O. A. Tula, O. O. Adekoya, and J. O. Gidiagba, "A review of smart green building technologies: Investigating the integration and impact of AI and IoT in sustainable building designs," *Computer Science & IT Research Journal*, Vol. 5 (1), pp. 141-165, 2024.

[5]. A. Valencia-Arias, J. Ramírez Dávila, W. Londoño-Celis, L. Palacios-Moya, J. L. Hernández, E. Agudelo Ceballos, and H. Uribe-Bedoya, "Research Trends in the Use of the Internet of Things in Sustainability Practices: A Systematic Review," *Sustainability*, Vol. 16 (7), pp. 2663, 2024.

[6]. K. Gupta, A. K. Kar, and M. P. Gupta, "Internet of Things and Sustainability: A Literature Review," *in Proc. Int. Conf. on Transfer, Diffusion and Adoption of Next-Generation Digital Technologies (TDIT 2023)*, IFIP Advances in Information and Communication Technology, Vol. (699), pp. 1-15, 2024.

[7]. C. Okolo, N. Schmieder, M. Hellwig, and E. Rigger, "Towards a digital twin for sustainable asset management of IoT devices in smart buildings," *in Proc. 2024 IEEE International Conference on Engineering, Technology, and Innovation (ICE/ITMC)*, pp. 1-9, 2024.

[8]. N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *Journal of Business Research*, Vol. 133, pp. 285–296, 2021.

[9]. L. Mora, R. Bolici, and M. Deakin, "The first two decades of smart-city research: A bibliometric analysis," *Journal of Urban Technology*, Vol. 24 (1), pp. 3-27, 2017.

[10]. İ. Özen Çınar, "Bibliometric analysis of breast cancer research in the period 2009-2018," *International Journal of Nursing Practice*, Vol. 26 (3), 2020.

[11]. B. Godin, "On the origins of bibliometrics," *Scientometrics*, Vol. 68 (1), pp. 109-133, 2006.

[12]. O. Öztürk and G. Gürler. Bir literatür incelemesi aracı olarak bibliyometrik analiz. Nobel, Ankara, Türkiye. 2021.

[13]. Y. Ding, G. G. Chowdhury, and S. Foo, "Bibliometric cartography of information retrieval research by using co-word analysis," *Information Processing & Management*, Vol. 37 (6), pp. 817-842, 2001.

[14]. A. Pritchard, "Statistical bibliography or bibliometrics?," *Journal of Documentation*, Vol. 25 (4), pp. 348-349, 1969.

[15]. E. Ukşul, "Evaluation of scientific publications made in measurement and evaluation in education field in Turkey with social network analysis: A bibliometric study," M.S. thesis, Inst. Educ. Sci., Akdeniz Univ., Antalya, Türkiye, 2016.

[16]. S. Yılmaz, U. Acar, M. F. Akbaba, T. Akbulut, C. Akgün, O. Akın, B. Akpınar, *et al.*, "The scientific outputs of earthquakes in Türkiye: A bibliometric analysis," *Sigma J. Eng. Nat. Sci.*, Vol. 43 (2), pp. 513-522, 2025.

[17]. M. Yıldız and T. Karakuş Yılmaz, "Bibliometric Analysis in Scientific Research Using R: A Review of Scopus and Web of Science Databases," *Journal of Data Applications*, (2), pp. 31-46, 2023.