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GLOBAL RESEARCH TRENDS ON GREEN TECHNOLOGY IN THE CONSTRUCTION AND MANUFACTURING INDUSTRIES: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

Green technology plays a pivotal role in promoting sustainability within the construction and manufacturing sectors. Growing global awareness of carbon emission reduction has accelerated research efforts to develop low impact and resource efficient solutions. This study applies a bibliometric approach to examine global research trends, thematic evolution, and

the scientific impact of green technology. A total of 227 publications indexed in the Web of Science database were analysed using RStudio and VOSviewer. The results reveal three developmental phases; the Early Growth Phase (2009–2013), the Major Growth Phase (2014–2018), and the Rapid Development Phase (2019–2025), with the latter showing a sharp increase in publication output, particularly in East and Southeast Asia. Dominant research themes include performance optimization, energy efficiency, environmental impact assessment, and resource management. Civil engineering, environmental sciences, and multidisciplinary domains contribute substantially to this knowledge base. Thematic and keyword analyses indicate a future research direction emphasizing regulatory policy transformation, green product innovation, life cycle assessment, and smart, energy-efficient systems, underscoring Asia's emerging leadership in sustainable industrial innovation.

Keywords: *Green technology, Construction industry, Manufacturing industry, Bibliometric analysis, Future topic trends.*

INTRODUCTION

The construction and manufacturing industries are among the most resource intensive sectors globally, exerting significant and long-term environmental impacts (Bonde & Vyas, 2023; Onat & Kucukvar, 2020; Panagiotopoulou et al., 2022). These industries consume large quantities of raw materials, energy, and water while generating considerable waste and greenhouse gas emissions (Josa & Borrion, 2024; Maoeng et al., 2018). In response to accelerating global climate change, environmental degradation, and the challenges of sustainable development, there is an increasing emphasis on transitioning to more environmentally friendly practices. This transition primarily depends on the advancement and widespread adoption of green technologies that minimize environmental footprints and enhance overall resource efficiency (Auktor, 2020; Fuchs, 2024). Green technology refers to the design, application, and continuous improvement of processes, equipment, and systems aimed at reducing environmental impacts and promoting sustainability across industrial operations. These include innovations such as renewable energy systems, low emission construction materials, waste recovery technologies, and circular manufacturing systems

(Banerjee & Palit, 2024; Mohammed, 2021).

The construction industry plays a vital role in the economic development of a country (Masyhur et al., 2024). It is responsible for building essential infrastructure such as residential, industrial, and commercial buildings, as well as roads and bridges, structures that possess substantial carbon footprints and have direct interactions with natural resources (Alsharef et al., 2024). Meanwhile, the manufacturing industry involves the transformation of diverse raw materials into finished goods through mechanical, physical, and chemical processes (Shastri et al., 2021), requiring significant energy input to achieve sustainable industrial development (Chowdhury et al., 2018; Estaji et al., 2024). Consequently, both sectors are increasingly prioritizing the integration of environmentally friendly technologies and innovative systems that enhance overall production efficiency while reducing pollution and waste generation. This paradigm shift closely aligns with the objectives of the United Nations Sustainable Development Goals (SDGs), particularly Goal 9 (Industry, Innovation, and Infrastructure), Goal 11 (Sustainable Cities and Communities), and Goal 13 (Climate Action) (Sachs et al., 2024).

In recent years, green technology in the construction and manufacturing sectors has emerged as a significant area of academic inquiry and policy development. Numerous studies have examined the role of technological innovation in improving environmental performance, the effectiveness of sustainable technologies in reducing emissions, and the economic implications of industrial transformation toward sustainability. However, despite the growing body of literature, there remains a lack of comprehensive insight into how this field has evolved over time on a global scale, what patterns of collaboration exist, and which themes have been most influential. To address this gap, this study employs bibliometric analysis to map the global research landscape on green technologies within the context of the construction and manufacturing industries. Bibliometric analysis is a robust method for quantitatively assessing scientific literature, enabling researchers to uncover publication trends, authorship patterns, influential works, and emerging research frontiers (Dinh et al., 2023). By systematically analysing large datasets from scientific databases such as Web of Science, bibliometrics provides a macroscopic view of how knowledge in a specific domain is structured and how it has evolved over time. This research aims to offer both scientific and practical insights into how green technologies

are being adopted and developed in industrial sectors. It contributes to the strategic discourse on sustainable industrial transformation and offers a roadmap for future research that bridges technological advancement with environmental sustainability.

METHODS

This study employed a comprehensive bibliometric analysis using the Web of Science (WoS) Core Collection database to map global research trends, collaboration networks, and thematic structures related to green technology in the construction and manufacturing industries. Bibliometric analysis is a robust quantitative approach used to evaluate the intellectual structure, development patterns, and research dynamics of a scientific field through its published literature (Ball, 2021). In this study, the analysis followed four sequential stages, as illustrated in Figure 1, encompassing data collection, preprocessing, visualization, and interpretation (Prayogo et al., 2025; Fitria et al., 2023; Azizah et al., 2025). The data collection stage involved defining the search strategy and retrieving bibliographic records using a Boolean operator-based query: ("Construction Industry" OR "Manufacturing Industry" OR "Building Industry" OR "Civil Construction" OR "Built Environment") AND ("Green Technology"). This query was applied to article titles, abstracts, and author keywords to ensure comprehensive coverage of publications addressing technological innovation and sustainability practices in both sectors. The search covered the period from January 2009 to June 2025, with the latter clearly identified as year to date (partial) to avoid misinterpretation of incomplete data and maintain analytical transparency. Only journal articles, conference proceedings, and review papers were included, resulting in a total of 227 records exported in BibTeX and Plain Text formats for further processing. Metadata, including titles, author names and affiliations, publication years, source titles, abstracts, keywords, citation counts, and countries of origin, were extracted using RStudio (Bibliometrix package). A rigorous cleaning process was performed to remove duplicates and standardize author names, institutional affiliations, and country labels, ensuring analytical consistency and reproducibility. Bibliometric networks, such as keyword co-occurrence, author collaboration, and thematic clusters, were constructed and visualized using VOSviewer (version 1.6.20) to identify intellectual linkages and

conceptual developments. Finally, the results were interpreted to evaluate scientific productivity, collaboration patterns, and the conceptual evolution of the field, providing both descriptive and inferential insights. This analysis was guided by four research questions: (1) What are the publication trends concerning green technology in the construction and manufacturing sectors between 2009 and June 2025? (2) Which countries, institutions, and authors are the most influential in this field? (3) What are the dominant topics, keywords, and scientific domains in the existing literature? and (4) What emerging research topics are likely to shape future studies? Together, these procedures provide a systematic, transparent, and reproducible framework for understanding the global research landscape, identifying intellectual frontiers, and delineating the trajectory of scholarly development in sustainable industrial transformation through green technology.

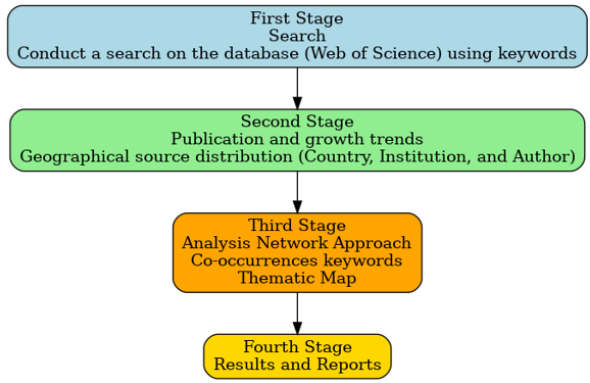

Figure 1. Structured Methodology Aligned with Research Goals
Source: Author

RESULT AND DISCUSSION

Publication and Growth Trends

To comprehensively understand the publication output and research growth, we analysed 227 documents using RStudio. The first stage of analysis focused on the number of publications, citation performance, and temporal trends in research concerning green technology. As shown in Figure 2a, the document types consisted of research articles (n = 166;

73.1%), proceeding papers (n = 49; 21.6%), and review articles (n = 12; 5.3%). This indicates a dominance of empirical studies and a notable scarcity of systematic reviews in this field. Regarding publication language, no restrictions were applied during data collection. As illustrated in Figure 2b, nearly all documents (n = 225; 99.1%) were written in English, reflecting its dominance as the lingua franca of scientific communication. Only a small number were published in Latvian (n = 1; 0.45%) and Spanish (n = 1; 0.45%). Figure 3 illustrates the growth trajectory of publications from 2009 to 2025. Over the past 17 years, the publication trend can be divided into three distinct phases: Early Growth (2009–2013), Primary Growth (2014–2018), and Rapid Development (2019–2025). During the Early Growth phase, the number of publications was minimal (n = 16; 7.05%), indicating that scholarly interest in green technology was still emerging, with limited conceptual and empirical contributions. In 2009, research primarily explored the foundations of green innovation and its implications for industrial competitiveness. A case study in Changzhou identified key barriers to adopting green technology in manufacturing, including weak management systems, insufficient policy incentives, and limited environmental awareness (Hong & He, 2009). In 2012, Granqvist introduced electrochromic as a promising green technology offering energy savings, thermal comfort, and cost efficiency, his paper became the most cited in this phase, with 360 citations (Granqvist, 2012). These early contributions underscore how green technology innovation began to gain momentum globally during this period.

Entering the Primary Growth phase, publication output rose substantially (n = 75; 33.04%), with a citation peak in 2016 reaching 1,260 citations. This surge indicates the appearance of several highly influential works addressing smart manufacturing (Kang et al., 2016), corporate impacts of green technology adoption (Cohen et al., 2016), transformation of green technologies into sustainable products (Guo et al., 2018), and ecological perspectives on green technological development (Peng et al., 2020). These seminal studies collectively catalysed the expansion of the field, provided strong conceptual foundations, and demonstrated increasing scholarly engagement with sustainability driven innovation across diverse industrial contexts and technological disciplines. Furthermore, the diffusion of these ideas across global research networks encouraged broader empirical validation, methodological diversification, and the emergence of hybrid

approaches linking digitalization with ecological modernization. The Rapid Development phase (2019–2025) witnessed an accelerated rise in publications (n = 136; 59.91%) and continuous growth through 2025, reflecting greater institutional collaboration, interdisciplinary integration, and enhanced international policy relevance. The cumulative publication trend (yellow line) increased sharply, reflecting intensified research on environmental regulations, technological advancements in sustainable systems (Song et al., 2022; Zhang et al., 2021), industrial robotics (Lee et al., 2022), and intelligent manufacturing for sustainable transformation (Yang et al., 2022). However, despite the rising publication volume, citation trends (red line) fluctuated and recently declined, suggesting that while the field continues to expand quantitatively, its overall qualitative impact, reflected through citations, research influence, and long-term theoretical consolidation, has yet to consistently mature, particularly for newer publications still gaining academic recognition.

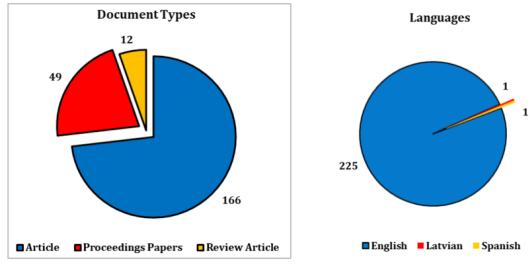

Figure 2. Publications containing "Green Technology"

Source: Author

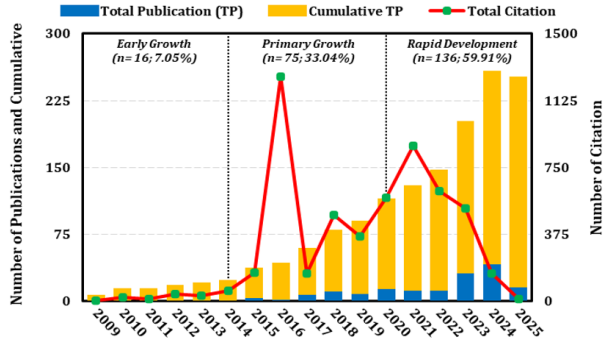

Figure 3. Annual Growth of Publications, Cumulative and Total Citations Web of Science 2009-2025 (n=227)

Source: Author

Each Web of Science record is classified into subject categories that represent the disciplinary orientation of the research. Table 1 presents the top ten research areas contributing to green technology publications between 2014 and 2025. The analysis indicates that Engineering, Science and Technology – Other Topics, and Environmental Science & Ecology were the most active categories, jointly accounting for over 240 papers and more than 6,000 citations. Engineering ranked first with 82 publications, 2,264 citations, and an H-index of 22, reflecting its central role in advancing sustainability science (Braun et al., 2022; Zhou et al., 2022), sustainable manufacturing (Chen & Jin, 2023; Gao et al., 2024), advanced concrete technologies (Chen et al., 2024; Zain et al., 2017), and project management innovations (Hu et al., 2024; F. Zhang et al., 2024). Science and Technology – Other Topics followed closely with 80 publications and the highest total citations (2,628; H = 21), highlighting the field's interdisciplinary scope and integration of cross-cutting technological innovations. Meanwhile, Environmental Science & Ecology exhibited rapid growth, from only six papers in 2014 to 2018, and fifty-five in 2021 to 2025, accumulating 1,492 citations (H = 19), which underscores the intensifying scholarly focus on environmental sustainability. Other active categories such as Construction and Building Technology, Materials Science, and Business and Economics produced 22 to 26 papers each, with H-indices ranging from 9 to 12. Notably, Business and Economics, despite having only 25 papers, achieved 1,372 citations (H = 12), signifying high citation impact. In contrast, Energy and Fuels, Physics, Operations Research, and Public Administration contributed fewer than 15 papers (H < 8), suggesting relatively narrow engagement with green technology discourse. Complementing this disciplinary pattern, Table 2 identifies the ten most active journals publishing green technology research during the same period. The International Journal of Precision Engineering and Manufacturing lead with 19 articles (H = 13, IF = 4.8), followed by Sustainability (17 articles, H = 6) and the Journal of Cleaner Production (11 articles, H = 9, IF = 9.8). These outlets, all classified as Q1 journals, represent the primary publication venues for engineering-oriented sustainability studies. Additional key sources include Environmental Science and Pollution Research, Frontiers in Environmental Science, and Technological Forecasting and Social Change, which emphasize the interdisciplinary nature of green technology research across environmental, social, and management domains. The overall distribution of journals demonstrates a strong concentration of high-impact publications in Q1

outlets (eight of ten), reflecting the field's increasing maturity and scientific visibility.

Table 1. Top 10 Most Active Research Areas on Green Technology Contributing to Publications

Research Area	2019-2014	2015-2020	2021-2025	TP	TC	HI
Engineering	8	38	36	82	2264	22
Environmental Science Ecology	6	21	55	82	1492	19
Science Technology Other Topics	1	36	43	80	2628	21
Construction Building Technology	2	8	16	26	382	9
Business Economics	3	5	17	25	1372	12
Materials Science	4	6	12	22	286	9
Energy Fuels	1	5	8	14	315	8
Physics	0	6	5	11	73	4
Operations Research Management Science	1	3	6	10	537	6
Public Administration	1	2	5	8	715	6

Source: Author

Table 2. Top 10 Most Active Journals in Contributing to Publications

Journals	TP	TC	HI	IF	SJR	Q	Publisher
International Journal of Precision Engineering and Manufacturing	19	1.126	13	4.8	1.072	Q1	Springer
Sustainability	17	416	6	3.3	0.688	Q1	MDPI
Journal of Cleaner Production	11	538	9	9.8	2.174	Q1	Elsevier
Environmental Science and Pollution Research	6	118	5	5.8	1.004	Q1	Springer
Frontiers in Environmental Science	6	24	3	3.3	0.859	Q1	Frontiers Media
Buildings	5	53	3	3.1	0.652	Q1	MDPI
Scientific Reports	5	56	3	3.8	0.874	Q1	Nature Research
Technological Forecasting and Social Change	5	668	4	12.9	3.472	Q1	Elsevier
International Journal of Environmental Research and Public Health	4	171	4	4.6	0.919	Q2	MDPI
Construction and Building Materials	3	95	3	7.4	2.094	Q1	Elsevier

Source: Author

Geographical Distribution of Research Contributions: Analysis by Country, Institution, and Author

●The most influential countries in the field of research

As illustrated in Figure 4, the distribution of publications by country reveals that East Asia overwhelmingly dominates global research production on green technology in the construction and manufacturing sectors, contributing 139 articles (46.5%) of the total output, with the vast majority originating from China (133 articles). Southeast Asia follows with 41 publications (13.8%), led by Malaysia (33 articles), reflecting notable research growth among developing economies actively pursuing sustainable industrial innovation and regional cooperation in technology adoption. In contrast, North America (15 articles; 5.2%) and Europe (36 articles; 12%) made comparatively smaller contributions, indicating a shift in research leadership toward the Asian region, supported by substantial investment, strong governmental frameworks, and comprehensive industrial modernization initiatives. Africa and South America remain considerably underrepresented, together contributing only 6 articles (2%), which underscores the persistent geographic disparity in global knowledge production and the unequal diffusion of green innovation research capacity across continents.

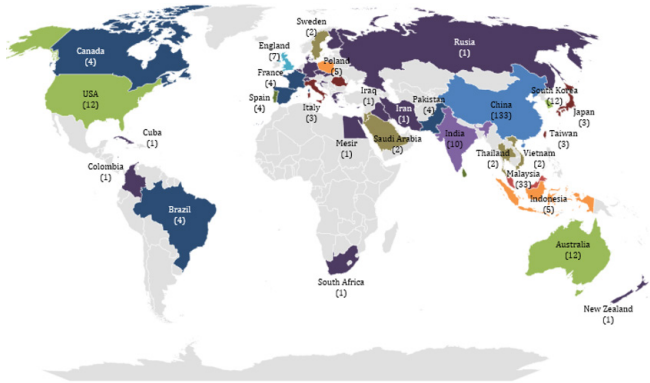

Figure 4. Distribution of Green Technology Publications by Country (WOS database)

Source: Author

Several factors explain the strong concentration of green technology research in Asia and Southeast Asia. First, robust policy support and

government incentives have been pivotal in promoting green construction and technological innovation across the region. In China, for instance, extensive government backing and large-scale investment in research and development have significantly accelerated green technology innovation and industrial transformation (Zhou et al., 2013). Second, many Asian countries, such as Malaysia, demonstrate a relatively high level of awareness and commitment toward adopting green technologies, driven by sustainability agendas and national development strategies, although the pace of implementation remains gradual (Kordi et al., 2018). Third, environmental and economic pressures serve as key motivators for technological transition. Developing nations in Asia are among the largest contributors to CO_2 emissions, making the adoption of green procurement policies, low-carbon production methods, and sustainable industrial practices a strategic necessity for reducing environmental impact (Bohari et al., 2022; Khan et al., 2018). In contrast, Europe and North America tend to emphasize energy and water efficiency, which, while valuable, do not always align directly with broader green technology frameworks or large-scale industrial sustainability transitions (Jones & Laquidara-Carr, 2016). Fourth, the market demand for green buildings and clean production technologies in Asia is notably high, driving continuous research and innovation in sustainable materials, design optimization, and energy-efficient systems (Sanmargaraja et al., 2024). Lastly, although initiatives such as the Timber TED framework in the United Kingdom aim to promote sustainable construction practices (Hitt et al., 2023), their influence remains localized and has yet to generate widespread impact comparable to the rapidly expanding green technology initiatives observed across Asian economies. Table 3 presents the top ten contributing countries. China ranks first in both publication count (n = 133) and H-index (30), reflecting its dominant research productivity and academic influence. South Korea and the United States record the highest average citations per article (83.25 and 60.83, respectively), indicating strong scientific impact despite smaller publication volumes. Malaysia ranks second in total publications but exhibits a lower average citation rate (8.15), suggesting broad dissemination but limited international influence. Australia and the United Kingdom demonstrate balanced contributions, combining moderate output with relatively high citation averages and mid-range H-indices. Meanwhile, Indonesia, though beginning to contribute, still shows limited output and a low H-index, signalling an emerging research presence. Figure 5 illustrates the global collaboration network for

green technology research from 2009 to 2025 (n = 227). The visualization identifies China as the central hub of international cooperation, maintaining strong partnerships with Malaysia, the United States, Australia, Pakistan, and New Zealand. Malaysia emerges as the second largest node, linking both Asian and European partners, such as Poland, Romania, and Singapore, and acting as a key regional connector. The United States and Australia also occupy prominent positions, reflecting active engagement and cross-regional collaboration with China and other nations. Distinct but integrated clusters, including Pakistan and Jordan, form secondary collaboration groups anchored to China's network. Other countries, such as the United Kingdom, Japan, Brazil, Iran, and Canada, play complementary yet smaller roles, indicating broader though less intensive global participation in green technology research.

Table 3. Top 10 Most Active Countries Contributed to the Publications

Countries	TP	TC	HI	AAC
China	133	3225	30	24.25
Malaysia	33	269	9	8.15
Australia	12	456	6	38
South Korea	12	999	7	83.25
Usa	12	730	8	60.83
India	10	199	6	19.9
England	7	262	6	37.43
Indonesia	5	79	2	15.8
Poland	5	96	3	19.2
Brazil	4	58	3	14.5

Source: Author

Figure 5. Network Visualization Map based on Document-Weights

Source: Author

●Most influential institutions in the field of research

The most influential institutions in green technology research

were identified based on their total publications (TP), total citations (TC), H-index, and average citations per article. As shown in Table 4, Sungkyunkwan University ranks first in total citations (TC = 886) and exhibits the highest average citations per article (Avg. = 177.2), underscoring the exceptional scientific impact of its research output. This is followed by Jiangsu University (Avg. = 64.8) and Xi'an Jiaotong University (Avg. = 61.0), both demonstrating strong citation performance and high-quality contributions. The Hong Kong Polytechnic University emerges as the most prolific institution, recording the highest total number of publications (TP = 8) and the highest H-index (H = 5), reflecting a strong balance between research productivity and scholarly influence. Notably, five of the top ten institutions are based in China, reinforcing the country's dominant leadership in advancing research on green technologies within the construction and manufacturing sectors. Institutions from South Korea and Malaysia also appear among the leading contributors, specifically Sungkyunkwan University and Universiti Teknologi MARA, though their citation performance remains relatively modest (e.g., Universiti Teknologi MARA, Avg. = 4.8). In contrast, universities such as Qingdao University of Technology and Southeast University (China) exhibit very low average citations per article (< 5), despite producing the same number of publications as other, more impactful institutions. This suggests variability in research visibility and international recognition even among institutions with comparable productivity levels.

Table 4. Top 10 Institutions by Number of Publications

Institutions	TP	TC	HI	AAC
Hong Kong Polytechnic University	8	166	5	20.75
Xi An Jiaotong University	6	366	5	61
Jiangsu University	5	324	3	64.8
Sungkyunkwan University Skku	5	886	3	177.2
Universiti Teknologi MARA	5	24	2	4.8
Wuhan University Of Technology	5	136	4	27.2
Anhui University Of Finance Economics	4	349	3	87.25
Chongqing University	4	81	3	20.25
Qingdao University Of Technology	4	13	2	3.25
Southeast University China	4	10	3	2.5

Source: Author

●Most influential authors in the field of research

Table 5 lists the top ten authors ranked by their publication contributions in green technology research. The most highly cited author is Noh, Sang Do from South Korea (TC = 844; TP = 3; H-index = 2), indicating moderate productivity but exceptionally high scientific impact. In contrast, Lu, Jianxin from China is the most prolific author (TP = 5; TC = 99; H-index = 3), demonstrating consistent scholarly output and sustained engagement in this field. A clear dominance of Chinese researchers is evident, with six of the ten leading authors affiliated with Chinese institutions, underscoring the nation's central role in advancing global green technology research. Among the remaining contributors, Abdullah Mohd Mustafa Al Bakri from Malaysia (TP = 4; TC = 107; H-index = 4) exhibits notable influence, comparable in impact to Noh from South Korea. In contrast, Martin Cyr from France shows the lowest research contribution among the top ten (TP = 2; TC = 5; H-index = 1), reflecting limited visibility despite multiple publications. Overall, these findings highlight that scientific influence in green technology research cannot be determined solely by publication volume. Instead, citation-based indicators such as total citations and the H-index offer a more comprehensive measure of an author's academic significance and the lasting impact of their work.

Table 5. Top 10 Most Active Contributors to Publications

Authors	TP	TC	HI	Country	WOS-ID
Lu, Jianxin	5	99	3	China	HGZ-2220-2022
Yin, Shi	4	107	4	China	AEA-6712-2022
Abdullah, Mohd Mustafa Al Bakri	4	107	4	Malaysia	C-9844-2012
Poon, Chi Sun	4	10	2	China	H-4152-2015
Song, Malin	3	349	3	China	AEQ-0507-2022
Noh, Sang Do	3	844	2	South Korea	J-1015-2018
CYR, Martin	2	5	1	France	A-8953-2013
Li, Xingwei	2	37	2	China	M-8450-2018
Razak, Rafiza Abd	2	32	2	Malaysia	AAL-1501-2020
Cai, Wei	2	43	2	China	AAP-5124-2020

Source: Author

Network Approach: Analysis by Keyword Co-Occurrence and Thematic Map

●Keyword co-occurrence

The bibliometric analysis presented in Figures 6(a) and 6(b) was conducted using VOSviewer to visualize the major keywords and the density of scientific attention related to green technology. A minimum occurrence threshold of five keywords was applied to ensure analytical relevance. Figure 6(a) illustrates the keyword co-occurrence network, where each node represents a keyword and the connecting edges indicate the strength of association based on their frequency of joint appearance in publications. Distinct colour clusters correspond to thematic groupings formed through semantic similarity and co-occurrence patterns. Five principal clusters were identified, collectively revealing the multidimensional scope of research in this field. Cluster I, labelled Economic Growth and Green Technological Innovation, connects economic growth with green innovation and industrial competitiveness, emphasizing macroeconomic and policy-oriented discussions on how green technologies enhance sustainable industrial performance. Cluster II, Technical and Systemic Dimensions of Green Energy and Construction, focuses on improving energy performance, emission reduction, and the development of sustainable construction and manufacturing systems. Cluster III, Strategic Adoption and Digital Transformation, highlights the integration of digital technologies and strategic innovation in industrial modernization. Cluster IV, Environmental and Technical Aspects of Sustainable Construction, centres on design, mechanical, and environmental challenges in adopting green construction technologies. Finally, Cluster V, Innovation Management and Supply Chain Integration, addresses managerial, operational, and life-cycle perspectives in embedding green innovation within industrial systems. Collectively, these interconnected clusters underscore the multidisciplinary nature of green technology research, bridging economic, technical, digital, environmental, and managerial domains that together drive sustainable industrial transformation.

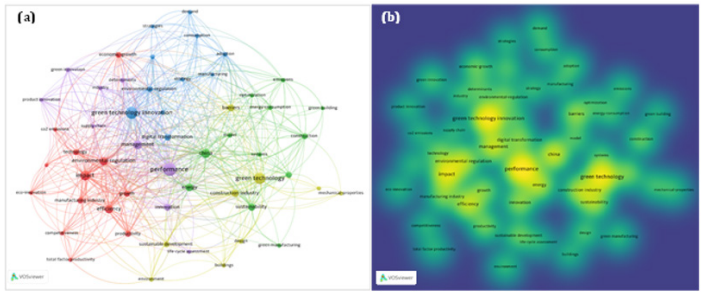

Figure 6: (a) Network visualization map of keyword co-occurrence based on document weights, generated using VOSviewer. Nodes represent keywords, line thickness indicates the strength of co-occurrence links, and colours denote distinct thematic clusters, (b) Density visualization map of keyword co-occurrence based on document weights. Warmer yellow colour gradients indicate higher concentration and frequency of keyword appearance, highlighting dominant areas of research focus

Source: Author

Figure 6(b) presents a density visualization map depicting the frequency and intensity of keyword co-occurrences within the analysed literature corpus. Areas shaded in bright yellow denote the highest density zones, representing the most frequently occurring and conceptually central terms in the research network. Prominent keywords such as performance, green technology, and green technology innovation dominate the conceptual core, reflecting their foundational role in shaping the thematic structure of the field. As the gradient transitions from yellow to green and dark blue, it indicates decreasing keyword frequency and the emergence of more peripheral themes. Complementing this visualization, Table 6 summarizes the ten most frequently occurring keywords across three distinct periods, from 2009 to 2014, 2015 to 2020, and 2021 to 2025, highlighting the temporal evolution of research priorities in the green technology domain. During the Early Phase (2009–2014), research was primarily technical and material centred, focusing on exploratory studies involving engineering materials such as acetic acids, amino acids, ash, cement, composites, and concrete. Broader contextual terms like buildings appeared occasionally, suggesting that early investigations were largely confined to laboratory-scale analyses. The Mid Phase (2015–2020) marks a transition toward applied and systemic inquiry, with keywords such as performance, management, efficiency, and impact reflecting growing attention to energy optimization, environmental management, and operational performance in sustainable

systems. Emerging terms like design and barriers point to rising interest in implementation challenges and institutional constraints, while the frequent occurrence of China underscores the nation's increasing prominence in global green technology research.

Entering the Recent Phase (2021–2025), the research landscape expands toward policy evaluation, systemic transformation, and governance frameworks. While performance remains central, the increasing prominence of impact, efficiency, management, environmental regulation, and innovation signals a shift toward multidimensional analyses integrating technology, policy, and sustainability governance. The recurrence of barriers and the rising frequency of growth, energy, and China further emphasize the persistent focus on implementation challenges and geopolitical influences. These temporal shifts are further illustrated in Figure 7, which visualizes the phase-specific keyword co-occurrence networks: (a) 2009–2014, (b) 2015–2020, and (c) 2021–2025. The figure clearly shows a progressive transition from material-based studies to system- and policy-oriented research themes. Together, Table 6 and Figure 7 reinforce the trends observed in Figure 6(b), demonstrating a clear movement toward implementation-oriented, cross-disciplinary, and digitally integrated green technology research. Core topics such as green technology, performance, and innovation remain dominant, while emerging frontiers, including carbon emissions, smart manufacturing, policy regulation, and digital transformation, appear in bright yellow zones, highlighting their rapidly expanding influence in the field.

Table 6. Top 10 Keywords in the Last 16 Years

2009-2014	Total	2015-2020	Total	2021-2025	Total
Acetic-Acids	1	Performance	12	Performance	22
Amino-Acid	1	Management	6	Impact	17
Ash	1	Design	5	Efficiency	12
Buildings	1	Efficiency	5	Management	12
Built	1	Impact	5	China	11
Butadiene-Styrene	1	Productivity	5	Energy	10
Cement	1	China	4	Environmental-Regulation	9
Composites	1	Energy	4	Innovation	9
Concrete	1	Barriers	3	Barriers	8

Deposition	1	Buildings	3	Growth	8

Source: Author

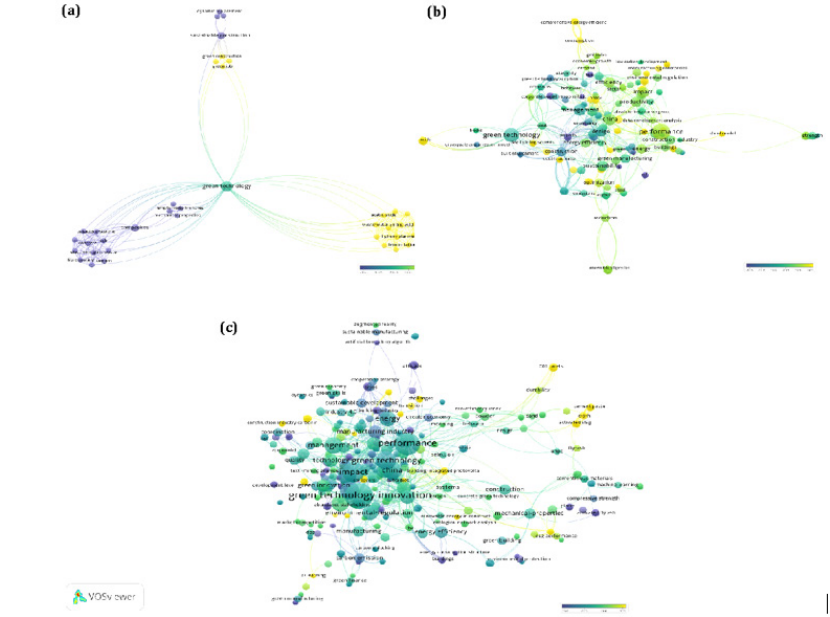

Figure 7. Phase co-occurrences: (a) 2009-2014; (b) 2015-2020; (c) 2021-2025
Source: Author

●Thematic map

Based on the thematic map analysis presented in Figure 8, the indicators of degree of development (density) and degree of relevance (centrality) reveal strong interconnections among keywords from 2009 to 2025, as visualized using VOSviewer. The alignment of these two dimensions provides a comprehensive depiction of the dynamics and evolution of research within the green technology field. Keywords positioned in the upper-right quadrant (motor themes), including performance, consumption, impact, demand, and management which represent well developed and highly relevant areas that have consistently gained prominence over time. For example, performance has remained the most dominant keyword, increasing in frequency from 12 to 22 occurrences throughout the study period. Similarly, impact and management exhibit strong upward trajectories, indicating that these themes are not only conceptually mature but also serve as core drivers shaping current and future research agendas in the construction and manufacturing sectors. In contrast, themes located

in the lower-right quadrant (basic themes), such as sustainability, buildings, mechanical properties, and concrete remain conceptually foundational to the field. These themes largely reflect the technical and material-oriented focus characteristic of early research (2009–2014). Although their frequency growth has been modest, their continued presence underscores their enduring relevance, particularly in studies addressing sustainable materials, green construction methods, and the engineering foundations of environmentally friendly technologies.

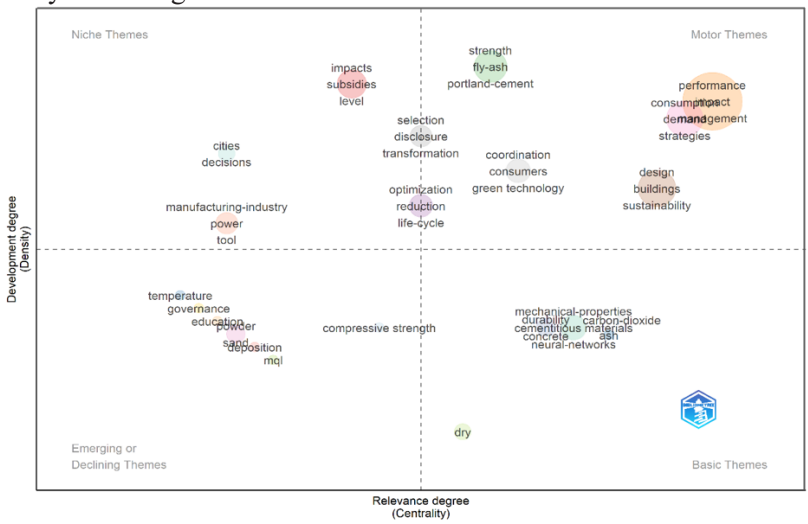

Figure 8. Network Approach-thematic Maps

Source: Author

Themes positioned in the upper-left quadrant (niche themes), such as impacts, subsidies, and cities, are relatively well-developed but exhibit limited scope and interdisciplinary integration. Keywords such as barriers and design, though not dominant in frequency, also belong to this quadrant due to their relevance in addressing design challenges and implementation constraints specific to green technology within the construction and manufacturing sectors. Conversely, the lower-left quadrant (emerging or declining themes) encompasses keywords including governance, education, and sand, all of which display low centrality and density. Their limited appearance across the three temporal phases suggests that these topics are either in the early stages of conceptual development or are declining in research attention, contributing marginally to the field's core intellectual structure. During the initial research phase, scholarly focus was largely

technical and material centred, emphasizing construction materials such as concrete, ash, and composites, as well as energy-efficient building methods. Within this period, construction and buildings served as dominant anchors framing investigations into structural performance and energy efficiency. Over time, however, the research orientation shifted toward a systemic and integrative perspective, redefining design not merely as a technical function but as a strategic process that integrates aesthetic, functional, energy, and sustainability dimensions, an evolution often characterized as eco-design. This conceptual transition aligns with the growing prominence of performance and efficiency, which have expanded beyond purely energy-based indicators to encompass thermal comfort, economic viability, and social performance of building systems. The increasing frequency of keywords such as sustainability and energy consumption reflects a deepening concern with balancing physical development and environmental preservation. In contemporary research, sustainability has evolved from a focus on resource efficiency to a multi-level paradigm encompassing life-cycle assessment, green supply chain management, and net-zero energy building design. Similarly, energy consumption has transitioned from a static performance metric to a dynamic evaluation framework incorporating user behaviour, building technologies, and climatic contexts. The growing prominence of impact and management in recent years signals a broader paradigm shift toward evidence based policymaking and strategic environmental governance. The assessment of environmental, social, and economic impacts has become central to the discourse, while management now extends beyond operational processes to encompass regulatory frameworks, cross-sectoral governance, and multi-stakeholder collaboration. Within this context, the subfields of green technology management and sustainability-oriented innovation management have emerged as rapidly expanding research domains. Overall, the thematic map underscores that current research trajectories have evolved from fragmented, technology-specific innovations to the development of adaptive, measurable, and integrated systems that underpin long-term sustainable development. At the same time, emerging themes such as education and governance, though still peripheral, highlight the growing potential to broaden research scope toward integrating social dimensions, capacity building, and public policy frameworks into the architecture of sustainability science.

CONCLUSION

This study provides a comprehensive overview of the global dynamics and developmental trajectory of green technology, with particular emphasis on its application in the construction and manufacturing sectors, through a bibliometric analysis of literature published between 2009 and 2025. The temporal analysis reveals that the evolution of research in this field can be categorized into three distinct phases: Early Growth, Primary Growth, and Rapid Development. The early phase was characterized by a limited number of publications and citations, primarily centred on foundational concepts and the emerging urgency to adopt green technology. Over time, a substantial expansion in both publication output and citation frequency reflects the growing academic and industrial commitment to sustainability, technological innovation, and their impacts on industrial performance. Keyword co-occurrence and thematic mapping analyses indicate that performance, management, impact, efficiency, and energy consumption have emerged as core motor themes, shaping the dominant discourse of the past decade. Meanwhile, themes such as sustainability, design, construction, and buildings continue to serve as conceptual foundations, anchoring the theoretical and methodological framework of the field. The identification of niche and emerging themes, including governance, education, and policy integration, highlights underexplored yet promising directions for future research, reflecting the field's ongoing diversification and maturation. Geographically, the findings indicate that Asia, particularly Southeast Asia and China, has become the global epicentre of green technology research. This prominence is driven by strong governmental policies, strategic investments in research and innovation, environmental imperatives, and growing market demand for sustainable construction technologies and green buildings. In contrast, Europe and North America maintain a narrower research focus on energy and water efficiency, representing specialized but less expansive engagement with broader frameworks of green technology adoption. Overall, the analysis underscores that green technology research in the construction and manufacturing sectors has evolved from conceptual discourse toward systemic and practical implementation. However, despite this notable quantitative growth, the qualitative impact of research, reflected in citation performance and international collaboration, still requires further consolidation. Future progress will depend on strengthening global cooperation, promoting interdisciplinary integration, and advancing

policy technology alignment to generate responsive, evidence based green innovations capable of addressing the interlinked challenges of climate change, industrial sustainability, and global development.

DECLARATION OF AI-GENERATED CONTENT

AI tools (e.g, ChatGPT, Grammarly) were used for drafting, assistance, paraphrasing and grammar checking. All content was critically reviewed and edited by researcher.

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State the information about the funding for this research. If there was no funding received, please state, 'there is no funding for this research.'

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State clearly the contribution of each author for this article. An example: All authors contributed to the design of the research, the questionnaire, and the write-up. The online survey, data cleaning and tabulation was undertaken by (state your university). All authors have read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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