JCBM (2026) 8(2) 28-42

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Nature-Based Solutions and Materials Promoting Net-Zero Construction in South Africa: Trends and Insights From a Bibliometric Review

Nana Akua Asabea Gyadu-Asiedu[1], Clinton Aigbavboa[2] and Seyi Stephen[3]

[1-3]Department of Construction Management and Quantity Surveying, Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa

Received 07 October 2025; received in revised form 06 November 2025, 27 December 2025; accepted 27 April 2025
https://doi.org/10.15641/jcbm.8.2.1925

Abstract

Buildings contribute approximately 40% of global greenhouse gas emissions, necessitating urgent action toward net-zero construction through Nature-based Solutions (NbS). While NbS have been studied individually, a systematic synthesis of how they integrate with sustainable materials for decarbonisation remains limited. This bibliometric review synthesises emerging trends in NbS and sustainable materials for net-zero construction, addressing a critical knowledge gap in the field. Using structured database analysis, 30 peer-reviewed studies were systematically retrieved and analysed through cluster analysis to identify thematic patterns and research trajectories. Five key research themes emerged: (1) Innovative Strategies for Decarbonisation and Circular Economy, (2) Sustainable Building Materials and Carbon Management, (3) Energy Efficiency and Decision-Making in Sustainable Architectural Design, (4) Zero-Carbon Strategies in Construction and Housing, and (5) Embodied Carbon and Sustainability in Construction Supply Chains. The analysis reveals that NbS significantly reduce carbon emissions, optimises supply chains, and enhances energy efficiency in building systems. However, critical gaps persist in integrating life-cycle analysis with nature-based materials and in addressing regional adoption disparities. This bibliometric approach provides a quantitative foundation for identifying research priorities and policy implications in sustainable construction, offering insights to researchers, practitioners, and policymakers working toward environmentally conscious building practices.

Keywords: Energy-Efficient Buildings, Nature-based Solutions (NbS), Net-Zero Construction, Sustainable Construction, Zero-carbon materials.

1. Introduction

The current trend of rapid population growth is driving an alarming rise in energy demand. The construction industry significantly contributes to global greenhouse gas emissions, accounting for nearly 40% of energy-related emissions worldwide (Mathur, Farouq & Labaran 2021). As the most prevalent greenhouse gas (GHG), carbon dioxide (CO2) emissions have become a growing concern for governments worldwide. In recent years, major carbon-emitting nations have formulated strategies and roadmaps to reduce their CO2 emissions, aiming to achieve a carbon-neutral future (Xiao et al., 2023). The construction industry also recognises the need to shift from a traditional linear economy to a circular economy, which offers a more sustainable and restorative approach (Otasowie et al. 2024). This reality has driven researchers and practitioners to explore innovative pathways toward achieving net-zero construction (Frota De Albuquerque Landi et al. 2023; Matthews 2024; Päätalo et al. 2024). Central to this effort is the integration of nature-based solutions (NbS) and sustainable materials, which promise to revolutionise building practices by reducing carbon footprints and promoting circular economies(Saint et al. 2023; Labaran et al. 2024). This study employs a bibliometric analysis to investigate the emerging role of nature-based solutions in advancing net-zero construction, using Elsevier's Scopus database as the primary source. It identifies research themes and trends and synthesises knowledge. VOS viewer text-mining software (version 16) was employed to identify and classify the emerging themes from sequencing cluster analysis in research, including innovative decarbonisation strategies, sustainable material use,

[1] Corresponding Author
Email address: nakasgyas@gmail.com

energy efficiency, zero-carbon construction methods, and the role of embodied carbon in supply chains. The contribution of this study, which sets it apart, is its bibliometric approach to uncovering gaps and opportunities within the current body of knowledge. While prior studies have explored aspects of sustainable construction and net-zero targets (Archila et al. 2023; Labaran et al. 2024), this work uniquely highlights the interplay between nature-based solutions and net-zero buildings. The originality of this study lies in its focus on synthesising diverse themes into a coherent framework that underpins net-zero construction efforts and informs evidence-based policy and practice in South Africa. This study further contributes to the growing discourse on sustainable construction practices, underscoring the critical importance of aligning innovative, nature-based solutions with global decarbonisation goals, offering actionable insights for stakeholders globally aiming to transform the built environment into a more sustainable and resilient industry. This can be achieved through the following objectives:

1. To conduct a systematic bibliometric review of peer-reviewed literature on NbS and sustainable materials in net-zero construction, using structured database analysis and cluster mapping techniques.

2. To quantify research contributions by geographic region, influential publications, and authors, identifying geographic concentrations and gaps in knowledge production.

3. To identify and map emerging research themes, thematic clusters, and knowledge gaps in the intersection of NbS, sustainable materials, embodied carbon reduction, and net-zero construction.

4. To provide future direction and insights for researchers, practitioners, policymakers, and industry stakeholders working toward environmentally conscious and resilient construction practices in South Africa and similar Global South contexts.

2. Literature Review

Nature-based solutions (NbS) are sustainable design strategies that leverage natural processes to address environmental, social, and economic challenges, including climate change mitigation and adaptation (Cohen-Shacham et al. 2016). In the context of net-zero carbon buildings, NbS incorporates green infrastructure, passive design strategies, biophilic architecture, and ecosystem-based approaches to enhance energy efficiency, carbon sequestration, and climate resilience (Raymond et al. 2017; Seddon et al. 2020). Nature-based Solutions (NbS) have gained recognition in environmental sciences and construction, offering sustainable strategies to achieve net-zero emission goals. By leveraging natural processes and ecosystems, NbS promotes sustainable infrastructure development, enhancing energy efficiency, reducing resource consumption, and mitigating climate impacts. (Chen, Yin, & Lyu, 2024). Net-zero energy buildings offer a promising approach to decarbonisation by reducing energy consumption and enhancing the integration of renewable energy (Hadba et al. 2024; Matthews 2024). As net-zero targets become more stringent, NbS offers a cost-effective, regenerative pathway to achieving sustainability goals in the construction industry (Seddon et al. 2020). Examples include green roofs, fog harvesting, and renewable materials such as clay, timber, and cypress, which not only improve air quality and reduce urban heat but also support the integration of renewable energy (Perera et al. 2022; Saint et al. 2023; Hadba et al. 2024; Matthews 2024). Net-zero energy buildings, defined as structures with zero net energy or carbon consumption, exemplify how NbS can transform the construction industry by reducing environmental footprints and aligning with decarbonisation goals (Ahmed et al. 2022).

Recent studies reveal that NbS have gained sufficient momentum under other related terms such as "biomimicry", "biophilic", and "nature-inspired" (AlAli et al. 2023; Moreira Da Silva et al. 2024). Oguntona and Aigbavboa (2023) highlighted the substantial role of nature-inspired solutions in combating climate change. Incorporating aspects such as green roofs and walls enhances cities' capacity for carbon sequestration, effectively reducing greenhouse gas emissions. Similarly, Singh and Ru (2022) demonstrated that these solutions align with clean energy goals by improving building energy efficiency, reducing energy consumption, and decreasing reliance on non-renewable energy sources. Moreover, urban green initiatives promote sustainable consumption patterns and help minimise the ecological footprint of urban areas.

Additionally, Azari et al. (2024) reveal that building envelopes adapt to environmental changes and are also essential for managing heat, air, and moisture exchange between a structure's interior and exterior. Their efficient design and implementation can significantly reduce energy use and carbon emissions throughout the building's life cycle. In regions like South Africa, where construction significantly contributes to greenhouse gas emissions (23 per cent) (Simpeh & Smallwood 2018), adopting NbS is crucial for mitigating environmental impacts and addressing energy poverty (Dosumu & Aigbavboa 2021). South Africa, as a developing economy with rapid urbanisation and infrastructure development, faces the dual challenge of expanding the built environment to

meet housing and economic development needs while simultaneously achieving net-zero carbon targets aligned with international climate commitments, including the Paris Agreement and African Union Agenda 2063 (Terblanche, May & Steward 2025). The integration of NbS with sustainable construction materials and net-zero building strategies remains understudied, particularly in Global South contexts like South Africa. Previous reviews have focused either on NbS applications in general or on sustainable construction materials in isolation, without synthesising their combined potential for net-zero outcomes (Yang et al. 2024; McPhearson et al. 2025). A critical gap in the existing NbS literature is the lack of systematic analysis of cross-regional research disparities and uneven global adoption patterns. Recent evidence confirms this fragmentation (McPhearson et al. 2025). The study identifies research priorities and gaps specific to the intersection of NbS and construction materials, informing future research agendas and contributing to the growing discourse on environmentally conscious construction by demonstrating the complementary roles of NbS and sustainable materials in achieving net-zero outcomes.

3. Research Methodology

This bibliometric analysis employs science mapping tools to visualise the physical aspects of scientific research domains while elucidating the structural composition of their disciplines (Waltman, Van Eck & Noyons 2010). As highlighted by Akinlolu et al. (2022), bibliometric analysis offers a quantitative and comprehensive approach to examining the existing literature, overcoming the limitations of manual reviews. For this research, the bibliometric analysis followed a four-step process outlined by Aliu and Aigbavboa (2023). Data were sourced from the *Scopus* database, renowned for its wide-ranging coverage and high-quality literature. As one of the largest abstract and citation databases, *Scopus* provides a vast collection of peer-reviewed books, book chapters, journals, and conference proceedings, surpassing other databases like *Clarivate Web of Science and Google Scholar* in scope and reliability (Aghimien et al. 2019; Aliu & Aigbavboa 2023).

The period for this study search was 2014-2024, and using the above keywords, 51 documents were retrieved. For transparency and replicability, the Boolean search was implemented in Scopus as follows: TITLE-ABS-KEY ("nature-based solutions" OR "nature based solutions") AND (“material") AND ("net" OR "net-zero") AND (“construction").

After applying the database filters, all records were manually screened at the title and abstract level. Studies were included when they (i) explicitly addressed nature-based solutions or materials, (ii) focused on buildings, construction or the built environment, and (iii) linked these interventions to net-zero, near-zero or low-carbon performance. Records were excluded if they were non-peer-reviewed items (editorials, notes, etc.) or were in English or had no relevance to the research subject.

Bibliometric mapping was conducted in VOSviewer (version 1.6.19). For keyword co-occurrence networks, the minimum occurrence threshold was set at two keywords, using complete counting and association-strength normalisation; the clustering resolution parameter was fixed at 1.00, with a total link strength of 627. For the global distribution maps, only countries with at least two documents were included. Highly cited publications were identified by a citation threshold of ten or more Scopus citations at the time of data extraction. The review period for this bibliometric study was limited to 2014–2024 to ensure inclusion of contemporary, high-impact research on Nature-Based Solutions (NbS) for achieving net-zero carbon buildings. Accordingly, academic publications on NBS and net-zero buildings gained momentum from 2014 onward, driven by advancements in green infrastructure, biophilic design, and regenerative materials.

In contrast, earlier studies lacked a strong focus on net-zero carbon buildings due to their recent emergence in policy frameworks, certification standards (e.g., Leadership in Energy and Environmental Design (LEED) Zero, EDGE Zero Carbon), and research funding priorities (Lützkendorf et al. 2015; Frantzeskaki et al. 2019; Seddon et al. 2020). Also, bibliometric analysis benefits from a well-defined time frame that captures relevant trends and emerging themes while ensuring data consistency (Donthu et al. 2021). Therefore, by setting the review period from 2014 onward, this study ensures the inclusion of recent, high-quality literature that reflects the latest technological advancements, policy shifts, and industry adoption of NbS in net-zero construction. The research design employed for the bibliometric analysis is shown in Figure 1.

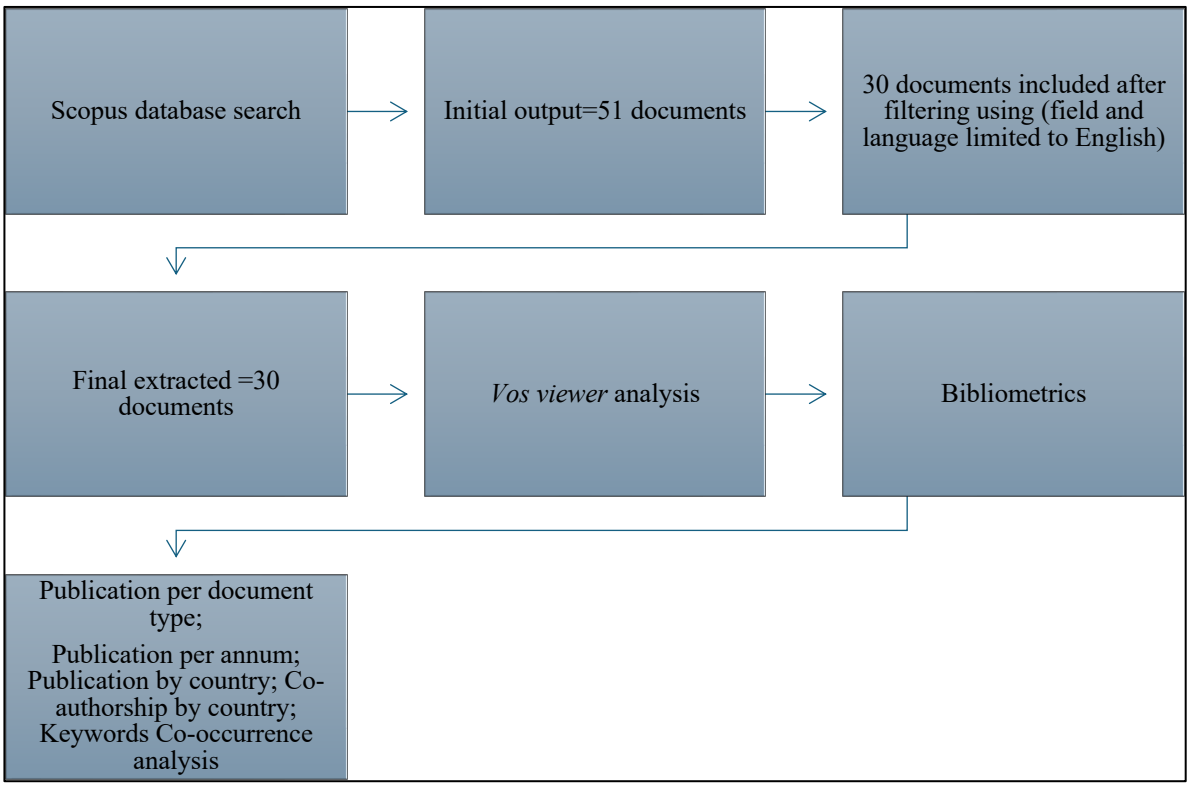

Figure 1: Research design for the study

The results were refined using two parameters: field (Engineering, Energy, Materials Science, and Environmental Science) and language (English). This filtering process initially identified 31 documents. Following manual screening, one document was excluded, leaving a final set of 30 relevant documents for review. Visualisation tools such as *CiteSpace, HiteSpace, VOS viewer, Gephi, and BibExcel* are frequently used in bibliometric studies (Moral-Munoz et al. 2019). This study utilised *VOSviewer* software to analyse bibliometric data and generate a keyword cluster network map (Van Eck & Waltman, 2014). *VOSviewer* is widely adopted in construction literature reviews (Aghimien et al., 2019; Akinlolu et al., 2022; Aliu & Aigbavboa, 2023). The analysis included: (1) the number of publications per document type, (2) publications by year. *VOS viewer* also analysed bibliometric networks based on several key metrics: (3) publications by country, (4) the keywords co-occurrence network. A thematic cluster analysis was performed after the co-occurrence network map of keywords was generated. The methodology guaranteed a systematic and in-depth investigation of the literature on Nature-based Solutions and Sustainable materials in the built environment.

4. Findings and Discussion

4.1. Publication Trend Analysis and Document Type

Results illustrate the annual publication trends on NbS and their influence on net-zero buildings from 2014 to 2024. Before 2014, no publications were recorded in this area. Between 2014 and 2019, research activity was minimal, with only four publications by 2019, reflecting slow initial growth. A decline occurred in 2021, with only one publication, but interest rallied in 2022. A notable surge followed in 2023, with the number of publications rising to seven, three more than the previous year. By 2024, research momentum had significantly increased, culminating in 12 publications to date. This upward trend aligns with the growing recognition of NbS as a vital strategy for promoting efficient energy use and innovative approaches to climate action.

Previous studies anticipate continued expansion in this field as researchers increasingly focus on leveraging NbS to address environmental challenges and support sustainable construction practices (Hadba et al. 2024; Labaran et al. 2024; Matthews 2024; Päätalo et al. 2024). A total of 30 documents were analysed, comprising 15 journal articles, seven conference papers, five review papers, and three book chapters. The relatively low number of journal articles may be attributed to the rigorous peer-review process required for publication, which can limit the volume of accepted articles. Similarly, the number of conference papers is modest, despite their quicker publication timelines and higher volumes, often influenced by the relevance of conference themes. African countries could capitalise on conference platforms to boost research output in this area. Figure 2 illustrates the findings.

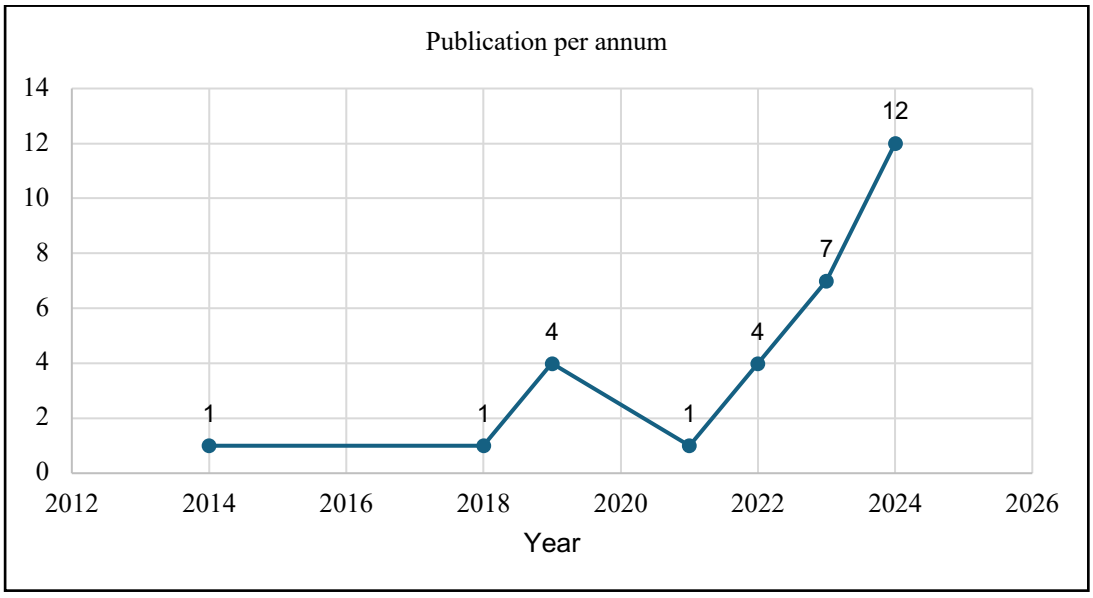

Figure 2: Publication per annum

4.2. Geographical Distribution of Publications

These findings highlight the global distribution of publications on Nature-based Solutions (NbS) in net-zero buildings, presenting the number of documents and citations by country. The data were analysed using a text mining tool with a minimum threshold of two publications per country, revealing 14 countries (depicted on the world map, Figure 3) with research outputs. The United Kingdom leads with 10 publications and 33 citations. Australia follows with five publications and 12 citations, while the United States and Finland each have four publications, accumulating 70 and 75 citations, respectively. Italy and India also recorded four publications and 75 citations, respectively. South Africa, by contrast, had only one publication, cited 3 times and did not meet the set threshold. This analysis reveals an uneven global research output, with some countries making significant contributions to the literature, particularly in Europe and North America. At the same time, regions like Africa remain underrepresented despite the growing importance of NbS in addressing climate challenges and net-zero construction. Table 1 presents the results for the top five countries discussed; Figure 3 presents the publication-by-country map.

4.2.1. Co-Authorship by Country Analysis

This *VOS viewer* co-authorship-by-country visualisation shows patterns of international collaboration in research on Nature-Based Solutions and Materials Promoting Net-Zero Construction. This analysis further reveals the dominating central hubs of research in this area. Using a threshold of at least two documents per country, the analysis reveals that countries such as the United Kingdom, Germany, Denmark, Italy, Switzerland, the United States, Australia, China, India, Turkey, and Finland are collaborating. The United Kingdom emerges as the most influential node (green), serving as a bridge between European partners such as Germany, Denmark, Italy, Switzerland, and Finland, and extra-European collaborators including the United States, Australia, China, India, and Turkey (red cluster). Figure 4 shows the clustering of co-authorships by country.

Table 1: Publication by Country (Top 5 countries)

Country	Number of documents	Citations
United Kingdom	10	33
Australia	5	12
United States of America	4	70
Finland	4	75
Italy	3	75
India	3	7

Source: Authors' compilation

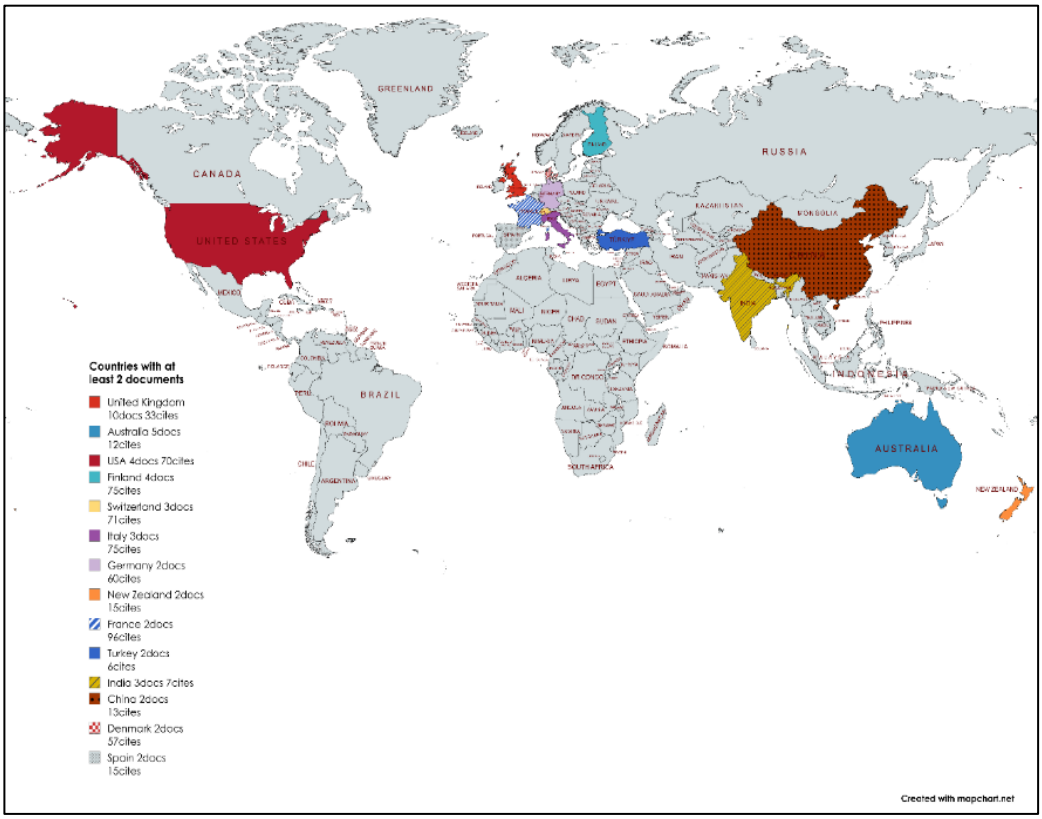

Figure 3: Map showing the number of publications per country

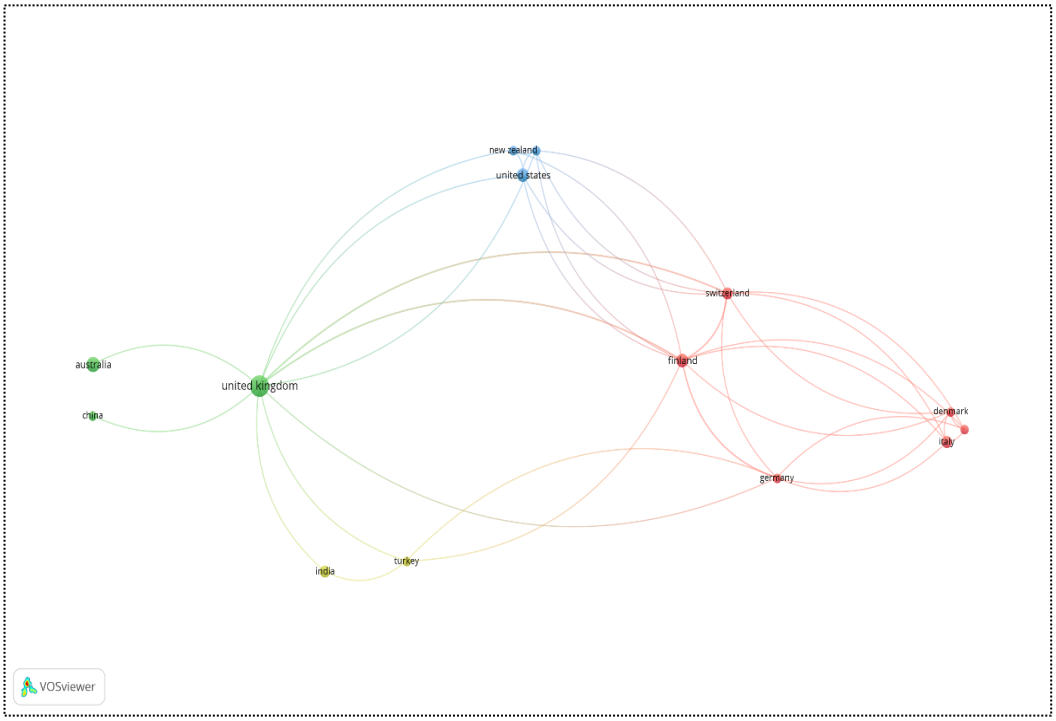

Figure 4: Map showing the Co-Country Authorship Patterns

cluster, reflecting shared policy and research commitments to sustainable construction. The United States also plays a significant bridging role, particularly linking New Zealand and northern Europe. By contrast, countries such as India, Turkey, and China remain more peripheral, engaging mainly through collaborations with the United Kingdom. The relative absence of African countries collaborating with European countries further underscores an existing research gap, highlighting opportunities to include more context-specific knowledge from the Global South. Additionally, the findings highlight that, despite South Africa's active construction industry and vulnerability to climate change, it does not appear among the leading countries in collaborative research on Nature-Based Solutions and net-zero construction materials. For South Africa, this presents both a challenge and an opportunity: by strategically leveraging partnerships with the UK and EU, which already act as central knowledge advisors, South Africa can strengthen its research footprint, access advanced methodologies, and adapt global innovations to local socio-economic and environmental realities. Such collaborations would not only enhance South Africa's visibility in the global discourse but also support the development of regionally specific frameworks that address Africa's unique sustainability challenges in the built environment.

4.3. Most Cited and Influential Publications

This analysis presents studies, distinguished by their high citation counts, that represent foundational and influential research on Nature-based solutions and materials and how they promote net-zero construction practices. Table 2 (See Appendix 1) shows the top six most cited publications; their impact is evident in their citation counts, which indicate they are frequently cited as key research sources in this area.

These studies advance knowledge in sustainable construction by broadening the scope of performance assessment beyond narrow energy metrics toward Net-Zero buildings. Byrne et al. (2019) present a technological innovation for energy-intensive tropical contexts, demonstrating that solar-PCM cooling is a viable solution. Frischknecht et al. (2019) contribute policy-relevant insights by revealing international inconsistencies in benchmarking and stressing the urgency of binding environmental targets.

Hu extends methodological frontiers by integrating LCA with MCDA, enabling multi-dimensional evaluation of buildings and demonstrating how trade-offs across energy, environment, water, and health can reshape design decisions.Bernard et al. (2023) introduce a materials science perspective, demonstrating how MgO-based cements could significantly reduce CO_2 emissions if durability and reinforcement challenges are addressed. Tagliabue et al.'s (2018) study adds a retrofit and optimisation perspective to the literature, focusing on envelope technologies for existing buildings. This complements Zhang et al.'s (2014) demonstration of new-build sustainability in China, showing how sustainability can also be embedded in the refurbishment of ageing building stock to meet NZEB goals. Their methodological contribution lies in combining parametric computational evaluation with LCA and LCC, offering a structured decision-making framework that balances environmental performance with cost and feasibility. Zhang et al. (2014) showcase design and construction strategies that combine architecture, renewable energy, and building systems to deliver a functional net-zero house. These scholarly publications push the discourse beyond narrow efficiency measures towards systemic sustainability, combining materials innovation, policy reform, advanced methods, and clean technologies to guide the transition to net-zero construction. Additionally, these studies emphasise the dual importance of sustainable design in both new builds and the retrofitting of existing stock, both of which are crucial for achieving Net Zero Energy Building (NZEB) goals.

Studies indicate that sustainable construction is not the result of a single innovation or policy, but rather a convergence of technological advancements, binding policy benchmarks, integrated assessment methods, material innovations, and practical design and retrofit strategies. Each perspective of these publications addresses a different layer of the challenge, reinforcing the view that achieving net-zero in construction requires a systemic approach that connects innovation at the micro-scale (materials and technologies) with structural reforms at the macro-scale (policy, standards, and industry practice). This integrated body of work provides a comprehensive basis for guiding future studies and practice toward more sustainable, resilient, and socially valuable built environments, particularly in South Africa. Figure 5 gives a conceptual diagram of the key research outputs.

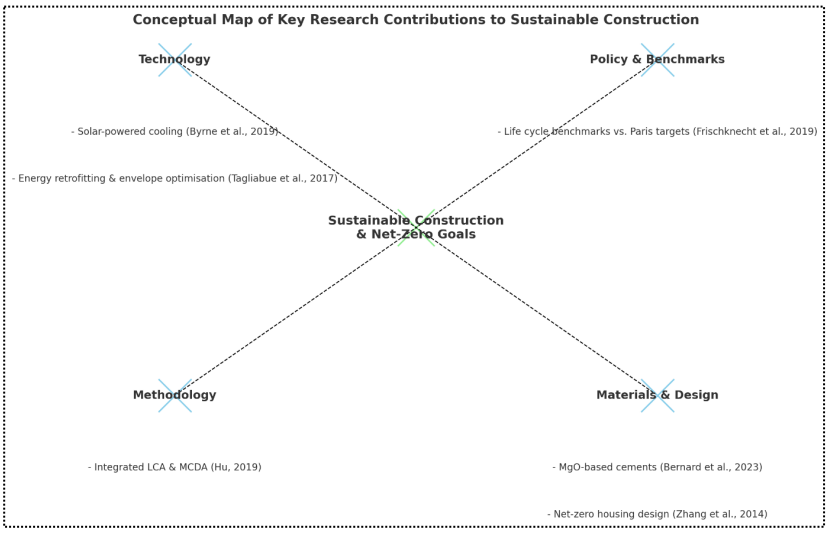

Figure 5: Concept diagram of key research contributions to sustainable and Net-zero construction

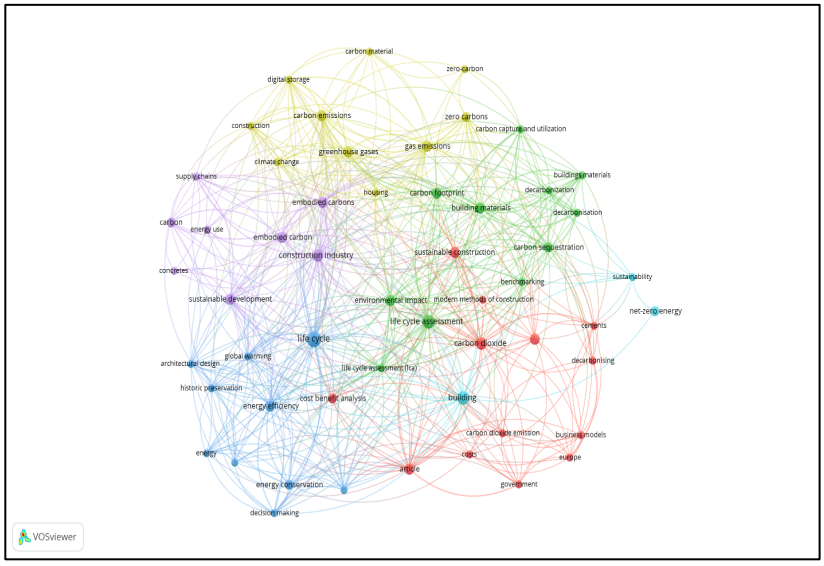

Figure 6: Network visualisation of Co-occurring Keywords

This conceptual diagram shows the key research contributions made over the review period to nature-based solutions and materials that advance net-zero construction. The four thematic pillars in research are Technology, Policy & Benchmarks, Methodology, and Materials & Design. They capture complementary directions, including innovative technologies, policy frameworks, integrative assessment approaches, and sustainable materials development. These emphasise the interdisciplinary pathways required to embed nature-based solutions and low-carbon materials into South Africa's construction industry to achieve net-zero goals.

4.4. Analysis of Co-occurring Keywords and Cluster Themes

Keywords are meaningful in describing research content and concepts, particularly in studies on sustainable construction strategies. Using bibliographic data from the output and *VOSviewer*, a network map was generated to reveal co-occurring keywords and research topic networks, where the proximity of keywords and their similarity indicate the degree of co-occurrence (Van Eck & Waltman, 2014). A co-occurrence analysis of keywords was thus conducted to uncover the core structure and thematic clusters within research on the impact of Nature-based Solutions (NbS) on net-zero construction. Using *VOSviewer* software, a visualisation map was generated from 395 keywords, of which 55 met the threshold of at least two occurrences. It was realised that some keywords repeated, emphasising their importance across multiple thematic clusters in literature. This analysis identified six prominent keyword clusters, as visualised in the network map presented in Figure 6.

Cluster 1: Innovative Strategies for Decarbonisation and Circular Economy in Net-Zero Construction. The

first cluster contains 13 keywords and corresponds to the red region of the map. The keywords were: article, business models, carbon dioxide, carbon dioxide emissions, cement, circular economy, cost-benefit analysis, decarbonising, costs, modern methods of construction, sustainability and sustainable construction. This theme underscores research on the role of nature-based solutions in reducing carbon dioxide emissions and integrating circular economy principles into construction (Tagliabue et al. 2018; Perera et al. 2022; Archila et al. 2023; Chakraborty, 2023). Materials such as low-carbon cement and modern construction methods can help achieve decarbonisation while addressing cost-benefit concerns (Frota De Albuquerque Landi et al. 2023; Khalid et al. 2023; Ahmadi et al. 2024).

Furthermore, these studies highlight that exploring business models aligned with sustainable development ensures cost-effective and environmentally conscious practices towards Net-Zero Construction. It also indicates that governance and regulatory frameworks shape market adoption. For example, in South Africa, this aligns with policy instruments needed to integrate NbS and sustainable materials into mainstream construction.

Cluster 2: Sustainable Building Materials and Carbon Management in Construction. Cluster 2, represented in green in the visualisation, comprises 11 keywords: benchmarking, building materials, carbon capture and utilisation, carbon footprint, carbon sequestration, decarbonisation, environmental impacts, and life cycle assessment. Research by Hu (2019), Saint et al. (2023), and Ekanayake et al. (2024) indicates that life-cycle assessment and carbon footprint analysis are critical for understanding the environmental impacts of building materials. Carbon capture, utilisation, and sequestration technologies can be leveraged to enhance material sustainability (Archila et al., 2023; Gallego Dávila & Aagesen, 2024). Integrating nature-based materials into construction processes supports decarbonisation and reduces long-term environmental impacts.

Cluster 3: Energy Efficiency and Decision-Making in Sustainable Architectural Design. The third cluster comprises the blue region and ten keywords: architectural design, decision-making, energy, energy conservation, energy efficiency, feasibility study, global warming, historic preservation, life cycle, and life cycle analysis. Energy conservation and efficiency are integral to achieving net-zero construction goals, as highlighted in several studies (Ehsan & Maryam, 2022; Azari, Kamel & Memari, 2024). Nature-based solutions in architectural design, such as passive solar design and green roofs, can reduce energy use (Hu, 2019; Labaran et al., 2024). Additionally, decision-making informed by feasibility studies and life cycle analysis ensures that design choices align with global warming mitigation and historic preservation (Frischknecht et al., 2019). This cluster highlights studies on emissions-focused work, emphasising the role of reduced energy demand and efficient resource use, which are particularly relevant to South Africa's energy-intensive construction industry.

Cluster 4: This cluster highlights the theme “Zero-Carbon Strategies in Construction and Housing," with 10 keywords in the yellow region on the map. The keywords include carbon emissions, carbon material, climate change, construction, digital storage, gas emissions, greenhouse gases, housing, zero carbon, and zero-carbon. This theme highlights studies that have focused on reducing greenhouse gas emissions through innovative materials and digital storage solutions in construction (Saint et al., 2023; Matthews, 2024; Pisini, Thammadi & Wilkinson, 2024). Nature-based housing materials and designs can minimise energy use, promote zero-carbon living, and enhance the well-being of inhabitants. Sustainable construction strategies align with climate change goals and support global net-zero initiatives, such as NbS. Additionally, the cluster-revealing studies on greenhouse gases and mitigation strategies, such as carbon capture and utilisation, position emissions monitoring and reduction as the backbone of NbS and material innovation in the construction industry (McGarry et al. 2022; Pisini et al. 2024).

Cluster 5: The fifth cluster, representing the purple section of the map, has eight keywords: carbon, concretes, construction industry, embodied carbon, supply chains, sustainable development, and is themed “Embodied Carbon and Sustainability in Construction Supply Chains.” Embodied carbon in construction materials is a significant contributor to overall emissions. The prominence of embodied carbon links directly to NbS, such as timber and bio-based materials, which can reduce life-cycle impacts. Using sustainable materials and optimising supply chains can reduce the environmental footprint (Weber, Mueller & Reinhart, 2022; Ahmadi et al., 2024; Azari, Kamel & Memari, 2024). Nature-based solutions provide alternatives that prioritise energy efficiency and sustainable development within the construction industry (McGarry, Martin & Winslow 2022). Studies reveal the challenge of balancing traditional practices with emerging sustainable alternatives, making it critical to local transitions, where affordability and availability drive material choices.

Cluster 6: Net-Zero Energy Buildings for Sustainability. The last cluster is represented by the turquoise region with three keywords: buildings, net-zero energy and sustainability. The theme highlights research on the importance of integrating nature-based solutions into building designs to achieve net-zero energy performance (Byrne et al. 2019; Villarruz 2019). Technologies such as energy-efficient materials and renewable energy systems ensure sustainability, as

indicated in studies by Ahmadi et al. (2024) and Azari, Kamel, and Memari (2024). Nature-based solutions and strategies not only reduce carbon emissions but also enhance long-term resilience and environmental harmony towards achieving a Net-Zero Construction industry. Studies around this theme provide the overarching frame that ties material innovation, emissions reduction, and energy efficiency into a holistic NbS-oriented pathway.

5. Discussions of Findings

The conceptual map (Figure 4) illustrates the interlinked pathways through which nature-based solutions and sustainable materials can support the transition towards net-zero construction for South Africa. Four thematic pillars emerged as critical. The first, Technology and NbS, highlights innovations such as green infrastructure for urban cooling and water-sensitive design for flood and ecosystem management. Byrne et al. (2019) and Perera et al. (2022) suggest that these approaches demonstrate how integrating natural systems into construction can simultaneously address climate resilience and social well-being. The second pillar, Policy and Benchmarks, which reflects research such as Ahmadi et al. (2024) and Frischknecht et al. (2019), points to the role of national frameworks and regulatory standards in institutionalising social and environmental values. South Africa's existing sustainable development strategies provide an entry point for embedding NBS into codes and procurement policies, although more vigorous enforcement remains essential. The third pillar, Methodology, underscores research that focuses on the need for robust assessment tools, including life-cycle assessments of bio-based materials and socio-ecological evaluations, to capture the long-term impacts of construction choices (Hu 2019). Finally, Materials and Design scholarly outputs emphasise the potential of bio-based, recycled, and low-carbon materials to reduce embodied carbon while maintaining performance (Zhang et al. 2014; Bernard et al. 2023). These four dimensions converge around the central theme of advancing NBS and net-zero construction, which can be adapted for South Africa, highlighting the importance of systemic, interdisciplinary, and context-specific approaches. This framing not only reveals the diverse research and practice frontiers but also signals the need for coordinated action across technology, policy, methods, and material innovation to achieve measurable sustainability outcomes.

From the content analysis of the keyword network visualisation map (Figure 5), six interrelated clusters are shown, each highlighting distinct yet complementary domains in advancing net-zero construction. The clusters validate that achieving net-zero construction requires multi-faceted integration (Azari et al. 2024). For the South African construction industry, the interplay of clusters highlights the dual challenge of reducing reliance on carbon-intensive materials while scaling context-appropriate NbS. Comparatively, analysing the findings, while material and emissions innovations dominate globally, life-cycle analysis, policy, governance, and socio-economic considerations are particularly decisive for South Africa's adoption pathway. Additionally, the network map shows that research over the years has been limited, with a weak connection between the 'what' and the 'how' of leveraging Nature-based solutions and innovations to promote Net-zero goals in the construction industry. Most research focuses on emissions, efficiency, and materials to be used, but not on social aspects such as affordability, local labour skills, and cultural acceptance (Päätalo et al. 2024). Also, keywords like concrete and carbon-intensive materials appear in separate clusters, suggesting a gap in research on realistic transitional strategies, such as hybrid solutions or scalable NbS alternatives that balance cost and performance. Especially for developing countries like South Africa, the integration of NbS, governance mechanisms, socio-economic drivers, and transitional pathways remains underdeveloped. Again, in the South African construction context, these implications intersect with persistent real-world challenges such as ageing, energy-inefficient building stock, high reliance on coal-based electricity, and a substantial housing backlog that constrains the uptake of higher-cost low-carbon materials and technologies (Chakwizira 2019). At the same time, legislative and policy instruments such as SANS 10400-XA:2021 energy-use regulations, green building incentives, and tax-based energy-efficiency schemes (e.g., Section 12L) are beginning to create enabling conditions for NbS-oriented, net-zero construction pathways.

Furthermore, the findings on the geographical distribution of research indicate a pronounced geographical inequality in research on NbS and net-zero construction, with most research emanating from or reporting to European and North American sources. At the same time, Africa contributes a small fraction, although it is vulnerable primarily to climate change (Seddon et al. 2020). This contemporary inequality results from persistent imbalances, but it does not necessarily reflect a lack of need for research. Africa accounts for approximately 10% of the global land-based climate observation infrastructure. However, a similar percentage of surface observation infrastructure is not working, which hampers Africa's self-driven research and verification of NbS (Dinku 2019). Climate research is similarly uneven, with fewer than 4% of worldwide research spending on climate change directed towards Africa, while when USD 1.26 billion is spent on Africa-focused climate research, less than 15% is spent within Africa, with more than 75% administered by European and United States institutions (Global Centre on Adaptation 2023). Limitations in human capital widen these research

imbalances, with Africa contributing 1.1% of the total world researchers, 79 researchers per million, compared to more than 4,000 per million in the United States (Olufadewa, Adesina & Ayorinde 2020). Submission barriers further worsen Africa's situation, with researchers being forced to pay high costs for article publication, typically USD 1,500 to 10,000, particularly in top journals, together with language inequities (Turba et al. 2025). Such conditions worsen a known, significant "coloniality of knowledge production," particularly in research goals, practices, and narratives on African NbS, which are generally fixed by Global North institutions (Mignolo, 2009). The result is that NbS research globally is primarily geared toward Global North conditions, which, understandably, lack locally grounded evidence on NbS routes to net-zero construction in Africa's urban areas, which most desperately need such knowledge.

6. Conclusion and Further Research

This study demonstrates the growing prominence of Nature-based Solutions (NbS) in achieving net-zero construction, particularly within Europe and North America. Research has demonstrated that incorporating nature-inspired strategies significantly reduces energy consumption, carbon emissions, and resource depletion while enhancing resilience to climate change. The analysis highlights NbS as a critical approach for reducing carbon emissions, optimising supply chains, and enhancing energy efficiency.

A keyword co-occurrence analysis identified six key research themes emerging in this field from 2014 to the present. However, the review also revealed significant gaps, including lower conference paper publication rates, limited integration of life cycle analysis with nature-based materials, and pronounced regional disparities in research output and adoption, particularly in Africa, where only South Africa featured in the results. This indicates that research in this area remains nascent in many developing regions, and that addressing these disparities through policy support, localised research and capacity building is critical to advancing net-zero buildings and broader sustainability goals. Because the study relies on a single database (Scopus) and on quantitative bibliometric techniques, the findings should be interpreted primarily as patterns of research activity and thematic structure, rather than an exhaustive assessment of all relevant work or of the effectiveness of specific NbS interventions. Future research should prioritise exploring the practical applications of NbS in diverse contexts, assessing their scalability in achieving net-zero construction, and addressing gaps in underrepresented regions, while extending coverage to multiple databases and multilingual sources to build a more inclusive evidence base. Thus, studies should examine governance and socio-economic enablers for net-zero transitions, including policy instruments, financing models, and community adoption strategies that bridge the gap between technical innovations and practical implementation in the Global South.

Prior Conference Presentation and Extended Version Statement:

This paper was first presented at the 2025 CBPM Conference, held from 23–25 April 2025 in Cape Town, South Africa, and published in the conference proceedings. The current manuscript is an extended and revised version of the paper presented in the conference proceedings.

References

Aghimien, D. O., Aigbavboa, C. O., Oke, A. E., & Thwala, W. D. (2019). Mapping out research focus for robotics and automation research in construction-related studies: A bibliometric approach. *Journal of Engineering, Design and Technology,* 18:1063–1079. https://doi.org/10.1108/JEDT-09-2019-0237

Ahmadi, M., Piadeh, F., Hosseini, M. R., Zuo, J., & Kocaturk, T. (2024). Unravelling building sector carbon mechanisms: Critique and solutions. *Renewable and Sustainable Energy Reviews,* 205:114873. https://doi.org/10.1016/j.rser.2024.114873

Ahmed, A., Ge, T., Peng, J., Yan, W.-C., Tee, B. T., & You, S. (2022). Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy and Buildings,* 256:111755. https://doi.org/10.1016/j.enbuild.2021.111755

Akinlolu, M., Haupt, T. C., Edwards, D. J., & Simpeh, F. (2022). A bibliometric review of the status and emerging research trends in construction safety management technologies. *International Journal of Construction Management,* 22:2699–2711. https://doi.org/10.1080/15623599.2020.1819584

AlAli, M., Mattar, Y., Alzaim, M., & Beheiry, S. (2023). Applications of biomimicry in architecture, construction and civil engineering. *Biomimetics,* 8(2):202. https://doi.org/10.3390/biomimetics8020202

Aliu, J., & Aigbavboa, C. (2023). Reviewing the trends of construction education research in the last decade: A bibliometric analysis. *International Journal of Construction Management,* 23:1571–1580. https://doi.org/10.1080/15623599.2021.1985777

Archila, H. F., Lashley, R., Lamond, J., Prabhakaran, A., Msipo, A., & Escamilla, E. Z. (2023). 'Smartifying' construction for circular and zero-carbon biobased buildings (SmartBioC). In S.

Amziane, I. Merta, & J. Page (Eds.), *Bio-based building materials*, 926–936. Springer. https://doi.org/10.1007/978-3-031-33465-8_71

Azari, R., Kamel, E., & Memari, A. M. (2024). Current developments and future directions in energy-efficient buildings from the perspective of building construction materials and enclosure systems. *Buildings,*14(7):1921. https://doi.org/10.3390/buildings14071921

Bernard, E, Nguyen, H, Kawashima, S, Lothenbach, B, Manzano, H, Provis, J, Scott, A, Unluer, C, et al. (2023). MgO-based cements – Current status and opportunities. *RILEM Technical Letters*, 8:65–78. https://doi.org/10.21809/rilemtechlett.2023.177

Byrne, P., Putra, N., Maré, T., Abdallah, N., Lalanne, P., Alhamid, I., Estelle, P., Yatim, A., & Tiffonnet, A.-L. (2019). Design of a solar AC system including a PCM storage for sustainable resorts in a tropical region. *Evergreen,* 6:143 148. https://doi.org/10.5109/2321009

Chakraborty, S. S. (2023). Engineering solutions for sustainable development. In *IABSE Congress, New Delhi 2023: Engineering for Sustainable Development,*21–33. https://doi.org/10.2749/newdelhi.2023.0021

Chakwizira, J. (2019). Low-Income Housing Backlogs and Deficits "Blues" in South Africa. What Solutions Can a Lean Construction Approach Proffer?. Journal of Settlements and Spatial Planning.10(2):71–88. https://doi.org/10.24193/JSSP.2019.2.01

Chen, Y., Yin, X., & Lyu, C. (2024). Circular design strategies and economic sustainability of construction projects in China: The mediating role of organisational culture. *Scientific Reports,* 14:7890. https://doi.org/10.1038/s41598-024-56452-0

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based solutions to address global societal challenges*. IUCN. https://doi.org/10.2305/IUCN.CH.2016.13.en

Dinku, T. (2019). Challenges with availability and quality of climate data in Africa. In Extreme Hydrology and Climate Variability. Elsevier. 71-80. https://doi.org/10.1016/B978-0-12-815998-9.00007-5

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research,* 133:285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Dosumu, O. S., & Aigbavboa, C. O. (2021). Drivers and effects of sustainable construction in the South African construction industry. *Acta Structilia,* 28:78-107. https://doi.org/10.18820/24150487/as28i2.4

Ehsan, M. S., & Maryam, Z. (2022). The simulation and design of zero-energy homes-A comparison between photo-voltaic, solar-thermal, and photo-voltaic-thermal systems. In *The 1st International Conference on Energy, Power and Environment*, 110.MDPI. https://doi.org/10.3390/engproc2021012110

Ekanayake, C., Mendis, P., Fernando, S., & Sofi, M. (2024). Sustainable construction with hemp—Toward net zero 2050. In R. Dissanayake et al. (Eds.), *Proceedings of the 14th International Conference on Sustainable Built Environment*,131-149. Springer. https://doi.org/10.1007/978-981-97-3737-6_11

Frantzeskaki, N., McPhearson, T., Collier, M. J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., Van Wyk, E., Ordóñez, C., Oke, C., & Pintér, L. (2019). Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. *BioScience,* 69(6):455-466. https://doi.org/10.1093/biosci/biz042

Frischknecht, R., Balouktsi, M., Lützkendorf, T., Aumann, A., Birgisdottir, H., Ruse, E. G., Hollberg, A., Kuittinen, M., Lavagna, M., Lupišek, A., Passer, A., Peuportier, B., Ramseier, L., Röck, M., Trigaux, D., & Vancso, D. (2019). Environmental benchmarks for buildings: Needs, challenges and solutions-71st LCA forum, Swiss Federal Institute of Technology, Zürich, 18 June 2019. *International Journal of Life Cycle Assessment,* 24:2272-2280. https://doi.org/10.1007/s11367-019-01690-y

Frota De Albuquerque Landi, F., Fabiani, C., Santini, C., Pisello, A. L., & Cotana, F. (2023). Environmental sustainability of earth-based materials for the carbon neutrality of the built environment. In A. M. Tarantino et al. (Eds.), *Shot-earth for an eco-friendly and human-comfortable construction industry*, 85-100. Springer. https://doi.org/10.1007/978-3-031-23507-8_5

Gallego Dávila, J., & Aagesen, M. (2024). How to accelerate CCS deployment in the cement industry? Assessing the impacts of uncertainties on the business case. *International Journal of Greenhouse Gas Control,* 137:104197. https://doi.org/10.1016/j.ijggc.2024.104197

Global Center on Adaptation. (2023). State and Trends in Adaptation Report 2023. (Global report).

Rotterdam and Abidjan: Climate Policy Initiative (CPI) and Global Center on Adaptation. Available: https://gca.org/wp-content/uploads/2024/04/STA23

Hadba, L., Bitonto, M. G. D., Oliveira, M., Mendonça, P., Zanelli, A., & Silva, L. T. (2024). A nature-inspired green–blue solution: Incorporating a fog harvesting technique into urban green wall design. *Sustainability,*16:792. https://doi.org/10.3390/su16020792

Hu, M. (2019). Building impact assessment-A combined life cycle assessment and multi-criteria decision analysis framework. *Resources, Conservation and Recycling,* 150:104410. https://doi.org/10.1016/j.resconrec.2019.104410

Khalid, Y., Ngwaka, U., Papworth, J., Ling-Chin, J., & Smallbone, A. (2023). Evaluation of decarbonisation options for heritage church buildings. *Journal of Building Engineering,* 77:107462. https://doi.org/10.1016/j.jobe.2023.107462

Labaran, Y. H., Mato, H., Saini, G., & Alhassan Musa, A. (2024). Towards net zero energy buildings: A review of barriers and facilitators to the adoption of building energy efficiency practices. *Environmental Research and Technology,* 7:118-130. https://doi.org/10.35208/ert.1320207

Lützkendorf, T., Foliente, G., Balouktsi, M., & Wiberg, A. H. (2015). Net-zero buildings: Incorporating embodied impacts. *Building Research & Information,*43(1):62-81. https://doi.org/10.1080/09613218.2014.935575

Mathur, V. S., Farouq, M. M., & Labaran, Y. H. (2021). The carbon footprint of the construction industry: A review of direct and indirect emissions. *Journal of Smart Cities and Management Technologies,* 6:101-115. https://doi.org/10.29187/jscmt.2021.66

Matthews, J. (2024). Eco cottages: Using local indigenous nontoxic renewable cypress resources for sustainable construction and production. In *Sustainability and Toxicity of Building Materials,* 481-495. Elsevier. https://doi.org/10.1016/B978-0-323-98336-5.00022-4

Mignolo, WD 2009, 'Epistemic Disobedience, Independent Thought and Decolonial Freedom', Theory, Culture & Society, vol. 26, no. 7–8, SAGE Publications, pp. 159–181, viewed http://dx.doi.org/10.1177/0263276409349275

McGarry, H., Martin, B., & Winslow, P. (2022). Delivering low-carbon concrete for Network Rail on the routemap to net zero. *Case Studies in Construction Materials,* 17:e01343. https://doi.org/10.1016/j.cscm.2022.e01343

McPhearson, T., Frantzeskaki, N., Ossola, A., Diep, L., Anderson, P.M.L., Blatch, T., Collier, M.J., Cook, E.M., et al. (2025). Global synthesis and regional insights for mainstreaming urban nature-based solutions. Proceedings of the National Academy of Sciences.122(29):e2315910121. https://doi.org/10.1073/pnas.2315910121

Moral-Muñoz, J. A., López-Herrera, A. G., Herrera-Viedma, E., & Cobo, M. J. (2019). Science mapping analysis software tools: A review. In W. Glänzel, H. F. Moed, U. Schmoch, & M. Thelwall (Eds.), *Springer Handbook of Science and Technology Indicators,*159–185.Springer. https://doi.org/10.1007/978-3-030-02511-3_7

Moreira Da Silva, M., Ferreira, L., Sarmento, T., & Selada, C. (2024). Engaging young people in the development of innovative nature-inspired technologies for carbon sequestration in cities: Case studies from Portugal. *Smart Cities,* 7:445-459. https://doi.org/10.3390/smartcities7010017

Oguntona, O. A., & Aigbavboa, C. O. (2023). Nature inspiration, imitation, and emulation: Biomimicry, a thinking path to sustainability in the construction industry. *Frontiers in Built Environment,* 9:1085979. https://doi.org/10.3389/fbuil.2023.1085979

Otasowie, O. K., Aigbavboa, C., Adekunle, P., & Oke, A. (2024). Drivers of circular economy adoption in the South African construction industry. In K. Papadikis, C. Zhang, S. Tang, E. Liu, & L. Di Sarno (Eds.), *Towards a carbon neutral future,* 197-205. Springer. https://doi.org/10.1007/978-981-99-7965-3_18

Päätalo, J., Alao, P. F., Rohumaa, A., Kers, J., Liblik, J., & Lylykangas, K. (2024). Prefab light clay-timber elements for net zero whole-life carbon buildings. *Scientific Journal of Civil Engineering,* 34(1):89-100. https://doi.org/10.5755/j01.sace.34.1.35561

Perera, J. S., Mendis, P., Baduge, S. K., & Hashemi, M. (2022). Cementless building materials made from recycled plastic and sand/glass: A review and road map for the future. *Electronic Journal of Structural Engineering,*22:56-63. https://doi.org/10.56748/ejse.223773

Pisini, S., Thammadi, S., & Wilkinson, S. (2024). Embodied carbon emissions for net-zero carbon buildings: A comprehensive study of New Zealand. In J. O. B. Rotimi, W. M. Shahzad, M. Sutrisna, & R. Kahandawa (Eds.), *Advances in engineering*

management, innovation, and sustainability, 739-755. Springer. https://doi.org/10.1007/978-3-031-56544-1_46

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy,*77:15-24. https://doi.org/10.1016/j.envsci.2017.07.008

Saint, R., Eltaweel, A., Adetooto, J., Pomponi, F., & Windapo, A. (2023). Sandbag housing construction in South Africa: Life cycle assessment and operational energy modelling. *International Journal of Life Cycle Assessment,* 28:1003-1018. https://doi.org/10.1007/s11367-023-02170-0

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences,*375:20190120. https://doi.org/10.1098/rstb.2019.0120

Simpeh, K. E., & Smallwood, J. (2018). Analysis of the Benefits of Green Building in South Africa. *Journal of Construction Project Management and Innovation*, 8(2):1829-1851. https://doi.org/10.36615/jcpmi.v8i2.161

Singh, S., & Ru, J. (2022). Accessibility, affordability, and efficiency of clean energy: A review and research agenda. *Environmental Science and Pollution Research,* 29: 18333-18347. https://doi.org/10.1007/s11356-022-18565-9

Tagliabue, LC, Di Giuda, GM, Villa, V, De Angelis, E & Ciribini, ALC. (2018). Techno-economical Analysis based on a Parametric Computational Evaluation for decision process on envelope technologies and configurations. *Energy and Buildings*,158:736-749. https://doi.org/10.1016/j.enbuild.2017.10.004

Terblanche, R., May, C. & Steward, J. (2025). Implementing and operating net zero buildings in South Africa. Buildings and Cities. 6(1):255-271. https://doi.org/10.5334/bc.549

Turba, R., Thoré, E. S. J., Bertram, M. G., Bridg, H., Sabet, S. S., Gamboa, M., Ríos-Orjuela, J. C., Takola, E., Capa Salinas, J., Sampaio Franco, A. C., & Marín, C. (2025).

Global North-South science inequalities due to language and funding barriers. Zenodo. https://doi.org/10.5281/zenodo.14902147

Van Eck, N. J., & Waltman, L. (2014). Visualising bibliometric networks. In Y. Ding, R. Rousseau, & D. Wolfram (Eds.), *Measuring scholarly impact*. 285-320. Springer. https://doi.org/10.1007/978-3-319-10377-8_13

Villarruz, A. N. J. (2019). Triple net zero bioclimatic canine oasis (Net zero home and communities). In *Proceedings of the Annual International Conference on Architecture and Civil Engineering*. Capiz State University, 406-415. https://doi.org/10.5176/2301-394X_ACE19.625

Waltman, L., Van Eck, N. J., & Noyons, E. C. M. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics,*4:629-635. https://doi.org/10.1016/j.joi.2010.07.002

Weber, R. E., Mueller, C., & Reinhart, C. (2022). Solar exoskeletons – An integrated building system combining solar gain control with structural efficiency. *Solar Energy,* 240:301-314. https://doi.org/10.1016/j.solener.2022.05.048

Xiao, Z., Ge, H., Lacasse, M., Wang, L., & Zmeureanu, R. (2023). Nature-based solutions for carbon neutral climate resilient buildings and communities: A review of technical evidence, design guidelines, and policies. *Buildings,* 13:1389. https://doi.org/10.3390/buildings13061389

Yang, H., Chae, J., Song, C., & Choi, E. (2024). Research trends of nature-based solutions: from urban to climate change. Frontiers in Forests and GlobalChange.7:1351189. https://doi.org/10.3389/ffgc.2024.1351189

Zhang, H, Li, J, Dong, L, & Chen, H. (2014). Integration of Sustainability in Net-Zero House: Experiences in Solar Decathlon China. *Energy Procedia*,57:1931-1940. https://doi.org/10.1016/j.egypro.2014.10.057

Appendix 1

Table 2: Top 6 influential and most cited research works (Focus, Methodologies & Contributions)

Author(s)	Research Focus	Citations	Methodologies Used	Knowledge Contribution
Byrne et al. (2019)	Design of a solar air-conditioning system with phase change material (PCM) storage for sustainable resorts in tropical regions	40	TRNSYS simulation for cooling demand; experimental design and characterisation of PCM-graphite composites; prototype calculations	Demonstrates the feasibility of solar-powered cooling in resorts without reliance on batteries; introduces innovative PCM storage for energy independence in tropical climates
Frischknecht et al. (2019)	Environmental benchmarks for buildings in line with Paris Agreement targets	56	Life Cycle Assessment (LCA) across 22 organisations in 21 countries; comparative round robin test on a standard office building; benchmarking workshops	Highlights the gap between current building benchmarks and net-zero targets; underscores the need for stricter, life cycle-based benchmarks; stresses government responsibility in defining legally binding requirements
Hu (2019)	Development of an integrated building impact assessment framework beyond energy-centric measures	43	Combined Life Cycle Assessment (LCA) and Multi-Criteria Decision Analysis (MCDA); case study with original building and three alternatives	Shifts focus from building performance to holistic impacts (energy, environment, water, and human health); demonstrates that single-criterion approaches are inadequate; and validates integrated assessment for decision-making in sustainable building design.
Tagliabue et al. (2017)	Techno-economic evaluation of envelope technologies and retrofit strategies for Nearly Zero Energy Buildings (NZEB)	19	Parametric computational analysis; Life Cycle Assessment (LCA); Life Cycle Costing (LCC); synoptic diagrams for multi-climate optimisation	Demonstrates how multi-criteria frameworks (energy, environment, economy) can optimise building envelope retrofits; shows the importance of embodied energy and payback in selecting sustainable envelope solutions.
Bernard et al. (2023)	Potential of MgO-based cements for CO_2 reduction in construction	15	Review of different MgO-based cements and chemistries; techno-economic analysis; discussion of durability and reinforcement studies	Establishes MgO-based cements as promising alternatives to Portland cement with potential for low-to-negative CO_2 emissions; identifies key R&D needs, including admixtures, durability, and LCA, for adoption.
Zhang et al. (2014)	Integration of sustainability strategies in net-zero residential housing (China)	12	Experimental design and construction of a net-zero house (Solar Decathlon China 2013); market-oriented survey; integrated framework analysis	Provides a practical case study of integrating architecture, renewable energy, and engineering systems for net-zero housing, highlighting both the potential and limitations of applying sustainability strategies in high-density urban contexts.

Source: Authors' compilation