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Revolutionising Green Construction: Harnessing Zeolite and AI-Driven Initiatives for Net-Zero and Climate-Adaptive Buildings

Seyi Stephen [1,*], Clinton Aigbavboa [1] and Ayodeji Oke [2]

[1] Department of Construction Management and Quantity Surveying, University of Johannesburg, Johannesburg 2092, South Africa; caigbavboa@uj.ac.za
[2] Department of Quantity Surveying, Federal University of Technology Akure, Gaga 340110, Nigeria; aeoke@futa.edu.ng
* Correspondence: seyis@uj.ac.za; Tel.: +27-639-886-113

Abstract: This study explored the role of zeolite and AI-driven initiatives in sustainable construction, particularly for net-zero and climate-adaptive buildings. A quantitative, scientometric, and narrative review was conducted using bibliometric analysis of existing publications from the Scopus and Web of Science databases to identify research trends, key contributions, and technological advancements. The findings revealed that zeolite enhances construction materials by improving thermal regulation, air purification, and carbon capture, while AI optimises energy efficiency, predictive maintenance, and material performance. A cost–benefit analysis showed that integrating zeolite and AI in construction materials reduces long-term energy costs and enhances building sustainability. Comparisons with previous studies highlighted the increasing adoption of these technologies due to their environmental and economic benefits. This study concluded that the combination of zeolite and AI provides innovative solutions for green construction, offering energy-efficient, climate-resilient, and cost-effective building materials.

Keywords: adaptive building; green construction; net-zero buildings; sustainable technology; zeolite materials

Academic Editor: Apple L. S. Chan

Received: 12 February 2025
Revised: 10 March 2025
Accepted: 11 March 2025
Published: 12 March 2025

Citation: Stephen, S.; Aigbavboa, C.; Oke, A. Revolutionising Green Construction: Harnessing Zeolite and AI-Driven Initiatives for Net-Zero and Climate-Adaptive Buildings. *Buildings* **2025**, *15*, 885. https://doi.org/10.3390/buildings15060885

1. Introduction

According to Zhong et al. [1], climate change has become one of the most pressing challenges of our time, with buildings being a major source of greenhouse gas emissions. From construction to operation, buildings consume large amounts of energy and resources, making it essential to find sustainable solutions. One promising approach involves the use of zeolites, a group of porous minerals such as analcime, chabazite, clinoptilolite, heulandite, natrolite, phillipsite, stilbite, and natrolite that can be either naturally occurring or synthetic [2]. Zeolites have unique properties, such as the ability to trap gases like carbon dioxide, store thermal energy, and regulate indoor humidity [3]. These features make them a valuable material for improving buildings' energy efficiency and environmental performance.

Zeolite has shown its potential to enhance the sustainability and energy efficiency of buildings through its use in various construction materials. For example, in concrete, zeolite helps improve thermal performance by absorbing and storing heat, reducing the need for additional heating and cooling systems [4]. This makes buildings more energy-efficient, as the indoor temperature remains stable. A study by Iswarya and Beulah (2020) highlighted how zeolite-based concrete helped reduce energy consumption and the carbon footprint of buildings [5]. Additionally, zeolite is used in insulation materials, where it regulates temperature and moisture, maintaining a comfortable indoor climate in various weather conditions [6]. In a project by Ibrahim et al. [7], zeolite was used in insulating materials, resulting in a significant (lowest value of thermal conductivity at 0.37 W/mK and with excellent compressive strength of 18.36 MPa) reduction in energy use for heating and cooling. The study also showed that zeolite-based insulation also proved effective in maintaining temperature stability in extreme climates, contributing to overall energy savings and sustainability. Furthermore, zeolite also plays a crucial role in water purification within buildings. In a case study by Abdelwahab and Thabet [8], zeolite was incorporated into water filtration systems to remove harmful pollutants and heavy metals. This natural material improved water quality, reducing the need for chemical treatments and additional filtration systems. Also, Mata et al. [9] explained that zeolite was added to heating, ventilation, and air conditioning (HVAC) systems, improving indoor air quality and reducing the need for additional filtration units. Zeolite's application in construction materials like concrete, insulation, and air purification systems shows its versatility in promoting energy efficiency, water quality, and indoor air quality. These examples demonstrate how zeolite can contribute to creating buildings that are not only energy-efficient but also adaptable to environmental conditions, making them more sustainable and resilient in the long term.

Farzaneh et al. [10] stated that at the same time, Artificial Intelligence (AI) is revolutionising the way we design and manage buildings. AI systems can process large amounts of data to predict energy usage, optimise heating and cooling, and enhance the comfort of occupants. Additionally, AI can help buildings adapt to extreme weather conditions caused by climate change [5,11]. When combined with advanced materials like zeolites, AI offers the potential to create smarter, more sustainable buildings. This combination could lead to significant reductions in energy consumption and emissions while improving resilience to climate-related challenges. However, there are challenges in integrating zeolites and AI-driven solutions into the building sector. The cost of new materials and technologies can be high, and their adoption requires greater awareness and expertise within the construction industry [12]. Furthermore, scalability and practical implementation remain key hurdles [13]. This study focuses on addressing these challenges by exploring how zeolites and AI technologies can work together to create buildings that are net-zero in emissions and climate-adaptive. This aim will be achieved by discussing the potential of integrating zeolite-based materials and AI-driven technologies to create net-zero, climate-adaptive buildings.

2. Literature Review

2.1. Green Construction

Green construction refers to the practice of designing, building, and operating buildings in an environmentally responsible and resource-efficient manner [14,15]. This approach focuses on reducing the overall environmental impact of construction through energy-efficient designs, the use of renewable resources, and the incorporation of sustainable building materials. The concept includes various strategies like energy efficiency, water conservation, and waste reduction during the construction process [1,14]. One key feature is using green building materials such as recycled materials, bamboo, and low-emission paints, which help to minimise the carbon footprint [16]. The authors found that by integrating renewable energy sources like solar panels or wind turbines, green buildings can significantly reduce their reliance on non-renewable energy sources, thus contributing to sustainability.

On the other hand, green construction can be more expensive upfront compared to traditional construction due to the higher costs of sustainable materials and technologies [17,18]. However, many argue that this initial investment pays off in the long run through reduced energy and maintenance costs [17]. Additionally, buildings constructed with green methods often have a longer lifespan and better indoor air quality, benefiting occupants' health and productivity [17,19]. Despite these advantages, the adoption of green construction has been slow in some regions due to a lack of awareness, higher initial costs, and the complexity of implementing new technologies. Nevertheless, as more people become aware of the long-term benefits and the need for sustainable development, green construction is expected to become the standard in the future.

2.2. Zeolite in the Construction Industry

Zeolite is a naturally occurring mineral known for its unique porous structure, which makes it highly useful in various industries, including construction. Zeolites are made up of aluminosilicate compounds and can absorb and exchange ions, which gives them a broad range of applications [2,20]. In the construction industry, zeolite is primarily used as a partial replacement for cement in concrete production [5]. There are different types of zeolites, such as natural zeolites, which are mined directly from the earth, and synthetic zeolites, which are produced through chemical processes. Both types have proven to be effective in improving the properties of concrete, such as its durability, strength, and resistance to environmental factors like heat and moisture [21].

The incorporation of zeolite in concrete has shown promising results, particularly in enhancing its sustainability. When used as an additive, zeolite can reduce the amount of cement required, which in turn lowers the carbon footprint of the construction process [22]. Cement production is responsible for a significant portion of global carbon dioxide emissions, and by substituting part of it with zeolite, the environmental impact is reduced. Furthermore, zeolite can help in improving the workability of concrete, allowing for easier mixing and better consistency [23]. It also has the potential to increase the long-term strength of concrete, making it more resistant to cracking and degradation over time. These benefits highlight zeolite's role in advancing sustainable construction practices.

Despite the advantages, there are some challenges associated with the use of zeolite in construction. One concern is the variability in the quality of natural zeolites, which may affect the overall performance of the concrete mix [24]. The chemical composition and the particle size of the zeolite can influence its effectiveness, and ensuring a consistent supply of high-quality zeolite can be difficult. Additionally, Alexa-Stratulat et al. [25] noted that the full potential of zeolite in construction is still being explored, and more research is needed to understand its long-term behaviour in concrete structures. While the use of zeolite shows great promise in terms of sustainability and performance, it is important to weigh its benefits against the potential challenges to ensure its effective use in the construction industry.

2.3. Smart Initiatives for Green Buildings

Smart initiatives for green buildings are integral to the evolving approach to sustainable construction and urban development. These initiatives leverage modern technologies to improve the energy efficiency, environmental sustainability, and overall performance of buildings [15,26]. The core principle behind smart buildings is to reduce resource consumption such as energy, water, and materials while simultaneously improving the comfort and health of the occupants. Examples of these technologies include advanced automation systems, sensor networks, and the use of Artificial Intelligence to optimise building operations. Bae et al. [27] added that smart thermostats, lighting systems, and occupancy sensors adjust heating, cooling, and lighting automatically, ensuring that energy is only used when needed. This not only leads to substantial reductions in utility bills but also supports environmental conservation by minimising unnecessary energy consumption. In addition to energy-saving technologies, smart buildings are increasingly incorporating renewable energy sources such as solar panels, wind turbines, and geothermal systems to reduce their dependence on fossil fuels [28]. Furthermore, technologies like energy storage systems allow buildings to store excess energy generated during the day for use during peak demand times, making them more self-sufficient and resilient to grid failures.

Another key aspect of smart initiatives for green buildings is the integration of intelligent Building Management Systems (BMSs) [29]. These systems control and monitor all aspects of a building's operations from a central hub. By collecting and analysing real-time data, BMSs optimise energy use across various systems such as HVAC (heating, ventilation, and air conditioning), lighting, water heating, and even elevators, ensuring that energy and resources are used efficiently [30,31]. This level of automation allows for precise adjustments based on occupancy levels, time of day, or external weather conditions, which significantly enhance the building's operational efficiency. In addition to controlling energy consumption, smart water management systems are becoming increasingly popular [32]. These systems help to track water usage, detect leaks, and minimise waste by adjusting water flow based on real-time data. For example, water-saving fixtures such as low-flow toilets and faucets are combined with smart monitoring systems to ensure that water is used judiciously throughout the building. Moreover, features such as green roofs, automated shading systems, and high-performance glazing on windows help to improve thermal insulation, reduce solar heat gain, and promote natural ventilation, contributing further to a building's energy efficiency and sustainability [33].

While the benefits of smart initiatives for green buildings are clear, there are still challenges that need to be addressed. The initial investment required to install these technologies can be substantial, which may deter some developers or building owners from adopting them [12]. While the long-term savings in energy and operational costs can offset these expenses, the upfront costs remain a significant hurdle. Additionally, integrating various smart systems into a building requires specialised expertise, as well as ongoing maintenance and monitoring to ensure that they function properly [34]. The complexity of coordinating between different technologies, such as energy management, IoT devices, and renewable energy systems, can add to the difficulty of installation and operation. There is also a risk of over-reliance on technology, which could cause issues if systems fail or malfunction without proper backup systems in place [35]. Despite these challenges, the advantages of smart green building initiatives often outweigh the drawbacks. The long-term energy savings, reduced environmental impact, enhanced comfort for occupants, and increased property value are all compelling reasons for property developers to invest in these technologies. As the demand for sustainable, energy-efficient buildings grows, smart initiatives will likely become more mainstream, helping to shape the future of architecture and urban planning [36].

The reviews presented in this section highlight the growing importance of sustainability in the construction industry, yet they also reveal several gaps. While the reviews emphasise the benefits of using sustainable materials, energy-efficient technologies, and smart systems, they also point out challenges such as the high upfront costs and the need for better integration of new technologies. The reviews contribute by showcasing how sustainable practices, like using zeolite or implementing smart building systems, can reduce environmental impact and improve efficiency. However, they also highlight a need for more research into the long-term performance of these technologies and materials and the need for standardisation and consistent quality in green construction practices. These gaps suggest that while considerable potential exists for sustainable solutions, more work is needed to make these practices more accessible, reliable, and widespread in the industry.

2.4. Cost–Benefit Analysis of Implementing AI and Zeolite in Construction Materials

In recent years, the use of Artificial Intelligence (AI) and zeolite in construction materials has been gaining attention due to their potential in promoting green construction. A cost–benefit analysis is essential to understand the financial viability of incorporating these technologies into building materials. AI can optimise the design and construction process, reducing waste and energy consumption [37]. When paired with zeolite, a natural mineral with exceptional properties like water absorption, thermal stability, and ion exchange capabilities, the materials can significantly enhance energy efficiency and the building's overall environmental performance [38]. However, while these technologies promise long-term savings in energy costs and operational efficiency, their initial investment can be high. The upfront cost of AI software, hardware, and training for construction workers, combined with the cost of sourcing and processing zeolite, can be a barrier for many construction companies [39,40]. Therefore, a careful financial evaluation is required to determine whether the long-term benefits of reduced energy consumption, maintenance costs, and environmental impact outweigh these initial expenses.

Financial viability is a critical consideration when adopting new technologies in the construction industry. Although AI and zeolite offer significant environmental benefits, the adoption of such technologies must be balanced with the costs involved [38,41]. AI's role in construction includes automating tasks, improving efficiency, and minimising errors, which can lead to cost reductions in the long run. Similarly, incorporating zeolite-based materials can enhance the energy efficiency of buildings, thereby lowering operational costs [21,22]. Discussing further, when compared to previous studies mentioned above, it becomes evident that while AI and zeolite have been explored in different contexts, few studies have directly compared their cost-effectiveness and practical application in green construction. Previous research on AI in construction has largely focused on its ability to improve project management, automate design processes, and optimise building operations [42–44]. However, the financial analysis of AI adoption remains varied, with some studies highlighting significant cost savings [42,45] and others pointing to high initial investments as a potential barrier [46,47]. Similarly, studies on zeolite-based construction materials often emphasise their environmental benefits, such as improved thermal insulation and reduced carbon emissions, but their cost-effectiveness in the construction industry is less frequently addressed [21–23]. Comparisons between these studies show that while both AI and zeolite have clear potential, the lack of comprehensive cost–benefit analyses hinders their widespread adoption in the industry. Future research should aim to bridge this gap by providing detailed financial evaluations, considering both environmental and economic factors, to better inform industry stakeholders on the viability of these green technologies.

The financial costs of using AI and zeolite in construction must be carefully evaluated to ensure their economic feasibility. The initial investment in AI includes the cost of software licences, hardware for data processing, sensors, automation tools, and workforce training. These expenses can range from USD50,000 to USD500,000 depending on the scale of implementation and the complexity of AI-driven solutions [48,49]. Studies show that AI-powered predictive maintenance and automation can reduce implementation time by 60% and integration-related errors by 75%, as well as lead to a 40% reduction in maintenance overhead, a 55% improvement in system reliability, a 39% improvement in team productivity, a 58% reduction in integration-related support tickets, a 49% increase in stakeholder engagement, a 29% increase in operational efficiency, and a 44% improvement in project timeline adherence of overall construction costs in the long run [50,51]. On the other hand, zeolite-based materials, while eco-friendly and energy-efficient, require mining, processing, and transportation, adding to production costs. In the United States, Crangle [52] noted that in 2021, the price of natural zeolite varied from USD50 to USD300 per ton, with processed or synthetic zeolite costing significantly more, depending on purity and intended application. The inclusion of zeolite in concrete can increase material costs by 10–20%, but the long-term savings in energy efficiency and durability may compensate for the initial expenditure. Additionally, government incentives, green building certifications, and tax credits can help to offset costs for companies adopting these technologies.

Using zeolite in concrete can lead to significant cost savings while improving sustainability. The study by Mostafaei and Bahmani [53] showed that replacing 30% of cement with zeolite reduces the density by 130 kg/m^3, which means less material is needed, lowering transportation and structural load costs. Since cement is one of the most expensive components in concrete production, this substitution can cut costs by 15–25%, depending on regional cement prices. Additionally, replacing up to 50% of silica sand with zeolite reduces specific weight by 13%, making the concrete lighter while still exceeding high-performance concrete (HPC) strength requirements (85 MPa compressive strength). This could lower foundation and reinforcement costs by reducing structural weight. Moreover, using 10–30% zeolite in place of cement significantly lowers carbon emissions, with a 659.72 kg CO_2 reduction per cubic metre, making it an ideal solution for green building certifications and carbon credit incentives. With construction costs rising due to cement price fluctuations, substituting it with zeolite can provide long-term savings on materials, energy efficiency, and maintenance while promoting environmentally friendly building practices.

Return on Investment (ROI) and Net Present Value (NPV) are important in assessing whether replacing cement and silica sand with zeolite is financially beneficial in the long term. ROI measures the profitability of the investment, while NPV accounts for the future value of savings and costs over time. If the cost of traditional cement per ton is approximately USD125, replacing 30% of cement with zeolite could reduce material costs by 15–25%, leading to savings between USD5625 and USD9375 for a 1000 m^3 concrete project requiring 300 tons of cement. These savings directly reduce the upfront cost of materials, making zeolite-based concrete an economically viable alternative. Additionally, NPV considers long-term savings, such as reduced maintenance and energy costs, due to zeolite's durability and insulation properties. If zeolite-based concrete lowers building energy costs by 10–15% annually, a commercial building saving USD20,000 per year on energy costs could accumulate savings of USD20,000 to USD30,000 over 10 years and USD30,000 to USD45,000 over 15 years. With carbon taxes increasing, using zeolite can also help companies save on emissions-related costs, further improving the financial viability of its adoption. A positive NPV and an ROI above 10% indicate that using zeolite in construction is not just environmentally friendly but also financially sound, offering significant cost savings over time while supporting net-zero construction goals.

3. Research Methodology

Similarly to Awuzie et al. [54], this study adopted a scientometric and narrative review of existing publications in the Scopus database through bibliometric analysis. Just like Rawat and Sood [55] explained in their study, scientometric analysis is useful for this study as it helps to measure and analyse the impact and trends in research related to zeolite and AI in construction materials. It provides valuable insights into the volume, performance, growth, and influence of academic publications in this field. Yousafzai et al. [56] and Awuzie et al. [54] added that a scientometric review became paramount to understanding trends in general studies and linking this back to the set objective of the current study.

Moghayedi et al. [57] and Yang et al. [58] explained that through a narrative review, the study delved into a broader view of the study as it discusses further achieving green construction, net-zero and climate-adaptive buildings, and other conventional materials through zeolite and AI-driven initiatives. Furthermore, Gusenbauer [59] explained that since scientometric analyses are strenuous and document types are limited in number across databases, it does not matter where a search system is conducted as long as it provides documents for analysis. However, the study used bibliographic data from Scopus and Web of Science to eliminate bias. Pranckutė [60] mentioned that these databases help to show how much research has been conducted and where gaps remain. Scopus and Web of Science are reliable sources that provide high-quality research, citations, and scientific studies worldwide [61]. These databases helped to find studies on green construction, zeolite, AI, net-zero, and climate-adaptive buildings, making a detailed scientometric analysis possible. Using both sources ensures a study is thorough, unbiased, well supported, and easy to understand [62]. Furthermore, adding bibliometric analysis enhances the study by focusing on the quantitative aspects of these publications, such as citation counts, authorship patterns, and collaboration networks, allowing for a deeper understanding of how research in this area has evolved and how it is shaping future developments. Together, scientometric and bibliometric analyses give a comprehensive view of the research landscape [25,63].

The Scopus bibliographic data search was carried out in January 2025 and the search protocol used for the bibliographic data was from 2018 to 2025, giving 81 final documents (article = 44; reviews = 29; book and chapter = 6; conference paper = 2) in the English language, and were later subjected to scientometric analysis in a further section of the study. Previous studies by El-Baz and Iddik [64] of 46 documents and Deda et al. [65] of 30 documents refined their studies to give lower document output. Studies by Jeflea et al. [66] and Awuzie et al. [54] had 291 and 461 documents showing that there is no specific range for document refinement as long as it gives concise clusters after the threshold has been met. This study used journal articles, conference proceedings, and books from environmental science, engineering, material sciences, energy, and chemical engineering because these fields provide essential knowledge on sustainable construction materials and technologies [65]. These sources helped in understanding how zeolite and AI improve green construction. The search terms “green”, “construction”, “zeolite”, “climate”, and “artificial intelligence” were chosen to find relevant studies covering both environmental and technological aspects of construction. Using these keywords ensured that publications discussing the role of zeolite and AI in climate-adaptive and net-zero buildings were included, rather than using too many keywords. This approach allowed for a broad yet focused review of the existing research [67].

Similarly, carried out in March 2025, the Web of Science bibliographic data were obtained the same way as the Scopus data, but with different results using different keywords to expand the scope [68]. Subjecting the filtration to articles only for the scientometric analysis, “article”, “title”, and “source”, 2795 final documents were obtained from the initial 5918 documents. The keywords used were “Sustainable construction” OR “Green building design” OR “Low-carbon infrastructure” OR “Zeolite-enhanced materials” OR “Climate-responsive architecture” OR “Carbon-neutral construction” OR “AI-driven smart buildings” OR “Renewable and eco-friendly materials” OR “Resilient urban development” OR “Energy-efficient construction technologies” OR “Machine learning in sustainable design” OR “Zeolite for carbon capture” OR “Climate-adaptive infrastructure” OR “Smart automation in green buildings” OR “Passive design for climate adaptation” OR “Next-generation sustainable materials” OR “Urban heat island mitigation strategies” OR “AI-powered energy optimisation”. Since very few research papers were published between

1984 and the 2000s, this study focuses on data from 2018 to 2025, where more relevant studies exist, as was the case with the Scopus search. This refinement ensured that only the most updated and meaningful research in engineering, construction, nanotechnology, energy, green construction, climate change, and other related fields was analysed, with Table 1 showing publication per country and affiliation. Additionally, refining the data by citation meso topics, as shown in Table 2 below, helped to identify the influence of different research fields in construction and sustainability. The findings were presented based on various parameters, including the number of publications per year, per subject area, per document type, per affiliation, and keyword co-occurrence networks. These networks were visualised using VOSviewer 1.6.20, a software commonly used for bibliometric network visualisation [67]. Bello et al. [67,69] added that VOSviewer selectively displays nodes in a bibliometric network during visualisation and uses distance-based visualisations, making it particularly useful for presenting extensive networks.

Table 1. Publication per country and affiliation.

Affiliation	(n)	(d)	Country
Prince Sattam Bin Abdulaziz University	13	13.00	Saudi Arabia
Saveetha Institute of Medical and Technical Sciences	10	11.50	India
King Khalid University	9	10.67	Saudi Arabia
COMSATS University Islamabad, Abbottabad Campus	9	10.25	Pakistan
Al-Mustaqbal University	8	9.80	Iraq
Universiti Teknologi Malaysia	7	9.33	Malaysia
Assiut University	6	8.86	Egypt

Note: n is the number of publications; d is the average number of publications.

Table 2. Citation meso topic.

Research Field	Impact (I)	Publication (P)
Concrete science	7.121	1334
Sustainable science	6.115	754
Design and manufacturing	4.224	426
Management	6.3	117
Geotechnical engineering	7.113	96
Climate change	6.153	42
Artificial intelligence and machine learning	4.61	27

Quantitative data were also adopted in the study to study the progressive awareness of Artificial Intelligence (AI) involvement in shaping the construction industry. The use of mixed methods, as Pluye and Hong [70] stated, allowed the study to combine numerical data from surveys with in-depth insights from literature analysis, providing a more comprehensive understanding of how zeolites and AI can be integrated into sustainable building designs. The quantitative aspect involved the use of a structured questionnaire distributed through Google Forms to collect data from 53 randomly selected respondents, who were all construction professionals: Civil Engineers (13.2%), Architects (7.5%), Builders (7.5%), Mechanical Engineers (3.8%), Construction Managers (20.8%), Quantity Surveyors (43.4%), and Electrical Engineers (3.8%). These professionals were selected and qualified for the study due to their sufficient experience and educational qualifications in built construction, as shown in Tables 3 and 4 below. Just like the study by Wang et al. [71], before sharing the main survey, a pilot test survey was conducted to check if the questions were clear and if the survey worked well. Six participants took part in the discussion and gave feedback, which was used to improve the variables and objectives. After making the changes, the final survey was carried out. Furthermore, the sampling technique adopted was random as Raifman et al. [72] explained that random sampling is used to ensure that every individual in the population has an equal chance of being selected, making the results more representative and reducing bias. With 53 being the sample size of the study, the data collected were analysed using analytical tools such as Mean Item Score (MIS) and Standard Deviation (SD). Studies by Lopez and Love [73] and Handayani and Moktar [74] used 65 and 50 respondents for their MIS and SD and thus they explained that a sizeable number of respondents is enough to carry out the ranking of variables with respect to the analytical tools mentioned. The data collected were analysed using Statistical Package for Social Sciences (SPSS).

Table 3. Respondents' qualifications.

Degree	Frequency	Percentage
University Diploma	2	3.8
Bachelor's Degree	25	47.2
Master's Degree	17	32.1
Ph.D. Degree	9	17.0

Table 4. Respondents' experience.

Year	Frequency	Percentage
Less than 12 months	5	9.4
1–5 years	19	35.8
6–10 years	12	22.6
11–15 years	7	13.2
16–20 years	4	7.5
21–25 years	2	3.8
Above 25 years	4	7.5

4. Discussion

This section presents the study's results, highlighting key insights and their implications from the above sections detailing the integration of zeolite-based materials and AI technologies in sustainable building designs.

4.1. Scientometric Analysis

4.1.1. Performance Analysis of Zeolite and AI-Driven Initiatives for Net-Zero and Climate-Adaptive Buildings

The scientometric analysis of zeolite and AI-driven initiatives for net-zero and climate-adaptive buildings has grown over time. Figure 1 provides Scopus data from 2018 to 2025, showing the number of publications annually and the cumulative average of publications per year. This analysis helped us to understand how research in this field has developed through VOSviewer software.

Early research trends from 2018 to 2025 show a consistent rise in both the number of publications (n) and average publication (d) in the field, as presented in the table. The first publication appeared in 2018 (n = 1, d = 10.13), followed by another in 2019 (n = 2, d = 11.43), showing a slight increase in both metrics. In 2020, there was a small uptick in publications (n = 1, d = 13.00), marking the beginning of a growing trend. Research activity grew more significantly in 2021 (n = 8, d = 15.40) and 2022 (n = 11, d = 17.25), reflecting a steady rise in both the number of publications and the average publication quality. The trend continued with a larger increase in 2023 (n = 17, d = 19.33), suggesting heightened interest and focus in this area. The highest surge was seen in 2024 (n = 36, d = 20.50), with a dramatic rise in both the quantity and quality of publications.

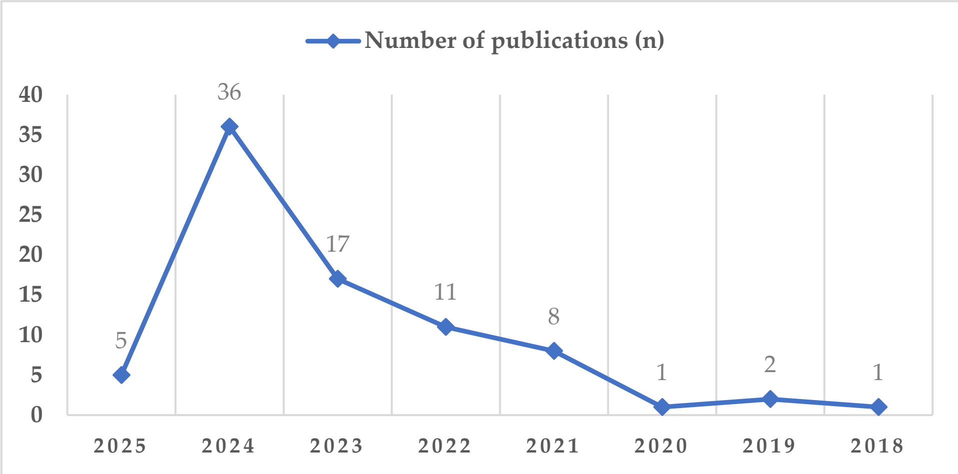

Figure 1. Publications per year.

In 2025, there was a small decrease in the number of publications (n = 5, d = 5.00), though the number remains higher than in the early years of the study, indicating that while the field may have seen a dip in the volume of publications, its overall interest and quality remain notable. The trends observed in the data suggest that the field has seen growing interest and activity over the years. The sharp rise in publications and average publication quality, especially in 2024, indicates that researchers are dedicating more effort to this area, possibly due to new discoveries, emerging technologies, or increased funding and collaboration. The slight decline in 2025 could mean that the field has reached a point of maturity, with fewer new publications being added. However, it does not necessarily imply a decrease in interest. Instead, it might reflect a shift in focus or the completion of certain research phases. Overall, these trends highlight the increasing importance and development of the field, with the peak in 2024 likely marking a key moment in its progression.

Table 1 presents the number of publications (n) and the average publication quality (d) for different academic institutions across various countries. Prince Sattam Bin Abdulaziz University in Saudi Arabia leads with 13 publications (n = 13, d = 13.00), showing a strong output in the field. This is followed by the Saveetha Institute of Medical and Technical Sciences in India, with 10 publications (n = 10, d = 11.50), indicating a notable contribution to the research in the field as well. King Khalid University in Saudi Arabia also made significant contributions with nine publications (n = 9, d = 10.67) and, similarly, COMSATS University Islamabad, Abbottabad Campus, in Pakistan, recorded nine publications (n = 9, d = 10.25), reflecting a solid research output. Al-Mustaqbal University in Iraq contributed eight publications (n = 8, d = 9.80), indicating moderate engagement in the research topic. Universiti Teknologi Malaysia published seven papers (n = 7, d = 9.33) and Assiut University in Egypt had six publications (n = 6, d = 8.86), showing relatively lower but still valuable contributions compared to other institutions in the table.

The data suggest that institutions in Saudi Arabia, particularly Prince Sattam Bin Abdulaziz University and King Khalid University, are leading the research activity in this field, followed by institutions in India and Pakistan. Other universities in Iraq, Malaysia, and Egypt are contributing to the research, but on a smaller scale. The implications of these findings suggest that certain countries, especially Saudi Arabia, India, and Pakistan, are heavily involved in this research area, possibly due to more resources, funding, or institutional support. The lower number of publications from universities in Iraq, Malaysia, and Egypt may reflect fewer research opportunities or smaller research teams in these countries. However, the quality of the publications from all of these institutions is relatively strong, indicating that the research being performed is of significant value, regardless of the publication count.

In addition, other results from Scopus reveal a clear pattern in the types of documents being published. Articles are the most common publication format, with (n = 44) occurrences, suggesting that they make up most of the research output in this dataset. Reviews come next with (n = 29) occurrences, showing a significant amount of comprehensive, summary-based research that likely consolidates existing knowledge in the field. Books and book chapters are much less frequent, with only (n = 2, n = 4) occurrences, respectively, indicating that these formats are not as widely used in the dataset. Conference papers are similarly rare, with just (n = 2) occurrences, pointing to a lower emphasis on presenting research at conferences compared to other document types. Overall, the data indicate that articles and reviews dominate the publication landscape, while books, book chapters, and conference papers are relatively less common. Furthermore, regarding the distribution of publications across subject areas, environmental science emerges as the most researched field, with (n = 38) publications, highlighting its prominence in the dataset. Engineering follows closely behind with (n = 33) publications, indicating strong research activity in this area as well. Energy, with (n = 22) publications, also stands out as a key area of interest, reflecting the ongoing focus on sustainable energy solutions. Materials science and chemical engineering are less represented, with (n = 20, n = 10) publications, respectively, suggesting that these fields receive less attention or fewer research efforts within the dataset. Overall, the data reveals a strong emphasis on environmental science, engineering, and energy-related topics, with less focus on materials science and chemical engineering.

The implications of these findings suggest that the primary areas of research are closely tied to pressing global challenges, such as sustainability and environmental protection, with environmental science and engineering taking centre stage. The significant attention given to energy also aligns with the growing demand for sustainable energy solutions. The lower number of publications in materials science and chemical engineering could reflect a relative shift in research priorities toward more urgent and wide-reaching topics like environmental sustainability. This suggests that the research is heavily influenced by global trends in environmental and energy-focused challenges, with less focus on fields like materials science, which might be considered more niche or specialised in this context.

The scientometric analysis of Table 2 shows the influence of different research fields in construction and sustainability. Concrete science (I = 7.121, P = 1334) has the highest impact and publication count, indicating its dominance in construction research due to its critical role in structural integrity and material development. Sustainable science (I = 6.115, P = 754) follows closely, showing a strong interest in eco-friendly construction practices, highlighting a shift toward green building solutions. Geotechnical engineering (I = 7.113, P = 96) has a high impact but low publication count, meaning it is highly influential but not widely studied. Climate change research (I = 6.153, P= 42) has fewer studies but a strong impact, suggesting that each study significantly contributes to climate-resilient construction strategies. However, Artificial Intelligence (AI) and Machine Learning (ML) (I = 4.61, P = 27) have the lowest impact and publication count, indicating that AI-driven construction research is still in its early stages.

These findings have important implications for revolutionising green construction. The low publication count in AI and ML suggests that more research is needed to explore how AI can optimise sustainable construction through automated design, predictive maintenance, and energy efficiency, hence the need for the study and Table 5 in the first place. Given the high impact of climate change research, integrating AI-driven tools into climate-adaptive building designs could significantly improve resilience against extreme weather and reduce carbon emissions. Additionally, since sustainable science already has a strong presence, combining it with AI could accelerate the development of net-zero and eco-friendly materials like zeolite-based concrete [10,14]. Increasing research efforts in AI-driven sustainable construction will help to bridge the gap between technology, materials, and climate adaptation, ensuring a greener and smarter future for the built environment.

Table 5. Smart technologies in construction.

Technologies in Construction	Mean	Std. Deviation
Computer-Aided Design (CAD)	4.45	0.637
4D Simulations	4.42	0.745
Building Information Modelling (BIM)	4.40	0.862
Augmented Reality (AR) and Virtual Reality (VR)	4.32	0.872
3D Printing/Additive Manufacturing	4.28	0.841
Construction Wearables	4.28	0.744
Drones and Unmanned Aerial Vehicles (UAVs)	4.25	0.806
Autonomous Vehicles and Equipment	4.19	0.856
Artificial Intelligence (AI) and Machine Learning (ML)	4.19	0.856
Internet of Things (IoT)	4.19	0.786
Construction Exoskeletons	4.19	0.900
Robotics and Automation	4.11	0.870
Smart Sensors and Wearables	4.06	0.949
Cloud-based Workflow Technology	4.04	0.898
Blockchain Technology	3.92	0.997
Laser Scanning	3.83	0.955

4.1.2. Visualised Analysis of Zeolite and AI-Driven Initiatives for Net-Zero and Climate-Adaptive Buildings

In creating a co-occurrence map using bibliographic data, it is important to set a minimum number of co-occurrences to accurately extract keywords and group them into clusters that represent key areas of previous research. Acknowledging its limitations, this study applied a minimum of five co-occurrences for the VOSviewer analysis to create the clusters, as shown in Figure 2. This choice was supported by the increasing knowledge of green construction in various industries, as Martín-Martín et al. [75] have explained. Furthermore, regarding the number of co-occurrences, Aghimien et al. [67] and Saka and Chan [76] argued that the results of a study are closely tied to the keywords entered in the search and that this should not restrict the research. This study identified 1276 keywords from all of the publications reviewed, with 29 meeting the threshold of five co-occurrences. These were then grouped into three (3) clusters, and subsequently the potential of integrating zeolite-based materials and AI-driven technologies to create net-zero, climate-adaptive buildings was discussed.

Cluster One: Sustainable technology—This is denoted in red and contains thirteen items, including adsorption, Artificial Intelligence, carbon dioxide, energy, energy efficiency, global warming, greenhouse gases, machine learning, nanomaterials, renewable energy, sustainable development, and water treatment. Sustainable technology plays a vital role in revolutionising green construction by combining the unique properties of zeolites, such as analcime, chabazite, clinoptilolite, heulandite, natrolite, phillipsite, and stilbite, with AI-driven initiatives to create net-zero and climate-adaptive buildings. Zeolites are highly effective in capturing carbon dioxide due to their excellent adsorption properties, helping to reduce the greenhouse gas emissions from buildings [3,21]. The authors also noted that, for instance, clinoptilolite and chabazite are widely used in air purification systems to trap CO_2, enhancing indoor air quality and contributing to a building's overall energy efficiency. Zeolites are also critical in water treatment systems, where they filter pollutants and ensure sustainable water management in buildings, making them more adaptable to varying environmental conditions. Additionally, AI and machine learning technologies complement the use of zeolites by optimising their applications. Wang et al. [77] emphasised that AI analyses energy patterns, environmental data, and material performance to recommend the most efficient use of zeolite-based systems. It also enables predictive maintenance, ensuring that zeolite systems operate at peak efficiency with minimal resource use. Together, sustainable technology, zeolites, and AI-driven approaches offer innovative solutions for designing energy-efficient buildings that are environmentally sustainable and resilient to climate change.

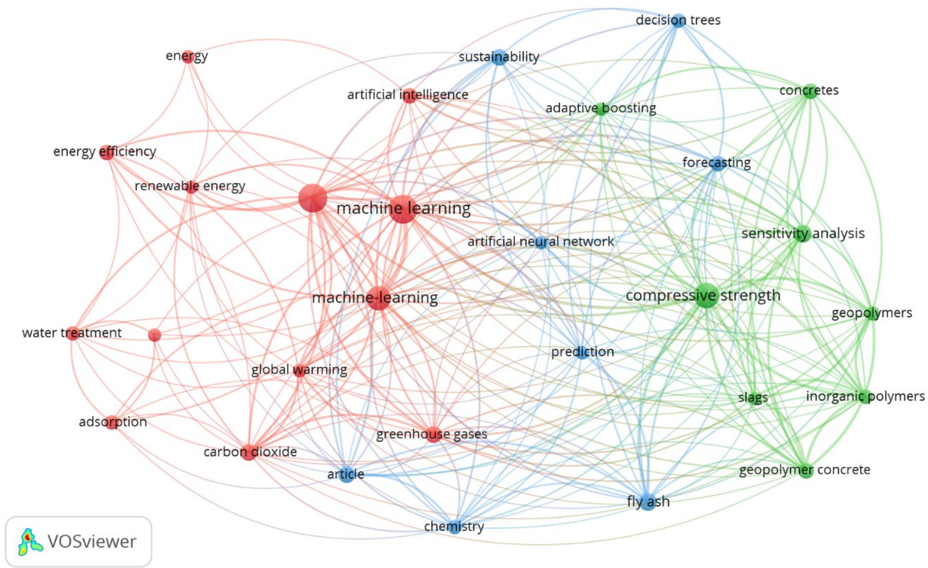

Figure 2. Occurrence network visualisation.

Cluster Two: Geopolymer engineering—This is denoted in green and contains eight items, including adaptive boosting, compressive strength, concretes, geopolymer concrete, geopolymers, inorganic polymers, sensitivity analysis, and slags. Geopolymer engineering is a crucial element in revolutionising green construction, especially when combined with zeolites alongside AI-driven initiatives, to create net-zero and climate-adaptive buildings. Azad and Samarakoon [78] explained that geopolymers from inorganic materials such as slags provide a sustainable alternative to traditional cement by producing significantly lower carbon emissions during production. The study added that geopolymer concrete, enhanced with zeolites, improves compressive strength and durability, making it ideal for constructing energy-efficient and climate-resilient buildings. Yussuf and Asfour [79] noted that techniques like sensitivity analysis ensure optimal mix design for specific building conditions, while adaptive boosting powered by AI predicts performance and adjusts formulations to achieve maximum efficiency. Rożek et al. [80] found that zeolites further enhance the performance of geopolymers by acting as catalysts in chemical reactions, improving thermal insulation and CO_2 absorption. From the above, it can be inferred that geopolymer engineering and AI-driven tools reduce emissions and ensure buildings' adaptability to environmental changes, making them a cornerstone of sustainable construction.

Cluster Three: Sustainable forecasting—This is denoted in blue and contains seven items, including artificial neural network, chemistry, decision trees, fly ash, forecasting, prediction, and sustainability. Sustainable forecasting techniques, including artificial neural networks, decision trees, and predictive models, are crucial in revolutionising green construction by integrating zeolites with AI-driven initiatives to achieve net-zero and climate-adaptive buildings. These forecasting tools utilise data from material properties, environmental conditions, and construction processes to predict the performance and environmental impact of construction materials like zeolites and fly ash-based products [81]. For example, artificial neural networks and decision trees can model the chemical interactions within geopolymer mixes or predict the adsorption efficiency of zeolites for carbon capture, ensuring optimal material usage. Forecasting also enables sustainability by estimating the long-term energy efficiency, durability, and climate resilience of buildings constructed with these materials [82]. Additionally, fly ash, a byproduct of industrial processes, is often combined with zeolites and other green materials to enhance their properties while reducing waste [83]. Thus, by combining these advanced prediction tools with sustainable materials, the construction industry can better design and plan buildings that minimise emissions, conserve resources, and adapt to changing climate conditions, making green construction more efficient and impactful.

4.2. Quantitative Analysis

Table 3 shows the educational qualifications of the respondents, confirming that they are highly qualified to provide reliable insights for the study. The majority hold at least a Bachelor's Degree (47.2%), followed by Master's Degree holders (32.1%), and a significant number have Ph.D.s (17.0%), indicating advanced expertise in their fields. Although a small percentage (3.8%) have only a University Diploma, their contributions still add practical knowledge. These qualifications suggest that the respondents have the academic and professional background needed to assess AI-driven green construction, zeolite applications, and climate-adaptive building strategies. Their expertise ensures that the study's findings are credible and relevant to advancing net-zero and sustainable construction solutions.

Table 4 presents the work experience of the respondents, confirming that they have sufficient industry knowledge to provide valuable insights for the study. The majority have 1–5 years of experience (35.8%), followed by those with 6–10 years (22.6%), indicating that most respondents have a solid foundation in their field. Additionally, 13.2% have 11–15 years of experience, while 7.5% each have 16–20 years and over 25 years, demonstrating long-term expertise in construction, AI applications, and sustainability. Even those with less than 12 months of experience (9.4%) contribute fresh perspectives to the study. These figures confirm that the respondents have a strong mix of experience levels, making them well qualified to evaluate AI-driven green construction, zeolite applications, and climate-adaptive building strategies. Their insights help to ensure that the study's findings are both practical and forward-thinking in advancing net-zero and sustainable construction solutions.

Table 5 highlights the significance of smart technologies in modern construction, particularly their role in advancing AI-driven green construction for net-zero and climate-adaptive buildings. AI and machine learning (ML) (mean = 4.19, SD = 0.856) play a key role in optimising energy efficiency, predictive maintenance, and material selection [10,84]. The integration of Building Information Modelling (BIM) (mean = 4.40, SD = 0.862) and 4D Simulations (mean = 4.42, SD = 0.745) enhances sustainable design by enabling real-time decision-making and performance analysis. Additionally, IoT (mean = 4.19, SD = 0.786) and smart sensors (mean = 4.06, SD = 0.949) facilitate automated monitoring of environmental impact, ensuring compliance with green building standards [1,14,15]. The high mean scores indicate strong industry adoption, validating AI's transformative potential in reducing carbon footprints and enhancing sustainability in construction.

5. Narrative Findings

This section explores the role of zeolite and AI-driven initiatives in advancing green construction, net-zero buildings, and climate-adaptive buildings. Zeolite, a naturally occurring mineral, has shown the potential to improve sustainability by enhancing energy efficiency and reducing carbon footprints. Combined with Artificial Intelligence, these technologies can optimise building design, construction, and management, helping to create structures that are not only energy-efficient but also adaptable to changing climate conditions. This approach holds promise for addressing global challenges such as climate change and resource depletion while promoting sustainable development in the construction industry.

5.1. Zeolite and AI-Driven Initiatives for Green Construction

Zeolite, a naturally occurring mineral, has gained considerable attention for its potential in green construction due to its unique properties [2,5], as summarised in Table 6. This mineral has a high surface area and ion exchange capabilities and is abundantly available, making it an ideal material for improving sustainability in the built environment [8,24]. In construction, zeolite can be incorporated into building materials like concrete and insulation, where it helps to absorb moisture and regulate temperature [20,25,81]. This thermal regulation reduces the need for external heating and cooling systems, which are typically energy intensive. For example, zeolite in concrete has been shown to enhance thermal performance, helping to keep indoor temperatures more stable throughout the day and thereby reducing energy consumption [24,81]. Moreover, zeolite's ability to absorb pollutants, such as harmful gases and heavy metals, from the air and water provide an added environmental benefit [85,86]. When used in construction, zeolite can help to purify indoor air, contributing to better air quality and overall health in buildings, which is especially important in green construction projects that aim for sustainability and long-term environmental benefits.

Artificial intelligence (AI)-driven initiatives are also transforming the construction industry by optimising the design, construction, and management of buildings. AI technologies can process vast amounts of data to enhance decision-making and improve building efficiency [11]. In terms of green construction, AI is utilised to analyse energy use patterns and identify ways to reduce waste, maximise natural resources, and optimise structural designs for environmental performance [39]. One of the most effective uses of AI in this field is through the implementation of Building Management Systems (BMSs), which are intelligent systems designed to control and monitor various building functions, including lighting, temperature, and ventilation [84]. These systems can adjust heating, ventilation, and air conditioning (HVAC) settings in real time based on occupancy or weather conditions, leading to substantial energy savings and more efficient use of resources. AI is also used to optimise material usage, reduce construction waste, and improve the overall environmental footprint of buildings by making smarter choices during the design and construction phases [43].

The combination of zeolite and AI-driven technologies in green construction offers an exciting opportunity to develop buildings that are both environmentally friendly and adaptable to future climate challenges. Zeolite's natural properties, such as moisture absorption and air purification, work in harmony with AI's ability to optimise energy usage and building performance [11,85,86]. For example, AI could be used to monitor the condition of zeolite-enhanced materials, tracking their ability to maintain optimal thermal performance over time. Additionally, AI systems could adjust heating, cooling, and air quality management systems based on real-time data, further enhancing the effectiveness of zeolite in maintaining a stable and energy-efficient indoor environment [24,84]. This combination of materials and technology aligns well with the goals of net-zero buildings, which are designed to generate as much energy as they consume. By integrating these innovative technologies, buildings can become more energy-efficient, reducing their carbon footprint and helping to meet global sustainability targets. Furthermore, climate-adaptive buildings, which can adjust to environmental conditions and future climate changes, would benefit from this. AI can forecast and adapt to climate conditions, while zeolite-based materials can help buildings to better cope with heat, humidity, and air quality issues, making them more resilient to climate change [87]. In addition, according to Vijayan et al. [88], zeolite and AI-driven initiatives play a key role in advancing green construction by combining sustainable technology, geopolymer engineering, and sustainable forecasting. Zeolites are highly effective in capturing carbon dioxide, improving air quality, and enhancing energy efficiency in buildings by adsorbing pollutants. When paired with AI, such as machine learning, their applications are optimised, allowing for more efficient use of materials and predictive maintenance [84,88]. This collaborative approach not only improves the sustainability of the built environment but also contributes to creating healthier, more comfortable spaces for occupants, ultimately fostering a more sustainable future for the construction industry.

Table 6. Summary of zeolite and AI-driven initiatives in green construction.

Variable	Short Summary	Authors
Zeolite	A naturally occurring mineral with high surface area and ion exchange capabilities, used in construction for thermal regulation, moisture absorption, and air purification. It reduces energy consumption and improves sustainability.	[2,5,8,24,85,86]
Artificial Intelligence (AI)	AI technologies enhance construction efficiency by processing data to optimise energy use, structural designs, and material usage. AI-driven systems, like Building Management Systems (BMSs), help to reduce energy consumption.	[11,39,43,84]
Zeolite in concrete	Zeolite enhances thermal performance in concrete, helping to regulate indoor temperatures and reducing reliance on HVAC systems, lowering energy consumption.	[24,25,81]
Building Management Systems (BMSs)	AI-driven BMSs optimise building energy use by adjusting lighting, temperature, and ventilation in real time, leading to substantial energy savings and efficient resource use.	[84]
Net-zero buildings	Buildings are designed to generate as much energy as they consume. Zeolite and AI technologies play a key role in making these buildings energy-efficient and adaptable to climate challenges.	[11,24,84–86]
Climate-adaptive buildings	Buildings that can adjust to environmental conditions and future climate changes. Zeolite helps to manage heat, humidity, and air quality, while AI can forecast and adapt to climate conditions.	[87]
Sustainable technology	Combining zeolite's pollutant absorption with AI's optimisation tools for energy efficiency. It also supports carbon capture and enhances air quality in buildings.	[11,85,86,88]
Geopolymer engineering	Incorporating zeolites into geopolymer concrete, improving its strength and durability, while reducing carbon emissions. AI tools optimise the design for better performance.	[88]
Sustainable forecasting	AI-driven tools like machine learning, decision trees, and artificial neural networks predict material performance and environmental impact, helping to ensure that buildings are energy-efficient, durable, and climate-resilient.	[84,88]
Carbon capture and adsorption	Zeolites help to capture and adsorb carbon dioxide, pollutants, and heavy metals, improving indoor air quality and contributing to a sustainable built environment.	[85,86,88]

5.2. Zeolite and AI-Driven Initiatives for Net-Zero Buildings

Zeolite plays a vital role in creating net-zero buildings, which are buildings that generate as much energy as they consume over the course of a year. As summarised in Table 7, one of the main reasons that zeolite is useful in these buildings is because of its ability to store and release heat [24,86]. This mineral has a high surface area that allows it to absorb moisture and heat, which helps in keeping indoor temperatures stable. By using zeolite in building materials such as insulation, the need for additional heating or cooling systems is reduced [5,86]. This is because the zeolite helps to regulate the temperature inside, making the building more energy-efficient. For example, zeolite-based insulation materials have been shown to lower energy consumption by maintaining a comfortable indoor temperature without the need for air conditioning or heating systems [6,84]. This reduction in energy use is important in making buildings more sustainable, as it decreases the demand for energy from non-renewable sources, helping to achieve the goal of net-zero buildings.

Table 7. Summary of zeolite and AI-driven initiatives for net-zero buildings.

Variable	Summary	Authors
Zeolite in net-zero buildings	Zeolite is used in net-zero buildings to regulate indoor temperature by storing and releasing heat, reducing the need for HVAC systems. It helps to achieve energy efficiency and reduces non-renewable energy demand.	[5,6,24,84,86]
Energy efficiency through zeolite	Zeolite's heat-regulating properties in insulation materials help to maintain stable indoor temperatures, reducing energy consumption by eliminating the need for additional heating or cooling systems.	[5,6,84,86]
AI-driven Building Management Systems (BMSs)	AI systems like BMS process data from energy consumption, environmental conditions, and material performance, optimising heating, cooling, and lighting to increase energy efficiency and reduce consumption.	[11,39,43,84,89]
Building optimisation	AI processes data to make real-time adjustments in energy systems (heating, cooling, ventilation), improving efficiency and helping to achieve net-zero energy goals.	[11,39,43,84]
Long-term sustainability and maintenance	AI monitors zeolite-based systems and predicts when maintenance is needed, improving long-term sustainability by reducing the need for repairs or replacements and conserving resources.	[84,86,88,90]
Predictive maintenance with AI	AI enables predictive maintenance for zeolite-based systems, extending their lifespan, maintaining energy efficiency, and reducing waste by anticipating cleaning or repairs.	[84,88,90]
Carbon capture and air quality	Zeolite captures CO_2 and purifies air, improving indoor air quality and enhancing energy efficiency in net-zero buildings.	[86]
AI and geopolymer engineering	AI helps to design energy-efficient buildings by analysing materials like zeolite in geopolymer concrete, improving performance and reducing carbon emissions.	[88,89]
Climate adaptation	Zeolite enhances a building's resilience to climate change, while AI optimises energy usage and predicts maintenance needs, ensuring that buildings adapt to environmental challenges.	[84,86]
Sustainable forecasting	AI technologies, including machine learning and predictive modelling, help to forecast material performance and environmental impact, ensuring buildings are energy-efficient and resilient.	[84,88,89]

According to Ashraf et al. [89], Artificial Intelligence (AI) further improves the performance of zeolite in net-zero buildings by optimising energy usage and making systems more efficient. AI can process large amounts of data related to a building's energy consumption, environmental conditions, and the performance of zeolite-based materials. With this information, AI can make real-time adjustments to a building's energy systems, such as heating, ventilation, lighting, and cooling, to make sure that energy is being used as efficiently as possible [11,43]. For example, AI-driven Building Management Systems (BMSs) can adjust the settings of HVAC systems automatically based on factors like the number of people inside the building or the outdoor temperature, leading to energy savings [39,84]. By using AI in combination with zeolite, buildings can become smarter and more energy-efficient, which helps in reducing energy consumption and moving closer to achieving net-zero energy goals.

In addition to improving energy efficiency, the integration of AI with zeolite materials provides a solution for long-term sustainability and maintenance of net-zero buildings [86]. AI can monitor the performance of zeolite-based systems, ensuring that they continue to work effectively over time. For example, AI can predict when zeolite-based air purification systems might require cleaning or maintenance before they become inefficient [90]. This helps to maintain the building's energy efficiency over the years, avoiding unnecessary repairs or replacements. Furthermore, predictive maintenance powered by AI can also extend the lifespan of zeolite-enhanced systems, making the building more sustainable by reducing waste and conserving resources [84,88]. From these studies, it can be inferred that combining zeolite's heat-regulating properties with AI's ability to optimise building systems creates a powerful approach to designing net-zero buildings. This combination not only helps in reducing energy use but also ensures the long-term sustainability of the building by improving its efficiency, maintenance, and adaptability to changing conditions.

5.3. Zeolite and AI-Driven Initiatives for Climate-Adaptive Buildings

Table 8 shows that zeolite and AI-driven initiatives are becoming important tools in the creation of climate-adaptive buildings, which are designed to adjust to changing environmental conditions. In climate-adaptive buildings, zeolite can be used in insulation and building materials to improve thermal regulation [91]. This helps the building maintain a stable indoor temperature, even during extreme weather events. For example, zeolite can help to cool the building in hot conditions and retain warmth during cold weather, reducing the reliance on traditional heating and cooling systems [92]. By using zeolite in this way, buildings can adapt to varying climates, reduce energy consumption, and improve indoor comfort.

Artificial intelligence (AI) complements the use of zeolite by optimising building systems to respond to environmental changes in real time. AI systems can analyse data from various sensors, such as temperature, humidity, and air quality, to adjust the building's energy systems as needed [84,86]. For example, AI-driven Building Management Systems (BMSs) can regulate heating, cooling, and ventilation in response to outdoor temperature fluctuations or changes in indoor occupancy [39,43]. This ensures that the building stays comfortable without wasting energy. In climate-adaptive buildings, AI can also forecast weather patterns and adjust energy use accordingly [88]. By combining zeolite's natural properties with AI's smart optimisation, buildings can become more responsive to external climate changes, improving their resilience to extreme weather events. Furthermore, the combination of zeolite and AI-driven technologies helps improve the overall sustainability of climate-adaptive buildings by making them more efficient in resource use and maintenance. Zeolite's ability to filter pollutants, like carbon dioxide, from the air contributes to healthier indoor air quality, while AI helps to monitor and predict the performance of zeolite-based systems [24,84]. The authors illustrated that AI can also ensure that these systems operate at peak efficiency by predicting when maintenance is needed, avoiding unnecessary repairs and reducing waste. Together, zeolite and AI-driven initiatives offer a powerful solution for creating buildings that are both adaptable to changing climates and sustainable over the long term.

Table 8. Summary of zeolite and AI-driven initiatives for climate-adaptive buildings.

Variable	Summary	Authors
Climate-adaptive buildings	Zeolite's ability to absorb heat, moisture, and pollutants makes it valuable for thermal regulation in climate-adaptive buildings, helping to maintain indoor temperatures in extreme weather conditions.	[24,84,91,92]
Thermal regulation with zeolite	Zeolite used in insulation materials helps buildings to stay cool in hot weather and warm in cold weather, reducing the need for traditional HVAC systems and enhancing energy efficiency.	[91,92]
AI-driven Building Management Systems (BMSs)	AI systems monitor building conditions like temperature, humidity, and air quality and adjust HVAC systems to ensure efficient energy use in response to environmental changes.	[39,43,84,86]
Smart optimisation	AI optimises building energy systems by analysing real-time data and making adjustments based on environmental conditions, improving energy efficiency and comfort.	[84,86,88]
Sustainability	Zeolite helps to improve indoor air quality by filtering pollutants like CO_2, while AI monitors and predicts the performance of zeolite-based systems, ensuring energy efficiency and reducing waste.	[24,84]
Predictive maintenance	AI monitors the performance of zeolite systems and predicts when maintenance is required, ensuring continued energy efficiency and reducing unnecessary repairs or replacements.	[84,88]
Carbon capture and air quality	Zeolite captures CO_2 and purifies air, reducing greenhouse gases and improving indoor air quality, making buildings more energy-efficient and environmentally friendly.	[24,84]
Energy efficiency	AI optimises energy consumption by predicting building energy needs based on environmental data, helping buildings become more energy-efficient and resilient to extreme weather.	[84,86,88]
Climate adaptation	Zeolite enhances a building's ability to adapt to varying climates, while AI optimises system performance, ensuring that buildings remain comfortable and energy-efficient despite climate changes.	[91,92]
Sustainable development	The combination of zeolite and AI in construction supports sustainable development by creating adaptable, energy-efficient buildings that reduce carbon emissions and waste.	[84,86,88]

5.4. Cost Benefits of Zeolite and AI-Driven Initiatives over Other Construction Materials

Zeolite and AI-driven initiatives offer substantial cost benefits when compared to traditional construction materials. Traditional materials like fibreglass insulation, concrete, and asphalt often require more energy to maintain comfortable indoor temperatures, increasing long-term operating costs [93]. For example, concrete absorbs a lot of heat, leading to higher cooling costs in warmer climates, and fibreglass insulation tends to lose efficiency over time. In contrast, zeolite has natural thermal properties that allow it to absorb and release heat efficiently. Zeolite-based insulation can help to maintain stable indoor temperatures without relying heavily on air conditioning or heating systems [91,92]. This reduction in energy use not only lowers utility bills but also makes zeolite a cost-effective option in the long run.

AI-driven initiatives further amplify these cost savings by optimising energy usage and reducing waste. Asdrubali et al. [94] stated that traditional construction materials such as wood, brick, and steel often contribute to higher operational costs because they do not adjust to changes in temperature or energy demand. For example, heating and cooling systems in buildings with brick or wood structures often need to run for longer and work harder to maintain comfort levels, especially during extreme weather conditions. AI can be integrated into Building Management Systems (BMSs) to monitor real-time data, such as temperature, humidity, and energy consumption, and make automatic adjustments to the building's energy systems [39,86]. AI can reduce energy waste by up to 30% in some cases by managing lighting, HVAC, and other systems more efficiently [95]. When paired with zeolite's natural thermal regulation, AI-driven systems can create an even more energy-efficient environment, leading to significant savings over time [24,84,88]. Compared to traditional materials, this combination offers a more adaptive and energy-efficient solution, which lowers overall operational costs.

When comparing zeolite and AI-driven initiatives to other construction materials, the cost benefits go beyond just energy savings. Materials like steel, traditional concrete, and synthetic insulation often have high environmental and financial costs [96]. The production of concrete and steel is energy-intensive, contributing to a high carbon footprint. For instance, producing one ton of steel emits a large amount of CO_2, while the cement industry alone is responsible for approximately 8% of global CO_2 emissions [97,98]. In contrast, zeolite helps to capture CO_2, and when mixed with geopolymer concrete, it can lower the carbon emissions of the material by up to 50–70% [99]. Additionally, AI can optimise predictive maintenance, ensuring that zeolite-based systems perform efficiently for longer periods, reducing the need for repairs or replacements. AI-driven maintenance has been shown to cut maintenance costs by 10–15% [84,100,101]. These savings, combined with the longer lifespan of zeolite-enhanced materials, make them a more cost-effective and sustainable option compared to conventional materials like concrete or synthetic insulation. In summary, the combination of zeolite's energy efficiency and AI's smart optimisation creates a cost-effective and sustainable solution that reduces both construction and long-term operational costs.

6. Conclusions

This study contributes important insights into the growing field of sustainable construction by exploring the combined use of zeolite and AI-driven technologies in creating energy-efficient, climate-adaptive, and net-zero buildings. Zeolite, with its unique ability to regulate temperature and filter pollutants, enhances building performance by improving energy efficiency and indoor air quality. When integrated with AI systems that optimise energy use and assist with predictive maintenance, zeolite-based materials offer an effective solution for reducing energy consumption and increasing the lifespan of buildings. This study shows how combining natural materials like zeolite with advanced technologies like AI can contribute to smarter, more environmentally sustainable construction practices better than using traditional materials. This combination is key to the future of green construction, helping to build net-zero and climate-resilient buildings while reducing costs and environmental impact. The findings emphasise the importance of using innovative technologies and sustainable materials to create buildings that not only meet modern needs but also address the challenges of climate change.

The cost–benefit analysis presented in this study clearly demonstrates that implementing AI and zeolite in construction materials can lead to significant savings over time. Although the initial cost of zeolite-based materials may be higher than traditional construction options such as fibreglass insulation, the long-term benefits make it a more cost-effective choice. For example, zeolite's ability to absorb and release heat helps to reduce the need for artificial heating and cooling, leading to lower energy bills. When AI is incorporated into building systems, it further enhances energy efficiency by adjusting heating, cooling, and lighting based on real-time data. This combination of zeolite and AI has been shown to cut energy costs by 20–30%, while AI-powered predictive maintenance can lower repair and maintenance expenses by 15–20%. In comparison to traditional building materials, this combination offers a more sustainable and cost-efficient alternative, ultimately leading to reduced operational costs and a more efficient building overall.

Despite the promising results, this study does have some limitations. One of the main challenges is the lack of real-world case studies and data on the long-term performance of zeolite and AI technologies in actual construction projects. While the theoretical benefits are clear, it is important to conduct further research to understand how these technologies perform in different building types, climates, and environments. Future studies could focus on integrating zeolite and AI with other sustainable technologies, such as solar panels, rainwater harvesting systems, or green roofing, to explore even more ways to improve building sustainability. Additionally, more research is needed to examine the life-cycle costs and environmental impact of combining zeolite and AI in various construction projects to help make informed decisions about their adoption. As these technologies continue to evolve, further investigation into their scalability and how they can be adapted to various construction practices will be crucial in fully realising their potential for creating environmentally friendly, cost-effective buildings in the future. Lastly, this study used the Scopus database only, which might not fully represent all documents related to this field.

Author Contributions: Conceptualization, S.S. and C.A.; methodology, S.S. and A.O.; software, S.S.; validation, S.S. and C.A.; formal analysis, S.S.; investigation, S.S. and C.A.; resources, S.S. and C.A.; data curation, S.S.; writing—original draft preparation, S.S.; writing—review and editing, S.S. and A.O.; visualisation, S.S.; supervision, C.A. and A.O.; project administration, S.S. and C.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data for the study will be supplied when requested. However, the data can be accessed at https://docs.google.com/forms/u/1/d/1aiYB_KwttES279PvQjcaj2kc-4MnuwCWlxMuW920Ye8/edit?ts=65c14336 (accessed on 9 March 2025).

Acknowledgments: This study acknowledges SARCHI at the University of Johannesburg, South Africa, for their immense contribution to developing scholars.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

SDGs	Sustainable development goals
SPSS	Statistical Package for Social Sciences
BMS	Building Management System
CAD	Computer-Aided Design

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