Research Article

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Optimizing Green Construction: The Role of Artificial Intelligence and Nanotechnology in Energy, Emission, and Waste Management

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ABSTRACT

The construction sector is a significant global consumer of energy and a major source of carbon emissions and waste. This review examines the potential of Artificial Intelligence (AI) and nanotechnology to mitigate these challenges. Artificial intelligence techniques, such as neural networks and metaheuristic algorithms, are evaluated for optimizing resource distribution and reducing emissions. Nanotechnology, through the use of advanced materials and sensors, enhances material durability and enables real-time monitoring. By integrating AI with renewable energy and nanotechnology-enabled IoT systems, this study identifies pathways toward near-zero carbon construction. The findings highlight the need for interdisciplinary cooperation and policy support to promote sustainable construction practices globally.

Keywords: Carbon emissions; Construction waste; Energy consumption; Hybrid models; Metaheuristic algorithms and Nanomaterials.

1. INTRODUCTION

The construction industry is crucial for economic growth but also contributes significantly to environmental degradation through high energy consumption, carbon emissions, and waste production. In 2023, construction activities accounted for 38-40% of global energy demand and one-third of CO_2 emissions, underscoring the significant environmental impact of the construction sector (Ajayi *et al.* 2024; Asdrubali, 2025). While green materials and energy-saving measures have been implemented, these strategies often fall short of achieving net-zero carbon goals due to inconsistent regulatory frameworks and limited technological adoption (Bera *et al.* 2025). As urbanization and infrastructure needs grow, there is a pressing need for advanced energy conservation and optimization techniques to reduce the ecological footprint of the built environment (Madlener and Sunak, 2011; Shahidehpour *et al.* 2018). Emerging technologies such as Artificial Intelligence (AI) and nanotechnology hold transformative potential for optimizing resource use and minimizing waste. Nanotechnology enables the fabrication of materials with advanced thermal, mechanical, and catalytic properties, such as self-cleaning concrete and high-performance insulation, while also supporting real-time energy monitoring through nano-enabled sensors. Simultaneously, AI-driven models provide the computational capabilities necessary for effective energy management and waste optimization (Rane, 2023a). This review examines the integration of these technologies to establish a scalable framework for sustainable green solutions, focusing on the interplay between energy demand, emissions, and waste management.

2. ENERGY CONSUMPTION, CARBON EMISSION AND WASTE IN CONSTRUCTION INDUSTRY

The construction sector plays a vital role in driving the global economy but simultaneously contributes to significant environmental pollution due to its excessive consumption of energy, carbon, and waste. In 2023, the sector was responsible for 38-40% of global energy consumption and one-third of global CO_2 emissions, underscoring its substantial global footprint (Ajayi *et al.* 2015; Asdrubali, 2025). While energy-saving measures and green materials are steps in the right direction, they are insufficient to meet net-zero carbon targets due to inconsistent regulations and low adoption rates in many regions (Bera *et al.* 2025). With urban populations continuing to grow and infrastructure demands increasing, it is crucial to focus on energy conservation, optimization, and reducing the environmental impact of buildings (Madlener and Sunak, 2011; Shahidehpour *et al.* 2018). Artificial intelligence and nanotechnology are emerging as critical tools in the construction sector to address these challenges. Nanomaterials with enhanced thermal, mechanical, and catalytic properties are essential for applications such as self-cleaning concrete, improved insulation, and real-time energy monitoring sensors. Additionally, AI-based

systems can help optimize energy use, resource management, and waste reduction in the construction process (Rane, 2023a). By better understanding energy consumption, emissions, and waste generation, these technologies can help develop scalable solutions for sustainable, low-carbon construction practices.

2.1 v Consumption in Construction Processes

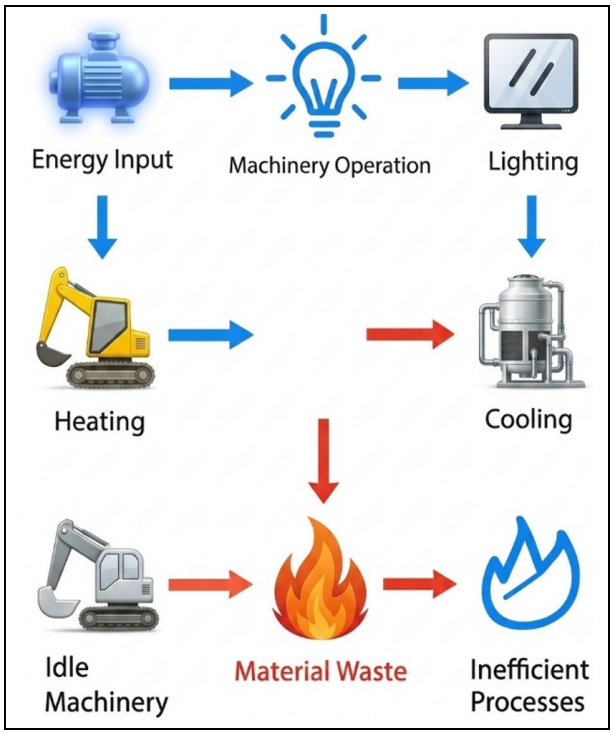


Fig. 1: Schematic of energy flow in construction industry

Fig. 1 illustrates the energy flow in construction, highlighting the complex relationship between material fabrication, transportation, and on-site energy use. On-site energy for machinery, lighting, and temperature control typically accounts for 20–25% of total project energy. The embodied energy of cement and steel mainly comes from indirect energy used in raw materials. Cement production, driven by high-temperature kilns and fossil fuels, is highly energy-intensive, requiring 3-7 GJ/ton. Site energy use varies with project size, building type, and location, with labor-intensive workflows and poor equipment scheduling contributing to higher energy consumption in conventional construction (Kisi *et al.* 2017; Kisi *et al.* 2018). Prefabrication, modular construction, and machine electrification help reduce energy use on-site (Pless *et al.* 2022; Mehraban *et al.* 2025). AI-based algorithms and nanotechnology-based materials could enhance efficiency and reduce building heating and cooling energy needs (Manuel *et al.* 2024; Vetrivel *et al.* 2026; Hussein *et al.* 2023). However, data recording system limitations, energy infrastructure disparities, and cost constraints hinder energy management. Advanced technologies and hybrid AI-metaheuristic models could address these challenges, supporting energy-neutral construction in line with global climate goals (Iqbal *et al.* 2021; Chen *et al.* 2024a).

2.2 Carbon Emissions in Construction Process

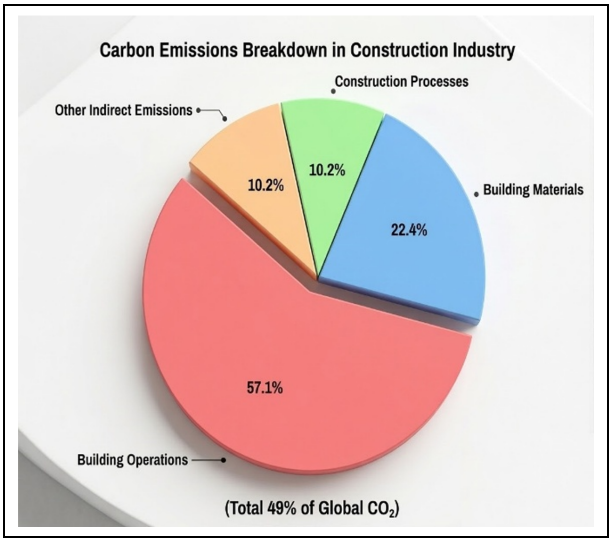


Fig. 2: Statistics of CO_2 emissions in construction sector

The construction industry significantly contributes to global CO_2 emissions. Fig. 2 illustrates sector-specific data. Building operations, including energy use for heating, cooling, and lighting, account for 28% of emissions. Material production (cement, steel, glass) adds 11%, due to energy-intensive manufacturing and high embodied carbon. Direct emissions from machinery, fuel use, and material transport make up 5%, while supply chain logistics, waste, and ancillary services contribute another 5%. Together, these areas account for 49% of global CO_2 emissions in the built environment, highlighting the need for low-carbon solutions throughout the construction lifecycle. Operational carbon is produced during use and maintenance, while material extraction, manufacturing, and transport release embodied carbon. Cement and steel production alone contribute 7-8% of global CO_2 emissions (Benhelal *et al.* 2013). Nanomaterial-based geopolymer cements and recovered steel reduce carbon intensity (Valente *et al.* 2021). Upstream activities emit 70-80% of carbon, with on-site emissions largely due to fuel burning (Jin *et al.* 2017). AI and LCA models help estimate emissions and inform decision-making (Mehraban *et al.* 2025). Modular construction, reuse, and AI resource scheduling can reduce emissions by 15–35% (Drzecnik and Klansek, 2025). Policy adoption is slow, and enforcement is inconsistent, limiting widespread carbon reduction (Etukudoh *et al.* 2024). Future research should focus on AI-driven process optimization and nanotechnology to further reduce emissions (Islam and Islam, 2025b). Net-zero carbon management may be achievable using nanotech sensors and AI in digital building site models (Elghaish *et al.* 2024).

2.3 Waste Generation in Construction

The amount and variability of construction and demolition waste (C&DW) is a major environmental concern. Construction and demolition waste comprises 30-40% of worldwide solid waste (Jain *et al.* 2021; Hassan *et al.* 2022). Concrete, wood, metal, plastic, demolition, remodeling, and building garbage are important sources. Methane from uncontrolled C&D dumping pollutes soil, groundwater, air, and landfills (Chen *et al.* 2022). Recent studies demonstrate a shift toward integrated waste management employing AI, robotics, and digital technologies to enhance garbage reduction and recovery. AI-based C&D waste sorting improves efficiency, accuracy, contamination, and recycling (Lakhouit, 2025). Building Information Modeling (BIM) and Geographic Information Systems (GIS) provide proactive resource reuse and reduction throughout construction by monitoring waste and inventory (Ahsan, 2024; Zubair *et al.* 2024).

Nanotechnology may enhance recycling and C&D waste remediation. Nanomaterials recycle pollutants, accelerate photochemical degradation of organic wastes, and generate self-healing concrete to delay fractures and prolong building life cycles, decreasing waste (Liu and Zhao, 2024). Other initiatives include nano-enabled coating to minimize metal waste corrosion and promote recycling (Brunelli *et al.* 2021; Islam and Islam, 2025b). New nanotech building waste management applications need scale-up validation. Despite increased interest, uncertain regulation, poor waste data, insufficient sorting and recycling infrastructure, and economic hurdles to technology adoption make it impossible (Zhang *et al.* 2019; Zhang *et al.* 2023). Green finance and circular economy laws are essential for sustainable waste management (Tian, 2018). Regionally tailored AI and nanotechnology-based technologies to decrease C&D wastes may be adopted faster via international cooperation and knowledge exchange.

3. MATERIAL SELECTION

Recycled aggregates, low-carbon cement mixes, and nanomaterials make construction material choices more sustainable. To increase structural performance and sustainability, (Alvi *et al.* 2023) tested recycled aggregates and graphene in cement composites. The research demonstrated that recovered agglomerated aggregates with nanomaterials can match conventional strength and durability while lowering embodied carbon and construction waste. It shows that recycled sand and nanomaterials improve ultra-high-performance concrete microstructure and mechanical performance. This study recommends combined use to reduce environmental impact and improve green building materials. Recent research found recycled construction and demolition waste aggregates feasible and green (Bardan and Czarnecki, 2025). Circular economy mixed recycled aggregate concrete will decrease resource loss and landfill effects. Aggregate quality swings, industry conservatism, and limited regulatory guidance continue to hinder viable adoption, as the researchers noted. New technologies for processing and bonding recycled aggregates (Bardan and Czarnecki, 2025) and incorporating nanomaterials to enhance physical and chemical characteristics will tackle such challenges.

3.1 Energy Efficient Machinery Operation

A shift in the construction equipment sector toward machine optimization, automation, and electrification is helping to save energy. Efficient machine designs emphasize strategic decision-making, such as using shared peripheral machines and multi-technology systems, to minimize energy use and boost productivity. Automation and shuttle machining reduce non-productive time on building sites, improving overall efficiency and lowering energy consumption (Chen *et al.* 2025). Regular maintenance of high-efficiency generators, excavators, and cranes helps save fuel (Jo *et al.* 2011). These energy-efficient technologies provide significant environmental and economic benefits, including reduced carbon footprints and better regulatory compliance (Mneimneh, 2023). Variable frequency drives, high-efficiency motors, and intelligent manufacturing systems can reduce energy usage by 20-50% while also cutting emissions. Case studies from various sectors show that equipment improvements and automation initiatives have led to reduced costs and enhanced sustainability. However, the shift toward energy-efficient machinery requires considerable initial investment and operator retraining, making it more challenging for small-scale or emerging construction companies to implement these systems (Onukwulu *et al.* 2021).

3.2 Construction Logistics and Scheduling

Logistics and scheduling optimization play a critical role in reducing the time, cost, and environmental impact of construction projects. (Zhang and Zhang, 2024a) propose a comprehensive method to manage material flow, distribute site allocation times, and eliminate congestion, delays, and pollution. Effective logistics planning should integrate last-minute delivery, vertical storage, and space-optimizing solutions. Automated multi-objective construction logistics systems can assist contractors in managing costs, time, and environmental impact by using advanced software analytics and AI-based forecasting models. Research has shown that managing logistics and scheduling effectively improves resource utilization, material responsiveness, and profitability. With the disruptions caused by COVID-19 and climate-related events, intelligent platforms and scheduling algorithms have been designed to adapt to changes in site conditions, supply chain disruptions, and

labor availability. Despite these advantages, digital twin systems and IoT-integrated logistics systems still struggle to fully integrate with construction processes, and reliable real-time data remains a challenge.

3.3 Waste Minimization Practices

Sustainable building practices focus on reducing C&D waste through preventative planning, digital platforms, and improved on-site practices. Jain *et al.* 2021) outlined key components of C&D waste management, including recycling, composting, and waste reduction strategies. (Ahsan, 2024) highlighted the role of BIM and GIS in managing material inventories, allowing for timely material ordering, minimizing stockpiling, and promoting reuse. Additionally, AI and robotic systems in waste sorting are shown to minimize contamination, enhance sorting accuracy, and increase recycling efficiency (Zubair *et al.* 2024).

Nanomaterials have the potential to further reduce construction waste by promoting self-healing concrete and photocatalytic coatings that minimize waste generation and material degradation (Liu and Zhao, 2024). These materials help extend the lifespan of structures, reduce maintenance needs, and cut down on waste. However, challenges remain, such as data privacy concerns, integration with existing IT infrastructure, and high installation and maintenance costs (Alabdulatif *et al.* 2023; Rana *et al.* 2024). Real-time analytics, powered by advanced machine learning algorithms and edge computing systems, are required to manage the large volumes of sensor data and enhance waste reduction efforts. Further research is needed to develop universal nanosensor manufacturing, effective data analysis, and improved integration with construction waste management systems.

3.4 Site Layout and Sustainability

Sustainability-driven site design and optimal layout are key factors in enhancing resource efficiency while minimizing energy consumption and material waste in construction. (Salem and Elwakil, 2024) and Mehraban *et al.* 2025) suggest that compact site architecture, which maximizes natural daylight, and the use of modular solutions can reduce transit distances and minimize energy needs. By designing sites that optimize space and reduce the distance between key operations, energy consumption can be reduced, leading to lower carbon emissions. Furthermore, AI metaheuristic models assist architects and engineers in creating energy-efficient, operationally convenient, and environmentally friendly designs. Studies have shown that careful site design facilitates the integration of renewable energy sources, such as solar panels and wind turbines, rainwater collection systems, and decentralized waste management. Incorporating these elements into site planning helps buildings become more self-sustaining and reduces their dependence on external energy sources (Rane *et al.* 2023b). For example, solar panels installed on green roofs and the use of waste recovery stations can significantly reduce operating energy needs and lower waste production. However, aligning sustainability measures across design, construction, and facility management remains challenging. The full potential of these technologies can only be realized when lifecycle-oriented digital systems are implemented to ensure that sustainability is maintained throughout the building's life cycle (Mehraban *et al.* 2025).

3.5 Integration of Nanomaterials in Construction

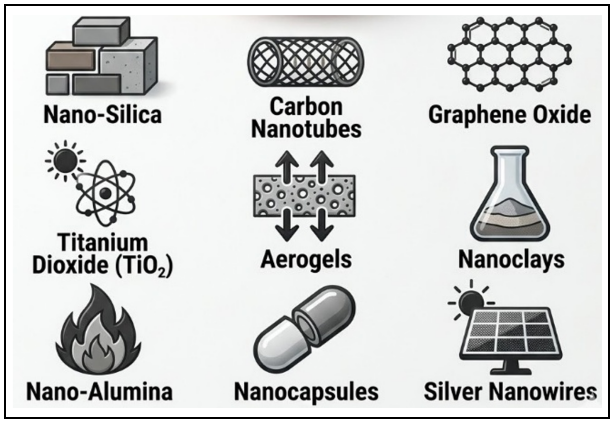


Fig. 3: Nanomaterials used in construction industry

Nanomaterials have significantly advanced the energy performance, durability, and sustainability of materials used in the construction industry. Recent studies by (Hasan *et al.* 2024) introduced nanomaterial-enhanced concretes with exceptional mechanical and thermal properties. These nanomaterials are designed to reduce heating and cooling energy consumption while extending the service life of building components. Fig. 3 illustrates various nanomaterials used in the construction industry, showcasing their application in improving material properties. Nanotechnology-based self-cleaning, anti-corrosive, and photocatalytic coatings are increasingly used to enhance the durability of materials, lower maintenance costs, and contribute to the principles of the circular economy (Brunelli *et al.* 2021). These coatings not only improve the performance of building materials but also reduce the frequency of repairs, helping to extend the life cycle of structures and reduce waste. However, despite the promising laboratory results, widespread adoption of nanomaterials in construction faces several challenges, including concerns about long-term environmental impacts, high production costs, and the absence of standardized material properties.

To facilitate the safe and scalable use of nanomaterials in construction, it is essential to conduct comprehensive field experiments, environmental risk assessments, and establish consensus standards (Liu and

Zhao, 2024). Additionally, interdisciplinary collaboration and the development of robust legislative frameworks are critical to unlocking the full sustainability potential of nanotechnology in building systems.

4.AI APPLICATIONS IN CONSTRUCTION OPTIMIZATION

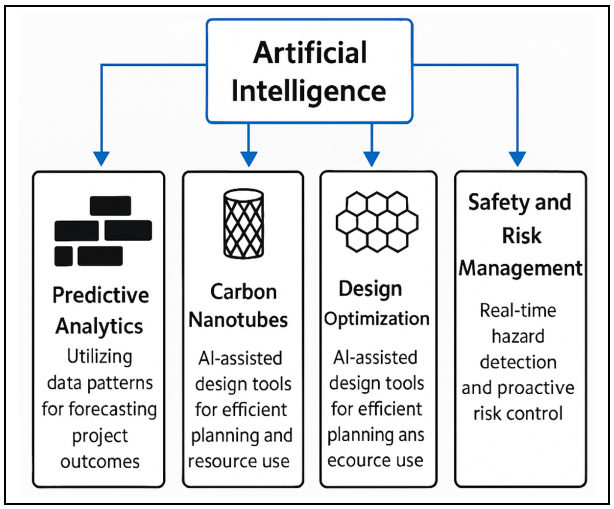


Fig. 4: AI applications in construction optimization

AI applications have revolutionized construction optimization by handling energy management, resource allocation, waste reduction, and emissions. Apart from these applications, AI plays a vital role in optimizing material used, design, risk and project management as depicted in Fig. 4. With huge amounts of construction data and unique computational approaches, AI models can do real-time predictive analytics, decision support, and process automation to improve sustainability. Artificial intelligence can optimise complicated, multi-dimensional building systems that are too difficult to optimise using conventional methods as net-zero carbon demands and sustainable development goals increase. A recent study shows that AI optimizes energy consumption throughout design, material selection, and operation to reduce greenhouse gas emissions and make designs more efficient and cost-effective (Oguntola *et al.* 2024).

Many construction optimization tasks have been completed using neural networks, metaheuristic algorithms, and hybrid models. Neural networks learn complicated nonlinear energy and material behavior correlations and help make accurate forecasts and adaptive controls. Metaheuristic algorithms like genetic algorithms and particle swarm optimization tackle multi-objective optimization issues like scheduling and resource allocation by exploring huge solution spaces. Hybrid models combine neural networks and metaheuristics to eliminate model weaknesses and increase accuracy and convergence.

4.1 ANN in Construction Optimization

Artificial Neural Networks (ANNs) are a powerful tool for optimizing construction processes, particularly in predicting energy usage and carbon emissions throughout the lifecycle of a building. They can model complex, nonlinear relationships in data without requiring predefined equations. A recent work has proposed using convolutional neural networks (CNNs) integrated with BIM to predict building energy needs and optimize consumption patterns (Zhang and Mo, 2024b). These predictive models are crucial for estimating operational carbon emissions and dynamically arranging energy resources. Artificial Neural Networks, when combined with multi-objective evolutionary algorithms, like Back Propagation (BP), can optimize design parameters, such as spatial distribution and material use, reducing energy consumption and emissions (Zhou *et al*. 2009; Asadi *et al*. 2014). Despite their effectiveness, model interpretability remains a challenge, as ANNs often function as a "black box," making it difficult for construction managers to understand how input factors affect the outcomes. Researchers are developing explainable neural network models to improve transparency and encourage stakeholder adoption (Shin, 2021; Mathew *et al.* 2025).

4.2 Metaheuristic Models

Metaheuristic algorithms, which are inspired by biological processes, offer efficient solutions to complex, multi-objective optimization problems in construction. Algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) have been applied to optimize material composition, resource allocation, and project scheduling, reducing energy consumption and carbon emissions over the course of a construction project. Studies have shown that PSO and ACO can reduce material waste and improve schedule accuracy while also lowering carbon footprints in construction projects (Behera *et al.* 2025). These algorithms work by exploring large solution spaces and refining candidate solutions through iterative processes, making them highly effective for complex construction problems that involve multiple, often conflicting, objectives. The use of GA-based solutions in low-carbon material selection and pricing for large-scale projects also helps balance structural integrity with sustainability goals. Although these algorithms have been successful in optimizing construction operations, their implementation requires problem-specific adaptations and expert knowledge, as well as significant computational resources.

Table 1. Summary of AI applications in construction optimization

Author(s) and Year	Summary of Findings	Research Gaps
(Zhang and Mo, 2024b)	Developed CNN-based models integrated with BIM to improve real-time building energy management and emission control.	Requires large, high-quality datasets and advances in explainability techniques to foster trust.
(Zhou *et al*. 2009; Asadi *et al.* 2014)	Showed BP neural networks combined with evolutionary algorithms enhance energy use and emissions optimization in building design.	Model interpretability and computational demands remain significant barriers.
(Shin, 2021; Mathew *et al.* 2025)	Proposed explainable ANN models for better transparency, improving stakeholder trust and decision-making in construction energy forecasting.	The balance between model accuracy and interpretability needs balancing.
(Abbass and Hamdy 2021; Kim *et al.* 2023)	Focused on noise reduction and hybrid learning techniques to improve robustness of ANNs in variable construction data environments.	Robust preprocessing and domain adaptation techniques require further development for real-world adoption.
(Liu *et al.* 2013; Guo *et al.* 2022)	Discussed GA, PSO, GWO, and ACO for optimizing material composition and scheduling to reduce energy use and carbon emissions.	Lack of standard tuning procedures and challenges in dynamic onsite adaptation impair broader use.
(Aramesh *et al.* 2023; Hussain and Hussain, 2023)	Demonstrated GA-based methods optimize low-carbon material selection balancing cost and structural integrity effectively.	Computational efficiency and practical integration with supply chains require improvements.
Behera *et al.* 2025)	Applied PSO and ACO in minimizing logistics carbon footprints leading to enhanced scheduling precision and emission reduction.	Difficulty in modeling unpredictable site conditions and supplier variability remains unsolved.
(Senaras *et al*. 2025); Duan *et al.* 2025)	GA and hybrid metaheuristics applied to large-scale construction projects for holistic energy and emission management optimization.	Scalability to very large projects and parallel computation is a research focus.
(Wang, 2025B); Elshafei *et al.* 2021)	Metaheuristic algorithms outperform heuristic methods in optimizing resource allocation and energy use, achieving cost-effective sustainability gains.	Hybrid approach automation and accessibility for practitioners lag behind theoretical advancements.
Baqer and Rashidi, 2025)	Hybrid GA-tuned ANN and PSO optimization models yield superior accuracy and faster convergence in construction scheduling and emissions prediction.	High computational cost restricts real-time application; expertise needed for model calibration.
(Obianyo *et al.* 2023); Singh, 2025)	Neuro-fuzzy and reinforcement learning-based hybrids enable adaptive learning and improved interpretability, applied to resource and cost optimization.	Balancing complexity, transparency, and computational demand is an ongoing challenge.
(Hosseinnia *et al.* 2025; Wang *et al*. 2025a)	Biogeography-based optimization combined with ANNs improves concrete durability predictions and carbonation modeling effectively.	Experimental validation essential to transition from lab to large-scale deployments.
(Rajagopalan *et al.* 2022; Almsallti *et al*. 2025)	Hybrid metaheuristic and gradient-learning models optimize microgrid operations in smart green construction, cutting costs and emissions by double digits.	User-friendly interface design and model simplification remain required for stakeholder adoption.
(Wu *et al.* 2025; Chen *et al.* 2024b)	Hybrid fuzzy-heuristic and metaheuristic-gradient descent models enhance site waste sorting, energy use forecasting, and reduce emissions.	Limited data on long-term real-world applications and IoT integration present barriers.

4.3 Hybrid Models

Hybrid AI models combine the strengths of different AI techniques, such as neural networks and metaheuristics, to overcome their individual limitations. These models are particularly effective in solving complex construction optimization problems, such as scheduling, resource allocation, and emissions prediction. For example, a hybrid approach that combines GA with ANN has been used to improve accuracy and convergence in construction scheduling and emissions prediction (Baqer and Rashidi, 2025). In the context of sustainable construction, hybrid models can optimize energy consumption, reduce emissions, and

minimize waste generation. These models have been applied to building design, resource management, and operational planning to align with net-zero carbon goals. Hybrid models allow for more accurate predictions and adaptive controls in dynamic construction environments, which is crucial for optimizing energy use and reducing carbon footprints. However, their complexity and computational demands limit their applicability, particularly in small-scale projects or settings with limited technical expertise. Despite these challenges, hybrid models represent a promising approach for achieving sustainable construction goals. Future research should focus on automating hybrid AI model design, improving their interpretability, and enhancing their real-time capabilities to increase adoption in the construction industry. By integrating the strengths of multiple AI techniques, hybrid models could help overcome the barriers that currently hinder optimization efforts in sustainable construction.

5. GREEN AND SUSTAINABLE MAP OF AI OPTIMIZATION

Green and sustainable construction demands AI optimization to efficiently manage renewable energy sources, monitor energy usage, and store energy. AI-enabled systems allow construction sites to dynamically adjust solar panels, wind turbines, and hybrid energy systems for maximum clean energy capture without relying on external power grids (Manuel *et al.* 2024). By forecasting energy demand, AI can adjust scheduling and balance supply and consumption, enhancing demand-side management. These systems contribute to sustainability by reducing the dependency on non-renewable energy sources. Additionally, AI can automate diagnostics and predictive maintenance for renewable energy assets, increasing system longevity and minimizing emissions, which are crucial for meeting net-zero carbon targets (Adewale *et al.* 2024; Jain and Babu, 2024). Nanotechnology-enabled IoT sensors have transformed real-time site monitoring and energy integration. These nanoscale sensors, embedded in construction materials, offer heightened sensitivity to environmental conditions, providing continuous monitoring of structure health, energy use, and operational parameters (Tovar-Lopez, 2023; Darwish *et al.* 2024). The combination of AI and nanotechnology provides a robust framework for achieving sustainable energy management on construction sites, enabling buildings to become self-sustaining and energy-efficient.

5.1 AI-driven Construction Site Renewable Energy Integration

AI-driven optimization plays a pivotal role in integrating renewable energy systems into construction sites. By exploiting AI algorithms, construction sites can dynamically adjust renewable energy systems such as photovoltaic panels and wind turbines to maximize energy capture, based on real-time weather and site conditions (Mamodiya *et al*. 2025). These AI systems continuously predict energy demand, optimize energy storage, and balance energy consumption with renewable energy supply, reducing reliance on non-renewable sources and enhancing grid stability (Rao *et al.* 2024; Shibi and Kanna, 2025).

AI-based demand-side energy management systems have been shown to reduce grid power usage and fossil fuel consumption by optimizing consumption patterns through predictive load forecasting and smart scheduling. In large infrastructure projects, AI-controlled renewable installations have reduced energy-related emissions by approximately 22%, demonstrating their potential for sustainable construction practices (Pimenow *et al.* 2024). Despite these advantages, integrating AI with existing construction management systems remains a challenge, as it requires accurate real-time data and sophisticated infrastructure.

5.2 Smart and Nano Sensors Based IoT for Real-time Monitoring

Nanotechnology-based sensors integrated with IoT platforms enable real-time monitoring and control on construction sites, facilitating data-driven decision-making and improving sustainability. These nanosensors, embedded in construction materials and equipment, offer high sensitivity to changes in temperature, humidity, structural strain, and pollutant levels. For example, electrochemical and fiber-optic nanosensors in concrete can detect micro-cracks and chemical changes, preventing premature repairs and material degradation (Civera *et al.* 2024). These sensors communicate wirelessly through IoT networks to cloud-based AI systems, allowing for continuous analysis, anomaly detection, and automated energy management. By monitoring structural health and environmental conditions in real-time, AI-driven IoT systems optimize energy consumption, reduce waste, and ensure sustainability. However, challenges such as data privacy concerns, integration with existing infrastructure, and high installation and maintenance costs hinder widespread deployment (Alabdulatif *et al.* 2023; Rana *et al.* 2024). Overcoming these barriers will require further research into universal sensor manufacturing and seamless integration with existing building management systems.

5.3 Predictive Models for Energy Storage and Efficiency in Construction Projects

AI-driven predictive models play a crucial role in optimizing energy storage and efficiency in construction projects. These models forecast energy demand and supply, allowing for the strategic use of energy storage systems such as thermal or battery storage to smooth demand peaks and integrate intermittent

renewable energy sources (Kiasari *et al.* 2024). By forecasting factors such as weather, occupancy, and energy use, AI models ensure that energy storage is deployed effectively, reducing reliance on grid power and minimizing carbon emissions. Stochastic Model Predictive Control systems have been applied to optimize energy dispatch in buildings and on-site microgrids, ensuring that renewable energy is efficiently utilized and stored. These systems improve grid stability, reduce operating costs, and cut non-renewable backup power demand, thus lowering carbon emissions. However, challenges related to model complexity, data quality, and the coordination of multi-scale construction projects hinder the widespread implementation of these predictive systems.

5.4 Nanotechnology-based Sustainable Materials and AI-controlled Process Optimization

Nanotechnology has revolutionized construction by improving the mechanical, thermal, and energy-saving properties of building materials. Recent studies emphasize the development of nano-enhanced cementitious materials, which improve thermal insulation and carbon sequestration, helping to reduce heating and cooling energy demands (Daneshazarian and Berardi, 2023). AI optimization algorithms adjust these nanomaterial formulations to meet site-specific environmental and structural needs, optimizing resource utilization and reducing emissions (Christopher and Devarajan, 2025). AI-controlled processes further improve sustainability by proactively adjusting material properties, enhancing the building process, and extending the service life of structures while reducing maintenance. Nanotechnology combined with AI enables predictive quality control and automated flaw detection during manufacturing, resulting in more durable and efficient materials (Sahith and Lal, 2024). However, industrial-scale adoption faces barriers, such as high production costs, material standardization, and environmental impact assessments. To overcome these challenges, research should focus on developing scalable manufacturing processes, standardizing material properties, and assessing the long-term environmental effects of nanomaterials (Wu, 2025).

Table 2. Summary of research gaps related to nanotechnology in construction sector

Author(s) and Year	Summary of Findings	Research Gaps
(Daneshazarian and Berardi, 2023)	Developed nanomaterial-enhanced cementitious composites improving insulation properties and supporting carbon sequestration to reduce energy demands.	Field validations and long-term durability studies needed for real-world applications.
(Christopher and, 2025)	AI optimization algorithms tailor nanomaterial formulations for local environmental and structural requirements, minimizing resources and emissions.	Requires extensive regional training data for accurate AI model functioning.
(Sahith and Lal, 2024)	AI combined with nanosensors and machine vision improves defect detection and quality assurance during construction material fabrication.	High integration costs and technical complexity restrict widespread industrial application.
(Nizam *et al*. 2021)	Reviewed health and environmental risks of nanomaterials in construction, emphasizing the need for standardized impact assessments.	Data gaps in long-term exposure and standardized regulations remain critical research needs.
(Wu, 2025)	Advocated lifecycle assessment models incorporating AI and nanotech impacts, balancing ecological safety with economic feasibility details.	Harmonization of standards and cross-sector regulatory alignment is required.
(Arun *et al.* 2025)	AI-driven manufacturing of nanocomposites demonstrates process efficiency improvement and resource wastage reduction for eco-friendly production.	Real-time adaptive controls and monitoring technologies remain under refinement.
(Zhao *et al.* 2024)	AI models predict aging and degradation of nanomaterials, optimizing maintenance schedules to minimize lifecycle emissions and failures.	Inclusion of environmental variability into models remains an open challenge.
(Verma and Kumar, 2024)	AI optimizes nanocomposite fabrication parameters to reduce energy input and material waste, contributing to sustainable manufacturing.	Full digital twin system integration for comprehensive process control is necessary.

6. IDENTIFIED RESEARCH GAPS

Despite significant progress in energy-efficient construction practices and the adoption of green materials, several challenges remain. Key research gaps include issues with data collection, regional infrastructure disparities, and financial and political barriers to implementing AI and nanotechnology optimization. Future studies should focus on hybrid AI-metaheuristic models for real-time energy management and comprehensive lifecycle assessments that consider energy use, carbon emissions, and waste streams. Recycling aggregates and nanomaterials offers great potential for advancing sustainability, but challenges such as poor material quality, regulatory opposition, and lack of standardized practices persist. Additionally, the long-term impacts of large-scale nanomaterial use remain uncertain. Research should explore advanced designs, material recycling, and integration into circular economy supply chains. In developing countries, high costs and the complexity of energy-efficient devices hinder adoption. Research should focus on cost-effective retrofitting solutions and automation technologies that balance energy use with productivity. Additionally, further studies are needed on the environmental and economic trade-offs of electrification and variable frequency drives. AI-assisted logistics and scheduling show promise but struggle with real-time data integration and adaptability to disruptions. Research should focus on developing systems capable of adjusting to dynamic construction environments. Nanotechnology offers significant promise for reducing construction waste, but its widespread application is constrained by uncertain environmental impacts and regulatory challenges. Research is needed to evaluate the long-term effects of nano-enabled waste treatment and develop digital frameworks for sustainable waste management.

7. CONCLUSION

This review highlights the significant environmental impact of the construction industry, particularly through its high energy consumption, carbon emissions, and waste generation. While current methods have made progress, achieving net-zero carbon targets requires more advanced, technology-driven solutions. Artificial Intelligence has emerged as a powerful enabler of optimization, offering advanced tools such as neural networks, metaheuristic models, and hybrid systems to enhance predictive accuracy and operational efficiency in design, material selection, and construction management.

Nanotechnology also plays a pivotal role by developing new materials with improved energy performance, durability, and self-healing capabilities. The integration of AI with nanotechnology offers promising potential for sustainable building practices, allowing for smarter use of resources, better energy management, and more effective waste reduction. Despite these advances, significant barriers remain, including high costs, regulatory limitations, and the need for more comprehensive data and infrastructure. To overcome these challenges, future research should focus on developing scalable hybrid AI models, improving the explainability of AI systems to build stakeholder trust, and ensuring the environmental safety of nanomaterials. Furthermore, there is a need for the establishment of robust policy frameworks and interdisciplinary collaboration to promote green building practices globally. By addressing these gaps, the construction industry can accelerate its transition toward sustainability, helping to achieve net-zero carbon goals and preserve valuable resources for future generations.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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