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Smart Water-Energy Nexus in Concrete Manufacturing: Harnessing Renewable Energy and AI for Sustainable Development

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Abstract. Concrete's high energy and water requirements contribute to environmental degradation and global resource use. This mini-review employs a scoping and thematic synthesis of peer reviewed literature from 2020 to 2024, focusing on the intersection of artificial intelligence (AI), renewable energy and sustainable water-energy management in concrete manufacturing. The review explores circular economy models for integrated energy-water systems AI-driven process optimization, water conservation and reuse techniques and the deployment of renewable energy technologies such as solar PV, biomass and biogas. Key findings highlight the potential of digital twins and smart sensors for real-time monitoring, the effectiveness of treated industrial wastewater in reducing freshwater dependency, and the economic viability of bio-based admixtures. While these innovations offer promising synergies for sustainability, adoption barriers such as high initial costs, technical complexity, and regulatory gaps remain. The study underscores the need for transdisciplinary innovation and policy alignment to foster low-carbon, water-efficient construction practices.

1. Introduction

Concrete remains foundational to modern construction due to its durability and affordability, yet its environmental footprint is increasingly problematic. Central to this issue is Portland cement, which accounts for 7–8% of global CO_2 emissions, resulting from energy-intensive clinker production and the calcination process [1,2]. Moreover, concrete manufacturing consumes vast volumes of natural aggregates and freshwater, with usage reaching up to 200 litres per cubic meter pressuring water-stressed regions [3,4].

The water-energy nexus highlights the reciprocal relationship between water and energy systems, aggravating sustainability challenges. Energy is needed to purify and transport water for concrete processes, while water supports energy generation. Climate change intensifies these pressures through resource scarcity and increased demand [5,6]. To combat this, the concrete sector is embracing circular economy principles, particularly through the adoption of treated industrial wastewater (TIWW) as mixing water. TIWW reduces freshwater dependency and supports industrial symbiosis, provided safety and performance thresholds are met [7]. In parallel, bio-based admixtures offer greener alternatives to petroleum-based chemicals, further lowering emissions [7,8].

However, variability in wastewater and natural admixtures demands intelligent control systems. Artificial intelligence (AI) and machine learning provide solutions for real-time monitoring,

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predictive mix design, and automated quality assurance [9,10]. Coupled with renewable energy sources, e.g., solar-powered wastewater treatment or green electricity for kilns, these innovations pave the way for sustainable production.

By harnessing these integrated strategies, the concrete industry can significantly reduce its ecological impact and align with climate mitigation goals. The fusion of AI, renewable energy, and circular practices marks a vital transition toward a resilient built environment [11]. Nonetheless, despite increasing interest in sustainable practices, a significant research gap persists in the thorough integration of artificial intelligence and renewable energy within the water-energy nexus of concrete production. Current research frequently examines these elements separately, failing to provide a cohesive framework that investigates their combined potential. This assessment seeks to integrate recent improvements and pinpoint prospects for comprehensive, AI-driven, low-carbon concrete production systems. While numerous studies have explored artificial intelligence, renewable energy, and water reuse in concrete manufacturing independently, there is a lack of integrated reviews that examine their combined application within the water-energy nexus. This review addresses this gap by synthesizing recent literature (2020–2024) to evaluate how these technologies can be jointly leveraged to enhance sustainability, efficiency, and resilience in concrete productio. It highlights the role of digital twins, smart sensors, and machine learning in optimizing water and energy use, while assessing the feasibility of renewable energy sources like solar PV, biomass, and wind in concrete production. Unlike previous reviews that focus on isolated technologies, this study emphasizes interconnected solutions and their potential to reshape concrete manufacturing in line with climate goals. By doing so, it contributes to the growing discourse on transdisciplinary innovation and policy alignment for sustainable infrastructure development.

2. Method

This mini-review employed a scoping thematic synthesis approach to analyze recent peer-reviewed literature on the integration of artificial intelligence (AI), renewable energy, and water-energy management in concrete manufacturing. The review focused on publications from 2020 to 2024, a period selected to capture the most recent technological and policy developments in sustainable construction. Relevant literature was sourced from Scopus and Google Scholar, using keyword combinations such as: (“concrete manufacturing” AND “artificial intelligence”, “renewable energy” AND “cement production”,” water-energy nexus” AND “construction”, “treated wastewater” AND “concrete”, “digital twin” AND “sustainable infrastructure”. An initial pool of over 250 articles was identified. The selection was narrowed down through a multi-stage screening process:

1. Title and abstract screening for relevance to the review’s scope.
2. Inclusion criteria: peer-reviewed journal articles, English language, and direct relevance to AI, renewable energy, or water reuse in concrete production.
3. Exclusion criteria: duplicate studies, non-peer-reviewed sources, and articles lacking methodological transparency or empirical grounding.
4. Final selection: 40 articles were chosen based on relevance, methodological quality, and contribution to thematic insights.

Further, thematic synthesis was conducted by clustering recurring concepts across the selected literature. Themes were developed through iterative coding and expert judgment, focusing on:

- Renewable energy integration in concrete production
- AI-driven optimization of water and energy use

- Environmental and economic impacts
- Policy, research, and implementation strategies

While this review provides a comprehensive overview, it is limited by its reliance on English-language publications and only two databases, which may exclude relevant regional or non-English studies. Nonetheless, the selected timeframe and sources offer a robust foundation for identifying emerging trends and interdisciplinary synergies in sustainable concrete manufacturing.

3. Thematic discussions

The screening and selection of the articles are further synthesized and discussed in the following sections.

3.1 Harnessing Renewable Energy in Concrete Manufacturing

The global construction industry faces significant pressure to reduce its carbon footprint while supporting urbanization and infrastructure growth, particularly in concrete production, which is energy-intensive and polluting, especially during cement manufacturing [12,13]. Utilizing renewable energy sources is essential for minimizing the carbon footprint of concrete manufacturing. This study examines relevant renewable energy sources, their applications in concrete production, and the associated benefits and drawbacks.

Table 1 shows key renewable energy options including solar energy, wind energy, and biomass. Solar photovoltaic (PV) systems can power equipment in concrete batching and mixing facilities, while solar thermal technologies can provide heat for cement kilns and curing processes. Wind turbines can generate electricity, particularly in remote locations, enhancing the sustainability of mobile batching plants. Also, as shown in Table 1, solar power offers the highest CO_2 reduction potential (up to 90%) among renewable sources [17], though its adoption remains limited due to high capital costs. Biomass can be converted into biogas or thermal energy, offering a carbon-neutral alternative to fossil fuels in cement kilns and on-site operations. In developing countries, mobile concrete batching plants often rely on diesel generators, presenting an opportunity to integrate renewable energy sources, reducing environmental impact and reliance on fossil fuels. However, challenges such as financial barriers, technical expertise requirements, and the intermittency of renewable energy sources must be addressed. The transition to renewable energy can significantly reduce greenhouse gas emissions, enhance energy security, and promote self-sufficiency, particularly in areas with unstable grid infrastructure. Despite the benefits, high upfront costs and the need for technical expertise remain significant barriers to adoption, especially for small and medium-sized enterprises (SMEs) in the construction sector [14,15]. Addressing these challenges through integrated system design, financial innovation, and government support is crucial for the concrete industry to meet global decarbonization targets and promote sustainable industrial development. The strategic integration of renewable energy will be vital for creating a cleaner, more resilient construction industry alongside resource-efficient practices and digital technology.

3.2 AI-Driven Optimization of the Water-Energy Nexus

Given the increasing demand for environmentally friendly building materials worldwide, the concrete industry needs to address its resource-intensive operations, especially regarding energy and water consumption. Concrete manufacturing is particularly impacted by the water-energy nexus, which is the interdependent relationship between water consumption and energy use, due to the high-water demand for mixing and curing and the significant energy consumption for cement production and plant operations, as shown in Figure 1. Optimizing this relationship is essential to achieving long-term sustainability, lowering environmental effects, and improving operational effectiveness. Using Artificial Intelligence (AI) technology is one of the most promising ways to

handle this complexity [16]. AI has the potential to completely transform resource efficiency in the manufacturing of concrete through automation, data analytics, and smart sensing.

Table 1: Harnessing Renewable Energy in Concrete Manufacturing

Renewable Energy Source	Application in Concrete Manufacturing	Energy Output Potential	Implementation Cost	Environmental Impact	Current Adoption Rate
Solar Power	Powering cement kilns, lighting, conveyor systems	150-400 kWh/m² annually	Medium ($2-4M for large plants)	85-90% CO_2 reduction	15-20% of plants [17]
Wind Energy	Operating crushing equipment, mixers, and transportation	2-3 MW per turbine	High ($3-5M initial)	80-85% CO_2 reduction	10-15% of plants [17]
Hydroelectric	Powering grinding mills, material handling	1-100 MW depending on site	Very High ($5-15M)	90-95% CO_2 reduction[3]	5-8% of plants [18]
Biomass Energy	Cement kiln fuel, steam generation	10-50 MW thermal	Medium ($1-3M)	60-70% CO_2 reduction[4]	25-30% of plants [18]
Geothermal	Process heating, facility climate control[5]	5-30 MW thermal[5]	High ($4-7M)	85-90% CO_2 reduction[5]	2-5% of plants [17]
Waste Heat Recovery	Capturing kiln exhaust, steam generation	10-30% efficiency gain	Low-Medium ($0.5-2M)	20-40% CO_2 reduction[6]	40-50% of plants [17]

Artificial intelligence (AI) encompasses a range of computing tools capable of analyzing large datasets, identifying patterns, and generating conclusions or suggestions. In concrete production, AI plays a crucial role in monitoring, forecasting, and optimizing the interconnected processes that manage energy and water usage. Smart sensors integrated into production lines collect real-time data on temperature, humidity, pressure, flow rates, and material composition, which are connected through the Internet of Things (IoT) for seamless data transfer. One of the most innovative AI technologies is the digital twin, a virtual model of a concrete plant that uses real-time sensor data and AI algorithms to predict outcomes, test optimization options, and simulate plant operations. Figure 1 illustrates the integration of AI-enabled technologies, highlighting how digital twins and smart sensors interact to optimize water and energy flows in real time. For example, a digital twin can model the impact of altering the water-to-cement ratio or cure conditions on concrete's strength and energy consumption, aiding operators in making informed decisions. For instance, a case study by Delnavaz et al. (2022) demonstrated the use of a digital twin in a precast concrete plant, achieving a 15% reduction in energy consumption through real-time optimization of curing cycles [13]. Similarly, Feola et al. (2023) reported that lignosulfonate-based admixtures derived from paper industry waste can reduce the carbon footprint of concrete mixes by up to 20% while maintaining structural performance [25]. While bio-based admixtures offer environmental benefits, their performance variability necessitates intelligent control systems, as discussed further in Section 3.3.

Despite the promise of AI and IoT in optimizing concrete production, several limitations persist. AI models require large, high-quality datasets, which may be unavailable or inconsistent across regions. Additionally, cybersecurity risks in IoT-enabled systems pose threats to operational

continuity and data integrity. Over-reliance on predictive algorithms without human oversight can also lead to suboptimal decisions in dynamic construction environments [16].

Machine learning (ML) algorithms, a subset of AI, are particularly effective in identifying complex relationships between operational outcomes and input variables. ML can analyze historical and current data to forecast water demand based on material characteristics and environmental conditions, estimate energy usage, and optimize curing cycles to conserve resources. These models continuously improve by adapting to new data, ensuring resource use is optimized according to current operational conditions. AI implementation in the water-energy nexus of concrete production focuses on four key areas such as predictive maintenance, energy load forecasting, water reuse monitoring, and mix design optimization.

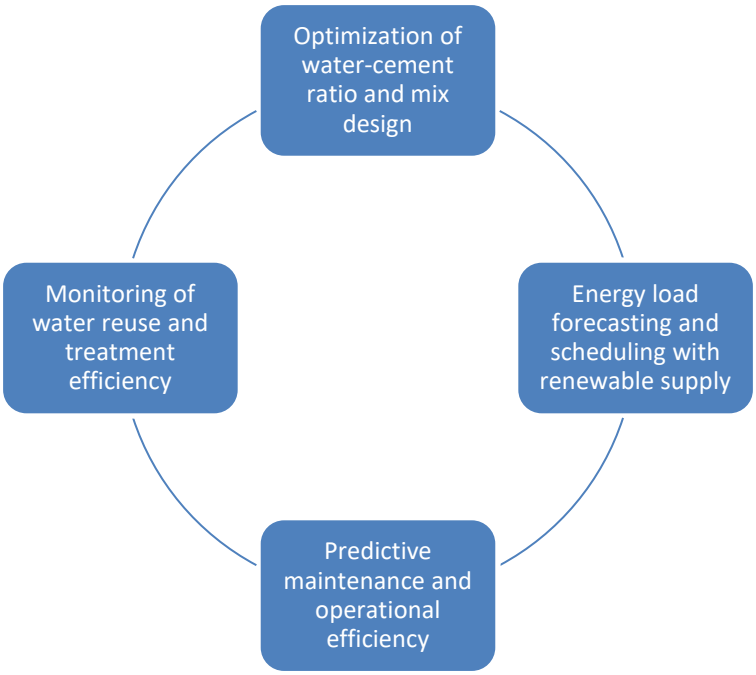


Figure 1: Overview of AI-Enabled Technologies in Concrete Production Systems

The water-to-cement (w/c) ratio, critical for concrete's strength and durability, can be dynamically adjusted by AI systems based on real-time data from embedded sensors, enhancing efficiency and performance. AI also plays a vital role in water recycling management by monitoring the pH, turbidity, and contaminants in process water, regulating chemical dosing and filtration, and identifying performance irregularities that could affect environmental safety and concrete quality. This ensures that reclaimed water meets reuse standards, reducing operational costs and environmental impact. In concrete manufacturing, which involves high energy loads, AI can predict energy demand and align it with renewable energy availability, optimizing operations to reduce reliance on the grid and lower costs [19,20]. AI can schedule energy-intensive tasks during peak solar hours and manage battery storage for renewable energy, thus promoting environmental sustainability.

Predictive maintenance powered by AI identifies potential equipment failures before they occur by analyzing data from various sensors, thereby minimizing downtime and resource waste. This approach enhances equipment lifespan and operational efficiency. Overall, AI is redefining efficiency and sustainability in concrete production by optimizing energy and water use, supporting responsible environmental practices, and improving resource management. The

integration of smart sensors, IoT, and digital twins facilitate real-time data collection and simulation, enabling AI-enabled concrete plants to optimize water-cement ratios, enhance water reuse, align energy consumption with renewable sources, and reduce downtime. These advancements contribute to broader environmental goals, such as reducing carbon emissions and freshwater withdrawal, while fostering economic growth and environmental stewardship in resource-constrained developing countries [21,22]. Embracing intelligent, data-driven systems is essential for the future of sustainable concrete production.

3.3 Environmental and Economic Impacts

The construction industry is experiencing significant transformation due to increasing economic and environmental demands, particularly in concrete production. Traditional concrete manufacturing relies heavily on freshwater, fossil fuels, and non-renewable mineral aggregates, leading to substantial industrial pollution, freshwater depletion, and greenhouse gas (GHG) emissions. Innovations such as bio-based admixtures, treated industrial effluence, renewable energy integration, and intelligent process control are essential for promoting sustainable concrete manufacturing [23]. These strategies not only address environmental concerns but also enhance economic performance, demonstrating the interconnection between economic viability and environmental stewardship. The environmental impact of conventional concrete is primarily driven by freshwater usage and carbon emissions, with cement production alone contributing to 7–8% of global CO_2 emissions due to energy-intensive processes. Additionally, the concrete sector consumes significant amounts of water, between 150 and 200 liters per cubic meter for mixing and curing.

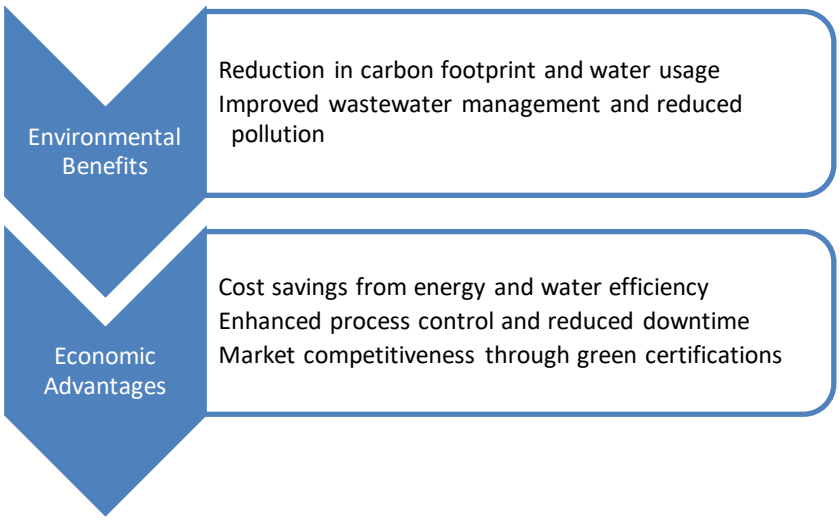


Figure 3: Environmental and Economic Impacts

The industry's reliance on freshwater resources can be significantly reduced by using treated industrial wastewater (TIWW) instead of potable water, allowing concrete plants to decrease their water footprint by up to 80% [24]. This practice is particularly impactful in areas with limited water resources where municipal and industrial water usage often compete [24]. Additionally, replacing petroleum-based chemical admixtures with bio-based alternatives derived from renewable resources like cellulose, starch, or lignin can lower embodied carbon. For example, using lignosulfonates from paper industry waste can reduce the carbon footprint of concrete mixes by up to 20% [25]. The incorporation of renewable energy sources, such as biomass, wind, and solar photovoltaic (PV), into the concrete production process can further aid decarbonization, potentially decreasing GHG emissions related to energy use by 30–70% when replacing fossil

fuels. Reusing industrial wastewater not only promotes better wastewater management but also aligns with the principles of the circular economy and industrial ecology.

Investing in advanced treatment systems that produce concrete-grade water helps companies reduce pollution and create financial incentives for water reuse. Moreover, bio-based admixtures mitigate environmental risks associated with synthetic chemical admixtures, contributing to safer construction sites and cleaner manufacturing processes. The economic benefits of sustainable concrete production are compelling, as using treated wastewater can lower water procurement and disposal costs, especially in regions with strict regulations. Transitioning to renewable energy sources can also lead to significant long-term savings despite initial infrastructure costs. Additionally, bio-admixtures, often made from inexpensive agricultural waste, present a cost-effective alternative to synthetic options.

The integration of smart technology, such as AI-based process monitoring, enhances operational efficiency by optimizing additive dosage and monitoring effluent quality, thereby reducing variability and minimizing downtime. Companies adopting sustainable practices are better positioned to achieve green building certifications like LEED, BREEAM, or EDGE, which can attract environmentally conscious investors and provide financial incentives. Overall, the use of bio-based admixtures and treated wastewater in concrete production offers substantial financial and environmental benefits, supporting resource conservation and climate resilience while improving operational efficiency and market positioning. As concrete remains essential for infrastructure development, integrating sustainability into its production processes is both feasible and necessary [26,27].

3.4. Policy, Research, and Implementation Strategies

The transition to sustainable concrete production requires more than just technological innovation; it necessitates the optimization of the water-energy nexus through renewable energy and artificial intelligence (AI), alongside strong policy frameworks, skilled human resources, and strategic research investments [28,29]. Three critical pillars, policy and regulatory support, capacity building, and future research directions are essential for embedding AI-driven, resource-efficient systems into modern concrete manufacturing. Effective policies and regulations are crucial for integrating renewable energy systems and AI technologies in concrete manufacturing. Governments must create an enabling environment through financial incentives such as tax credits and subsidies, and public-private partnerships (PPPs) can help fund necessary infrastructure [30,31]. Laws that support carbon pricing can also incentivize low-emission facilities, while regulatory agencies should establish sustainability standards based on international best practices like ISO 14046 and ISO 50001. Human capital is vital for the successful integration of AI and renewable energy in concrete production. Educational institutions must develop curricula that equip engineers and technicians with the skills to manage AI-driven systems and renewable energy installations. Customized workforce development programs and community-based learning initiatives can democratize access to these technologies. To promote adoption, government organizations should provide best-practice guides and case studies that demonstrate the benefits of integrating AI with renewable energy. Continuous innovation is necessary to enhance performance and adapt to varying industrial conditions [32,33]. Research should focus on developing adaptive AI models that can improve decision-making in real time, as well as comprehensive life-cycle evaluations (LCA) to assess the environmental impacts of AI-optimized concrete systems. Localization of AI and renewable energy technologies to the specific contexts of developing countries is another important research area [[34,35]. Collaborative efforts between research institutions and local stakeholders can lead to context-specific solutions that address local development needs. Pilot projects and living labs can serve as innovation incubators for sustainable concrete solutions [36,37]. A concerted, multi-stakeholder approach is necessary to fully realize the potential of AI-driven, resource-optimized concrete manufacturing. Investing in intelligent,

sustainable infrastructure is essential for a resilient and inclusive future as urbanization and climate challenges grow [38–40].

Conclusion

The construction sector is undergoing a revolutionary change towards greater resilience, efficiency, and sustainability through the integration of bio-based admixtures, treated industrial wastewater, and renewable energy sources in concrete production. This transition relies on the intelligent integration of the water-energy nexus, which enhances resource efficiency, reduces emissions, and preserves the environment. This review has examined the integration of artificial intelligence (AI), renewable energy technologies, and water reuse strategies within the context of sustainable concrete manufacturing. The findings underscore the potential of a smart water-energy nexus framework to address the environmental and operational inefficiencies. Specifically, the use of treated industrial wastewater (TIWW) can reduce freshwater consumption by up to 80% while solar photovoltaic (PV) systems offer CO_2 emission reductions of up to 90% when replacing fossil fuel-based energy sources. AI-enabled technologies including digital twins, machine learning algorithms, and smart sensors facilitate real-time monitoring, predictive mix design, and dynamic energy-water optimization. These tools, when integrated with renewable energy systems and circular resource flows, enable significant gains in process efficiency, mitigation, and resource conservation. Importantly, intelligent monitoring systems are not developed by bio-admixtures or renewable technologies but are deployed in conjunction with them to enhance system responsiveness and performance consistency. Despite these advancements, several research gaps remain. Future investigations should prioritize validation of AI models across diverse material compositions and climatic conditions, localization of renewable energy systems for off-grid or resource-constrained construction environments, and comprehensive life-cycle assessments (LCA) to quantify the long-term environmental and economic impacts of integrated systems.

To accelerate adoption, coordinated efforts are required across academia, industry, and policy domains. This includes the development of performance-based procurement frameworks, investment in pilot-scale demonstration projects, and the establishment of interdisciplinary training programs that bridge digital technologies, environmental engineering, and materials science. Embedding these innovations into mainstream concrete production is essential for achieving low-carbon, water-efficient, and resilient infrastructure aligned with global sustainability targets.

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