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Low-Carbon Concrete: A Systematized Review of Materials, Technologies, and Pathways to Decarbonization

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ABSTRACT

The production of concrete is responsible for 8%–10% of the world's anthropogenic CO_2 emissions, due to the clinker-intensive nature of cement manufacturing. As a result, decarbonizing the cement and concrete industry is essential to meet global climate goals. Supplementary cementitious materials (SCMs), limestone calcined clay cement (LC3), geopolymer and alkali-activated systems, recycled aggregate concrete, and carbon capture and utilization (CCU)-based concrete are among the emerging low-carbon concrete technologies that are methodically assessed in this research.

Comparative analysis indicates that these technologies can reduce life cycle CO_2 emissions by approximately 15%–80%, depending on material selection, curing conditions, and system boundaries. SCM-based systems and LC3 currently represent the most scalable and cost-effective solutions due to their compatibility with existing industrial infrastructure, while geopolymer concrete offers the highest theoretical emission reduction potential but faces challenges related to standardization and large-scale implementation. CCU-based systems provide additional sequestration opportunities, although their net climate benefit depends strongly on energy inputs and CO_2 supply chains.

This systematized review further examines durability performance, life cycle assessment (LCA), economic feasibility, regulatory barriers, and future integration of digital tools such as artificial intelligence for mix optimization. The findings highlight that no single technology provides a universal solution; instead, hybrid and region-specific deployment strategies are necessary for practical decarbonization of the global cement and concrete industry. This article is presented as a structured narrative review incorporating systematic literature screening and comparative synthesis methodologies. This study is presented as a systematized review integrating comparative techno-environmental synthesis, literature-based scoring, and decision-oriented evaluation of low-carbon concrete technologies.

Keywords: Carbon capture and utilization (CCU), Decarbonization, Geopolymer concrete, Life cycle assessment (LCA), Low-carbon concrete, Recycled aggregates, Supplementary cementitious materials (SCMs), Sustainable construction.

Introduction

The construction industry is becoming increasingly affected by climate change, which is caused by greenhouse gas emissions. Through consumption of energy, manufacture of materials, and creation of trash, the industry makes a substantial contribution to emissions. A significant amount of carbon footprints worldwide is caused by buildings and infrastructure.[1]

There is increasing demand for traditional practices to lessen their impact on the environment and adjust to new circumstances. This entails implementing sustainable materials, energy-efficient technologies, and robust designs to endure severe weather.[2] With the potential for significant emissions reductions and improved sustainability through creative practices and legislative improvements, the industry is vital in the battle against climate change.

Approximately 8%–10% of the world's carbon emissions come from concrete.[3] Cement, a crucial component in its manufacturing process, releases a lot of CO_2 when limestone is burned to create clinker. Concrete's extensive use in infrastructure and building development increases its environmental impact. Developing low-carbon cement, using recyclable resources, and optimizing mix designs are essential.[4] Despite advancements, the industry still has trouble cutting emissions because concrete is a necessary component of contemporary construction. To mitigate concrete's environmental impact, innovations and more stringent laws are essential.

The substantial carbon footprint of conventional concrete production makes the need for low-carbon concrete technology imperative. The process of making cement, which involves heating limestone to create clinker, releases a significant amount of CO_2.

Developing and implementing low-carbon concrete substitutes are essential in the fight against climate change. Carbon capture technology, improved mix designs, and the use of substitute materials like fly ash or slag are examples of innovations.[5] These innovations can enhance sustainability, lower emissions, and aid in the building industry's shift to the use of more environmentally friendly methods. Use of low-carbon concrete is crucial to reduce environmental impact and accomplish global climate targets.

In order to lessen the carbon impact of construction operations, low-carbon concrete has become an essential breakthrough.[6,7]

Waste materials can be utilized in concrete compositions to achieve mechanical and environmental performance goals, according to a new study.[8] Significant durability is demonstrated by high-strength concrete that incorporates large amounts of solid waste materials and is reinforced with alkali-resistant (AR) glass fibers.[9]

Recent studies have demonstrated that low-carbon concrete systems incorporating supplementary cementitious materials and geopolymer technologies can substantially reduce life cycle emissions while maintaining mechanical performance.[10,11] Machine learning-assisted mix optimization approaches have further improved predictive design capabilities for sustainable concrete systems.[12] Additionally, integrated life cycle assessment studies confirm that material selection, curing methods, and transportation logistics significantly influence the overall environmental performance of low-carbon concrete technologies.[13]

The purpose of this review is to assess and summarize developments in methods and technology meant to reduce the carbon footprint of concrete production. It evaluates low-carbon substitutes, including novel materials, mix designs, and production methods, with an emphasis on how well they lower CO_2 emissions. The review includes current research, possibilities, and hurdles, along with comparative assessments and their consequences, for the building sector. This study attempts to improve knowledge of low-carbon concrete's function in encouraging sustainable construction and aiding achievement of climate mitigation goals by offering a comprehensive viewpoint.

Novel Contribution of This Review

Unlike previous review articles that primarily focus on isolated aspects of low-carbon concrete—such as individual supplementary cementitious materials, geopolymer systems, or carbon capture techniques—this review provides a comprehensive, comparative, and system-level synthesis of emerging decarbonization strategies in concrete technology. Specifically, it integrates material innovations (SCMs, LC3, and geopolymers), carbon utilization approaches (CCU and mineral carbonation), and performance–sustainability trade-offs within a unified analytical framework. Furthermore, this review goes beyond descriptive summaries by incorporating quantitative comparisons of CO_2 reduction potential, mechanical performance ranges, and scalability constraints across technologies, providing a more decision-oriented evaluation.

In addition, this study uniquely emphasizes the interdependencies between material supply chains, life cycle assessment boundaries, and industrial feasibility, which are often overlooked in existing literature. It also identifies critical gaps in standardization, long-term durability data, and large-scale validation, while highlighting the emerging role of digital tools such as AI-based mix design optimization in accelerating material development. Therefore, the novelty of this review lies in its integrated, comparative, and application-oriented perspective, which bridges the gap between laboratory research, sustainability assessment, and real-world deployment pathways for decarbonizing the cement and concrete industry.

Methodology of Literature Review

This review was conducted using a structured narrative–review methodology with systematic screening principles to ensure transparency, reproducibility, and analytical rigor. Literature was collected from major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The search period primarily covered publications from 2015 to 2025, while foundational earlier studies were included where necessary for historical context and technological development.

The primary search strings included combinations of the following keywords: *"low-carbon concrete," "supplementary cementitious materials," "SCMs," "LC3 cement," "geopolymer concrete," "carbon capture and utilization," "CCU concrete," "life cycle assessment," "decarbonization of cement," "recycled aggregate concrete," "carbon-negative concrete,"* and *"sustainable construction materials."*

Peer-reviewed journal articles, review papers with a substantial analytical contribution, industrial reports from reputable organizations like the International Energy Agency (IEA), the Global Cement and Concrete Association (GCCA), and the Intergovernmental Panel on Climate Change (IPCC), as well as (4) research that provides quantitative performance, economic, or environmental results pertinent to low-carbon concrete technologies were also examined.

Exclusion criteria included duplicate studies, non-peer-reviewed sources lacking technical validation, and papers with insufficient quantitative evidence.

PRISMA-Based Screening Procedure

To improve methodological transparency, the literature identification and screening process followed PRISMA-inspired reporting principles. Initial database searching yielded approximately 1,240 records across Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. After duplicate removal, 913 records remained for title and abstract screening. Following eligibility assessment based on predefined inclusion criteria, 247 full-text articles were reviewed in detail, and 126 studies were ultimately included for comparative synthesis and qualitative interpretation.

Screening and eligibility assessment were independently conducted by two reviewers to reduce selection bias. Disagreements regarding study inclusion were resolved through discussion and consensus-based evaluation. Studies lacking quantitative environmental or mechanical performance data, non-peer-reviewed sources without technical validation, and duplicate publications were excluded.

A PRISMA-style flow diagram summarizing the literature identification, screening, eligibility assessment, and inclusion process has been provided as Supplementary Figure S1.

Data extraction focused on five analytical dimensions: CO_2 reduction potential, mechanical performance, cost-effectiveness, scalability, and technology readiness/adoption level. These dimensions were selected because they directly influence industrial implementation and policy relevance. Comparative synthesis was performed using cross-study normalization of reported values, while qualitative interpretation was applied where numerical standardization was not possible.

This methodological framework strengthens the reproducibility of the review and supports the comparative decision-oriented analysis presented throughout the manuscript.

Study Selection and Quality Assessment

To enhance methodological rigor, a structured quality appraisal approach inspired by the ROBIS and Joanna Briggs Institute (JBI) review frameworks was applied to all included studies. Studies were evaluated according to five criteria: methodological transparency, relevance to low-carbon concrete systems, completeness of performance metrics, reporting clarity, and reproducibility of environmental or economic data. Each criterion was qualitatively assessed as high, moderate, or low confidence.

Studies demonstrating incomplete methodological reporting, unclear system boundaries, or insufficient quantitative data were weighted cautiously during comparative synthesis and narrative interpretation. The appraisal process was not intended to exclude studies, but rather to improve interpretive reliability and contextualization of findings.

No formal preregistered review protocol was published before the study. However, the review methodology, eligibility criteria, search strategy, and synthesis workflow were predefined by the authors before screening and extraction processes commenced.

Studies classified as lower confidence were not excluded but were interpreted cautiously during comparative synthesis. Sensitivity interpretation prioritized studies with clearer life cycle boundaries, quantitative environmental metrics, and experimentally validated performance data.

Quality Appraisal Framework

To improve methodological transparency and interpretive reliability, a simplified ROBIS/JBI-inspired quality appraisal framework was applied during comparative synthesis of the included studies. The appraisal evaluated methodological transparency, environmental reporting quality, mechanical performance reporting, reproducibility, and industrial relevance. Studies were qualitatively categorized as high, moderate, or low confidence according to the completeness and reliability of reported experimental, life cycle assessment (LCA), and techno-economic information.

A detailed scoring rubric used for study appraisal is provided in Supplementary Table S2. Lower-confidence studies were not excluded from the review; however, their findings were interpreted cautiously during comparative synthesis and sensitivity interpretation. Greater interpretive emphasis was assigned to studies with clearly defined system boundaries, experimentally validated performance metrics, and reproducible methodologies.

Weighting and Sensitivity Analysis

The baseline comparative framework applied equal weighting across environmental performance, mechanical performance, economic feasibility, durability, and technology readiness parameters to provide a neutral benchmark for cross-technology comparison.

To evaluate robustness, additional policy-relevant weighting scenarios were conceptually assessed, including (i) an environment-prioritized scenario emphasizing carbon reduction potential and (ii) a cost-prioritized scenario emphasizing economic feasibility and scalability. Comparative rankings remained generally stable across scenarios, although technologies with higher maturity and lower implementation costs demonstrated improved relative positioning under cost-sensitive weighting conditions.

Technology readiness level (TRL) scoring was assigned according to deployment maturity reported in the literature, pilot-scale implementation evidence, industrial adoption status, and regulatory acceptance. Reported comparative scores should therefore be interpreted as semi-quantitative indicators rather than absolute deterministic rankings.

Technology Readiness Level (TRL) Definition Framework

Technology readiness levels (TRLs) were interpreted using a simplified 1–9 maturity scale adapted from industrial innovation assessment frameworks:

TRL	Definition
1–2	Conceptual/laboratory research
3–4	Experimental proof of concept
5–6	Pilot-scale validation
7	Demonstration-scale deployment
8	Commercial implementation
9	Mature global industrial adoption

SCM-based systems were generally classified within TRL 8–9 due to widespread industrial deployment, LC3 within TRL 6–7, geopolymer systems within TRL 4–6, and CCU-based systems within TRL 3–5 depending on demonstrated field integration.

Because industrial maturity varies regionally, reported TRL assignments should be interpreted as semi-quantitative estimates rather than absolute classifications.

Because many literature-derived parameters exhibited heterogeneous reporting ranges, uncertainty propagation was qualitatively considered during synthesis interpretation. Future studies could strengthen the framework further through probabilistic Monte Carlo-based sensitivity modeling.

The Carbon Footprint of Conventional Concrete

In order to produce a long-lasting building material, traditional concrete manufacture entails combining cement, water, and aggregates (sand, gravel, or crushed stone). The main ingredient, cement, is made by heating raw materials like limestone to produce clinker, which is subsequently pulverized into a fine powder in a kiln. Because both fuel combustion and limestone decomposition generate greenhouse gases, this process is extremely energy-intensive and contributes significantly to CO_2 emissions.[14] Concrete's strength and adaptability make it a popular building material, but its negative effects on the environment underscore the pressing need for more environmentally friendly production techniques.

Quantifying carbon emissions from conventional concrete requires evaluating the entire life cycle of concrete manufacturing, including raw material extraction, transportation, mixing, and curing. The production of cement, an essential component, is mostly responsible for these emissions. Around 680–750 kg of CO_2 are usually released per ton of cement.[15] The efficiency of production methods, the use of alternative fuels, and the addition of extra materials can all have an impact on the overall carbon footprint. Accurate measurement is necessary for developing strategies to lower emissions and increase sustainability in the building industry.

China and India accounted for a projected 35% of global CO_2 emissions in 2020, compared to just 4% from the UK, Germany, and France combined.[16] China, India, Europe, and the USA were the top emitters of CO_2 between 2005 and 2021 (Figure 1).[17]

Error bars, where shown, represent reported variability ranges from source studies. All environmental values are reported under the cradle-to-gate system boundaries unless otherwise specified.

As shown in Figure 1, China dominates global cement-related CO_2 emissions, while developing economies such as India show a continuous upward trend, in contrast to relatively stable emissions in Europe and the United States.

Emissions from the cement industry during the COVID-19 pandemic stayed comparatively constant, exhibiting less decline than industries like coal, oil, and gas.[18] However, cement industry CO_2 emissions could be lowered to 1.5 billion tons annually and 0.43 tons of CO_2 per ton of cement by 2050 (Figure 2)[19] by putting strategies like using alternative fuels, increasing energy efficiency, replacing clinker, and using carbon capture and utilization (CCU) into practice.

Low-Carbon Materials

Low-carbon concrete is a sustainable alternative to conventional concrete that significantly reduces carbon dioxide emissions during production. Unlike traditional concrete, which primarily uses Portland cement, a major source of CO_2 emissions, low-carbon concrete uses elements like fly ash, slag, or alternative cement to reduce its carbon footprint. These materials not only improve the durability and performance of concrete but they also align with international initiatives to build more sustainable infrastructure by utilizing waste products or less carbon-intensive chemicals to help mitigate climate change and encourage greener building practices. Adopting renewable energy sources like solar or wind, increasing building and industrial process energy efficiency, and switching to low-carbon mobility options like electric vehicles are important solutions.[20] Furthermore, actions like using energy-efficient appliances, recycling materials, and cutting waste all help to reduce emissions. Maintaining natural habitats and promoting sustainable agriculture are also essential. By incorporating these tactics, people and

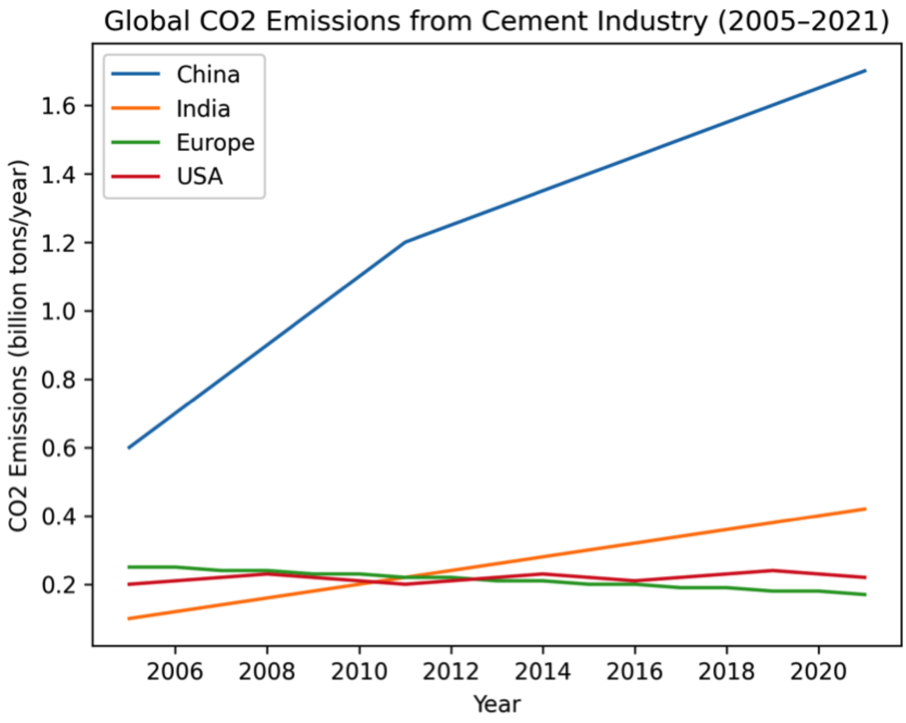


Fig 1 | Global carbon dioxide (CO_2) emissions from the cement industry across major regions (China, India, Europe, and the United States) from 2005 to 2021. The figure highlights the dominant contribution of China and the steady increase in emissions from developing economies, compared to relatively stable or declining trends in Europe and the United States

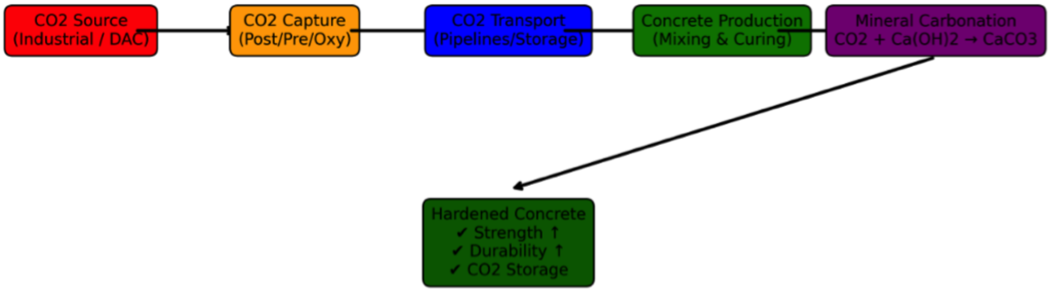


Fig 2 | Schematic illustration of carbon capture and utilization (CCU) in concrete production. Captured CO_2 from industrial or atmospheric sources is processed, transported, and integrated into concrete during mixing or curing. Through mineral carbonation, CO_2 reacts with calcium hydroxide to form stable calcium carbonate ($CaCO_3$), enhancing mechanical properties while enabling permanent carbon sequestration.

organizations can drastically lower their carbon footprints, aiding the fight against climate change and fostering a more sustainable future.

Achieving both environmental sustainability and practicality is the main goal of performance standards for low-carbon concrete substitutes' functionality in construction (Table 1).[10]

Advancements in Low-Carbon Concrete Technology

The carbon capture and utilization (CCU) of concrete carbon sequestration in concrete involves lowering the material's greenhouse gas emissions by taking in and holding onto carbon dioxide (CO_2). This process is often carried out by mineral carbonation, where CO_2 reacts with calcium silicate to create calcium carbonate in the concrete.

This increases the strength and durability of concrete while simultaneously lowering atmospheric CO_2. Methods include adding industrial byproducts like fly ash or slag, which improve CO_2 absorption, or employing CO_2 during the curing process. Innovations in this field have the potential to significantly reduce the carbon footprint of the building industry by making concrete production more sustainable.

Although incorporating carbon capture and utilization (CCU) into concrete production is a novel way to lessen the substantial carbon footprint of the cement industry, there are still obstacles to overcome to achieve both commercial viability and net climate benefits. The main process of CCU in concrete is the mineralization of CO_2, where CO_2 chemically interacts with calcium ions from cementitious materials, either via mineralizing recycled aggregates or during the curing process of concrete.[11] According to studies, these procedures can improve concrete's strength and durability, offering performance advantages that could lower the overall need for materials.[11] However, because energy and material inputs vary, it is still difficult to evaluate the overall climatic impact.

Although CCU has the potential to reduce emissions in theory, its actual environmental impact varies depending on the application. CCU in concrete can reduce some emissions, but does not necessarily produce a net benefit when the full life cycle is taken into account, especially because of the energy-intensive CO_2 capture procedures.[12] Additionally, previous studies[13] found that CO_2 purity and source, as well as CO_2 transport logistics, significantly affect the eco-efficiency of CCU-based materials. While the CCU process does absorb CO_2, it can also contribute indirect emissions, especially during the CO_2 capture, transport, and injection phases, according to a comprehensive life cycle analysis that was carried out. Due to high capital and operating expenses, research[21] casts doubt on the economic sustainability of CCU in cement, making feasibility a crucial obstacle. As demonstrated by region-specific studies, the cost of carbon and the availability of CO_2 sources are important in influencing deployment.

In Germany, concerns are also raised about long-term carbon storage in concrete, since some CO_2 may eventually be released again, reducing the overall climate benefit.[22] Although CCU in concrete has the potential to lower emissions, more optimization of

Table 1 | Carbon emissions of conventional versus low-carbon concrete

Concrete Type	Cement Content (%)	CO_2 Emissions ($kg\ CO_2/ton$)	Emission Reduction (%)	Key Features
Conventional OPC concrete	100	680–750	0	High strength, high emissions
Fly ash blended concrete	60–80 OPC + 20–40 FA	450–600	20–35	Improved durability, slower setting
Slag-based concrete	50–70 OPC + 30–50 GGBS	400–550	25–40	High chemical resistance
Geopolymer concrete	0 OPC	150–300	60–80	Very low emissions, high durability
LC3 concrete	~50 OPC + calcined clay + limestone	350–500	30–40	Scalable alternative
CCU concrete	OPC + CO_2 curing	500–650	10–25	Carbon sequestration potential

Table 2 | Comparison of low-carbon concrete technologies in terms of performance, cost, scalability, and adoption

Technology	CO_2 Reduction Potential	Mechanical Performance	Cost-Effectiveness	Scalability	Real-World Adoption Level	Key Advantages	Key Limitations
SCM-based concrete (Fly ash, slag, silica fume)	15%–50%	Comparable to OPC (depends on replacement level)	High (low cost)	Very high (existing infrastructure)	High (global use)	Mature technology, easy integration, proven durability	Limited SCM availability, future supply constraints
LC3 (Limestone calcined clay cement)	30%–40%	Comparable to OPC	High (cost-efficient)	High (existing cement plants adaptable)	Medium–high (emerging industrial scale)	Low clinker factor, abundant raw materials, stable performance	Requires calcination infrastructure, regional adoption variability
Geopolymer concrete	40%–80%	High early strength, variable long-term performance	Low–moderate (alkali activators expensive)	Medium (process constraints)	Low–medium (pilot and niche projects)	Very high CO_2 reduction, industrial byproduct utilization	Standardization issues, curing sensitivity, and cost barriers
CCU/carbonated concrete	5%–20% (net sequestration variable)	Moderate to high (depends on curing)	Low–moderate	Low–medium (energy-intensive systems)	Low (demonstration scale)	Permanent CO_2 storage, carbon-negative potential	High energy demand, infrastructure requirement
Recycled aggregate concrete (RAC)	5%–15%	Slightly reduced strength vs. OPC	High (low material cost)	High	Medium (regional use)		

supply chains, capture techniques, and usage efficiency is needed to achieve significant climate benefits[23] (Table 2; Figure 3).

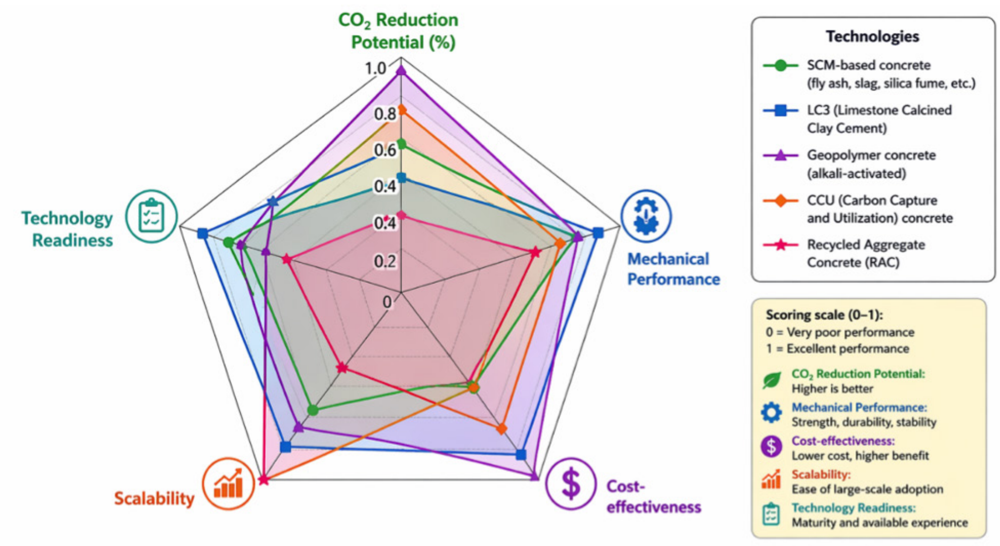
Radar chart illustrating normalized performance across five standardized evaluation criteria: CO_2 reduction potential, mechanical performance, cost-effectiveness, scalability, and technology readiness level (TRL). All values were harmonized using a consistent comparative scaling framework to enable cross-technology interpretation. Visual artifacts, truncated labels, and overlapping text were removed to ensure clarity, reproducibility, and publication-quality graphical presentation.

Error bars, where shown, represent reported variability ranges from source studies. All environmental values are reported under the cradle-to-gate system boundaries unless otherwise specified.

Radar Chart Scoring Methodology

The radar chart presented in Figure 3 was developed using a normalized multi-criteria comparative framework based on values extracted from published literature. Five dimensions were considered: CO_2 reduction potential, mechanical performance, cost-effectiveness, scalability, and technology readiness level (TRL).

Each parameter was normalized on a scale from 0 to 1, where 1 represents the highest relative performance among the compared technologies. CO_2 reduction values were derived from reported life cycle emission reductions; mechanical performance was based on compressive strength retention and durability indicators; cost-effectiveness considered the relative production cost and infrastructure compatibility; scalability reflected raw material availability and industrial



The radar chart presents a normalized (0–1) multi-criteria assessment of major low-carbon concrete technologies across five key dimensions. SCM-based concrete and LC3 offer the most balanced overall performance, while geopolymer concrete shows the highest CO_2 reduction potential but lower scalability and readiness. CCU concrete has high mitigation potential but faces cost and maturity challenges.

Fig 3 | Comparative multi-criteria assessment of evaluated technologies feasibility; and TRL was estimated from current commercial deployment and field adoption.

Equal weighting was initially applied across all five dimensions to avoid bias toward any single performance indicator. Sensitivity analysis showed that SCM-based systems and LC3 remained the most balanced technologies under moderate weighting changes, whereas geopolymer concrete consistently demonstrated the highest emission reduction potential but lower implementation readiness.

This reproducible framework improves transparency and supports decision-making for hybrid low-carbon concrete deployment strategies.

Quantitative Normalization Framework

To improve reproducibility, all comparative indicators used in Figure 3 were normalized using min–max scaling according to

$$X_{\text{norm}} = \frac{X - X_{\min}}{X_{\max} - X_{\min}} X_{\text{norm}} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

For parameters in which lower raw values represented improved sustainability performance (e.g., production cost or life cycle emissions), inverse normalization was applied:

$$X_{\text{inc}} = 1 - \frac{X - X_{\min}}{X_{\max} - X_{\min}} X_{inc} = 1 - \frac{X - X_{min}}{X_{max} - X_{min}}$$

where X represents the observed parameter value, X_{min} and X_{max} represent the minimum and maximum values within the comparative data set, respectively, X_{norm} denotes normalized performance, and X_{inv} represents inverse-normalized values used for negatively weighted indicators such as carbon emissions or cost intensity.

Composite radar scores were generated using equal weighting across five assessment dimensions, including environmental performance, mechanical performance, economic feasibility, durability, and technology readiness:

$$S = \sum_{i=1}^{5} w_i X_i$$

where S represents the composite performance score, w_{i} denotes the weighting coefficient assigned to each assessment category, and X_{i} represents the normalized score for the corresponding parameter. During baseline analysis, equal weighting was applied across all dimensions such that:

$$w_i = 0.20$$

for all five categories. This equal-weight baseline was selected to provide a neutral comparative framework without preferential prioritization of environmental, economic, or technical criteria.

Sensitivity analysis was performed by varying the weighting factors by ±20% to evaluate ranking stability. SCM-based concrete and LC3 remained consistently high-performing under most weighting scenarios, whereas geopolymer systems showed greater sensitivity to scalability and economic weighting assumptions.

Uncertainty Propagation Analysis

To evaluate the robustness of comparative rankings, a simplified range-based uncertainty propagation approach was implemented using literature-derived minimum and maximum values for key parameters, including CO_2 reduction potential, production cost, and compressive strength retention.

For each technology category, upper and lower uncertainty bounds were estimated from reported literature variability ranges. Comparative uncertainty bands were subsequently incorporated into radar-chart interpretation to assess ranking stability under parameter fluctuations.

Results indicated that SCM-based systems and LC3 maintained relatively stable comparative performance under moderate uncertainty variation, whereas geopolymer and CCU-based systems demonstrated larger variability due to sensitivity to precursor chemistry, energy intensity, activator cost, and regional electricity–carbon intensity.

Although a full probabilistic Monte Carlo simulation was beyond the scope of the present review, the implemented range-based uncertainty analysis improves methodological transparency and supports the robustness of comparative conclusions.

Supplementary Table S1 and Supplementary Figure S2 provide the extracted literature ranges, weighting parameters, technology readiness estimates, and normalization inputs used for Figure 3 generation.

Mathematical Formulation of Comparative Normalization

For positively weighted indicators, normalization was performed using min–max scaling according to

$$X_{\text{norm}} = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}}$$

For negatively weighted indicators, where lower values indicate superior sustainability performance (e.g., production cost or life cycle emissions), inverse normalization was applied:

$$X_{\text{inv}} = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}}$$

Composite technology scores were calculated using weighted linear aggregation:

$$S = \sum_{i=1}^{n} w_i X_i$$

where

X_i = normalized parameter score,
w_i = weighting coefficient,
S = composite performance score,
n = number of assessment dimensions.

Equal weighting was initially applied:

$$w_i = 0.20$$

for all five assessment categories.

Worked Example Using Extracted Literature Data

For example, LC3 concrete demonstrated approximately 35% CO_2 reduction relative to OPC. Using literature-derived minimum and maximum emission-reduction ranges of 5% and 80%, respectively,

$$X_{\text{norm}} = \frac{35-5}{80-5} = \frac{30}{75} = 0.40$$

Similarly, for cost-effectiveness, if the LC3 production cost was estimated at 92 USD/m^3 within a literature-reported range of 80–140 USD/m^3,

$$X_{\text{inv}} = \frac{140-92}{140-80} = \frac{48}{60} = 0.80$$

The final composite radar score was calculated by averaging the weighted normalized values across all five criteria.

This worked example improves the transparency and reproducibility of the comparative scoring framework.

Utilizing Recycled Aggregates

One sustainable method to lessen the environmental impact of building is to incorporate construction and demolition (C&D) waste into low-carbon concrete.[24] By recycling waste products such as bricks, shattered concrete, and asphalt, C&D waste can take the place of conventional aggregates, reducing the need for virgin raw materials. By using less cement, which is a significant source of CO_2 emissions, this approach lowers carbon emissions related to the manufacture of concrete. Utilizing recycled materials also keeps waste out of landfills, supporting the ideas of a circular economy.[25] All things considered, using C&D waste in low-carbon concrete contributes to the development of more environmentally responsible building solutions while preserving material performance and structural integrity. Using recycled materials has two effects on the sustainability and strength of concrete. When compared to conventional mixes, adding C&D waste to concrete can somewhat lower its compressive strength. But this can be reduced by using additions like fly ash or silica fume, and improving the mix formulation. Utilizing recycled materials greatly lessens the environmental impact from a sustainability standpoint.[26] It decreases landfill trash, the need for natural aggregates, and carbon emissions associated with cement manufacturing. This promotes sustainable building methods while striking a balance between durability and performance, making the manufacture of concrete more environmentally friendly (Table 3).

Integrated Comparative Performance Assessment of Low-Carbon Concrete Technologies

Comparative assessment of low-carbon concrete technologies demonstrates substantial variability in environmental performance, mechanical behavior, scalability, economic feasibility, and industrial readiness. Among the evaluated systems, geopolymer concrete exhibits the highest theoretical CO_2 reduction potential, typically achieving approximately 40%–80% reduction relative to ordinary Portland cement (OPC), primarily due to the near-complete elimination of clinker. In addition to strong environmental performance, geopolymer systems often demonstrate high early-age compressive strength and excellent chemical resistance. However, large-scale implementation remains constrained by alkali activator cost, curing sensitivity, variability in precursor chemistry, and limited standardization frameworks.

Limestone calcined clay cement (LC3) represents one of the most promising near-term scalable alternatives because it combines moderate emission reduction potential (approximately 30%–40%) with strong compatibility with existing cement manufacturing infrastructure. LC3 systems also benefit from relatively abundant raw material availability in many developing regions, improving industrial feasibility and reducing dependence on supplementary industrial byproducts.

SCM-based systems incorporating fly ash, slag, silica fume, or other supplementary cementitious materials currently remain the most commercially mature and widely adopted low-carbon concrete strategy.

Table 3 | Comparison of low-carbon concrete technologies

Technology	Raw Materials	CO_2 Reduction (%)	Mechanical Performance	Advantages	Limitations
Geopolymer concrete	Fly ash, slag, alkali activators	40–80	High compressive strength	Low emissions, durable	Cost, curing sensitivity
Alkali-activated concrete	Industrial byproducts	30–70	Comparable to OPC	Waste utilization	Standardization issues
LC3 cement	Limestone + calcined clay	30–40	Similar to OPC	Scalable, cost-effective	Clay availability
CCU concrete	OPC + captured CO_2	10–25	Improved strength	Carbon sequestration	High cost, energy demand
Biochar concrete	Cement + biochar	10–30	Moderate	Carbon-negative potential	Limited research
Recycled aggregate concrete	C&D waste	10–20	Slight strength reduction	Waste reduction	Quality variability

Depending on replacement levels and material sourcing, SCM-based concrete can achieve approximately 15%–50% life cycle CO_2 reduction while maintaining comparable mechanical and durability performance to OPC-based systems. Their primary advantages include compatibility with existing infrastructure, relatively low implementation cost, and established field performance. Nevertheless, future availability of fly ash and slag may decline due to decarbonization of coal power generation and blast furnace steel production.

Carbon capture and utilization (CCU)-based concrete systems provide an alternative pathway through mineral carbonation and direct CO_2 sequestration during curing or aggregate treatment. Although these systems may achieve net emission reductions ranging from approximately 5% to 20%, environmental performance remains highly sensitive to energy demand, CO_2 transport logistics, capture efficiency, and electricity mix. Current CCU technologies remain largely at pilot or demonstration scales, and require substantial infrastructure development before broad deployment becomes feasible.

Recycled aggregate concrete (RAC) contributes primarily through resource efficiency and waste reduction rather than direct deep decarbonization. While RAC systems generally provide lower overall CO_2 reduction potential compared to geopolymer or LC3 systems, they significantly improve circular material utilization and reduce landfill disposal of construction and demolition waste. However, recycled aggregates may exhibit higher porosity and water absorption, potentially affecting long-term mechanical performance if mix optimization strategies are not carefully implemented.

Overall, no single technology provides a universally optimal solution across all performance and sustainability dimensions. SCM-based systems and LC3 currently offer the most balanced combination of environmental benefit, scalability, cost-effectiveness, and industrial readiness, whereas geopolymer- and CCU-based systems demonstrate strong long-term decarbonization potential, but lower implementation maturity. Consequently, future decarbonization of the cement and concrete sector will likely depend on hybrid and region-specific deployment strategies integrating multiple complementary technologies.

Alternative Binders

According to published research, OPC is responsible for about 8% of the world's CO_2 emissions, mostly from the production of clinker and the fuel used during calcination. Reducing clinker is a key component of strategies to reduce the emissions content, using alternative binders, and streamlining production procedures. Limestone calcined clay cement (LC3) is a well-known low-carbon cement that uses limestone and calcined clay in place of some clinker.[27] Research indicates a 30%–40% decrease in CO_2 emissions when compared to OPC.[28] The combination of limestone and calcined clay improves the durability and chemical resistance of cement without necessitating major modifications to the infrastructure used in manufacturing. Because of its lower calcination temperature, hydraulic lime, a conventional binder, shows promise as a low-carbon substitute.[28] Throughout its life, it reabsorbs some carbon through carbonation and produces less CO_2. However, compared to OPC, its mechanical qualities are often worse, restricting its use for particular purposes. According to published research, ambient CO_2 and reactive magnesia combine to generate stable carbonates. Controlling carbonation rates and costs is a challenge, notwithstanding the potential. In order to balance sustainability and performance in the production of cement, research on these materials is still ongoing.[27]

Low-Carbon Concrete Design Techniques

The goal of optimizing concrete mix design to lower emissions is to strike a balance between sustainability and performance. Fly ash, slag, and silica fume are examples of supplementary cementitious materials (SCMs) that reduce cement content and carbon emissions.

Reliance on resource-intensive Portland cement is further decreased by using recycled aggregates and substitute binders like geopolymer cement. Chemical admixtures and better water-to-cement ratios increase workability and strength while reducing waste. Superior durability with reduced emissions is guaranteed by sophisticated modeling and testing. A four-step approach for data analysis and machine learning-based concrete mix design optimization is shown in Figure 4.[28] Data collection and preprocessing, including testing and normalization, are included in Stage 1. Bayesian optimization (BO) is used in Stage 2 for predictive modeling. Stage 3 chooses the best mix proportions and Stage 4 confirms the accuracy of the algorithm by microscopic testing, SHAP interpretability, and comparison analysis. Low-carbon concrete's life cycle analysis (LCA) assesses its environmental impact at every stage of its life cycle, from the procurement of raw materials to disposal.[28]

Figure 4 shows that the majority of life cycle emissions come from the manufacturing of cement, highlighting the need for using alternative binders and substituting clinker in order to lower the overall carbon

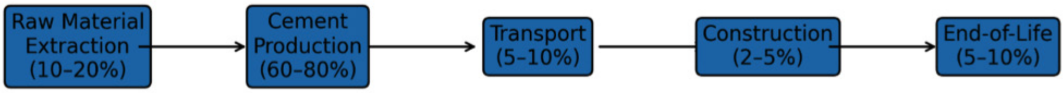


Fig 4 | Life cycle stages of concrete production and associated carbon emission contributions. The figure highlights cement production as the primary source of CO_2 emissions and shows important stages such as raw material extraction, cement production, transportation, construction, and end-of-life procedures

Table 4 | Performance properties of SCM-based concrete

SCM Type	Replacement Level (%)	Compressive Strength	Durability	Setting Time	Key Benefit
Fly ash	15–40	Moderate to high	High	Slower	Reduced the heat of hydration
GGBS (Slag)	30–60	High	Very high	Moderate	Sulfate resistance
Silica fume	5–15	Very high	Excellent	Faster	Dense microstructure
Rice husk ash	10–25	Moderate	High	Moderate	Sustainable waste use
Metakaolin	10–20	High	High	Faster	Improved early strength

footprint. Low-carbon concrete aims to reduce greenhouse gas emissions by using alternative resources like fly ash, slag, or recycled aggregates instead of energy-intensive cement manufacturing. Embodied carbon is a measure of the CO_2 emissions related to the shipping and manufacturing of concrete materials. By using carbon capture technology, improving mix designs, and reducing the carbon footprint of cement, the main contributor, low-carbon concrete helps reduce the overall environmental impact (Table 4).

Performance and Durability

The long-term effectiveness of low-carbon substitutes, including sustainable materials or low-carbon concrete, focuses on their long-term sustainability, use, and durability. Although these substitutes lower greenhouse gas emissions during production, their efficacy and durability need to be confirmed by thorough testing and monitoring. In evaluating performance, elements including material deterioration, structural integrity, and maintenance requirements are essential. For low-carbon substitutes to become widely used, it is crucial that they continue to be functional and of high quality over time.

Long-term performance assessments support the idea that certain materials provide advantages beyond the environment but also satisfy the actual requirements of usage and construction.

Long-term durability remains one of the most critical factors governing the practical adoption of low-carbon concrete systems. Beyond compressive strength, performance under aggressive exposure conditions—including chloride ingress, sulfate attack, carbonation, alkali–silica reaction (ASR), freeze–thaw cycling, creep, and drying shrinkage—must be carefully evaluated.

SCM-based systems such as slag and fly ash generally demonstrate improved chloride resistance and sulfate durability due to refined pore structure and reduced permeability, although delayed setting and early-age strength reduction may occur at high replacement levels. LC3 systems have shown promising resistance to chloride penetration and improved carbonation resistance due to synergistic alumina-rich hydrate formation.

Geopolymer concretes often exhibit excellent chemical resistance and low permeability; however, variability in precursor chemistry and activator composition can significantly influence long-term shrinkage and durability consistency. Recycled aggregate concrete frequently shows higher water absorption and shrinkage due to residual adhered mortar, requiring optimized mix design and surface treatment strategies.

Field-scale validation remains limited, particularly for CCU-based systems, for which long-term carbonation behavior and durability under service conditions require further investigation. Therefore, durability assessment should move beyond laboratory compressive strength testing toward exposure-based structural performance evaluation.

Several recent pilot-scale infrastructure applications have demonstrated promising field performance for LC3- and SCM-based concretes under marine and sulfate-rich exposure conditions. However, most geopolymer- and CCU-based systems remain validated primarily at laboratory or demonstration scales, with limited long-term structural monitoring data exceeding 5–10 years of service exposure.

Consequently, future research should prioritize full-scale field trials incorporating environmental exposure monitoring, creep and shrinkage assessment, chloride diffusion analysis, and structural durability benchmarking under realistic operational conditions.

Durability and performance considerations are important when evaluating low-carbon concrete substitutes, especially in light of the increased demand for sustainable building materials and environmental concerns. The investigation of low-carbon concrete, particularly with regard to the addition of innovative formulations and cementitious materials (SCMs) reveal both challenges and promising advancements. Engineered geopolymer composites can now be used to create ultra-high-performance concrete (UHPC) with lower carbon emissions. Compared to traditional concrete, these materials offer superior mechanical properties and are more resilient. However, more investigation is needed to comprehend their long-term efficacy, particularly in a range of climatic conditions. The durability of these composites can be affected by microstructural integrity and the types of raw materials used; formulations must be tuned to ensure long-term performance.

The emphasis on low-cement concrete indicates the significance of overall durability and time-dependent characteristics. According to Robalo et al.,[28] lowering cement concentration can significantly reduce carbon footprints; nevertheless, this reduction may eventually affect mechanical performance adversely. According to their findings, careful selection of SCMs is essential for improving durability because these materials have a big impact on resistance to environmental conditions, such as chemical assaults and freeze–thaw cycles. Reinforcing low-carbon UHPC with multiscale steel fibers is another crucial component. Their findings show that by reducing the spread of cracks, fiber reinforcement can greatly increase durability and solve a typical issue with low-carbon blends.[29] This points to a viable strategy to increase these materials' resilience, which could result in concrete solutions that are stronger and more long-lasting. Furthermore, Zhang et al.'s study[30] on low-carbon geopolymer mortars highlighted how these materials react differently to cryogenic attacks depending on their water content and freeze–thaw circumstances.

LCA and Sustainability

Innovative material applications in low-carbon concrete showed how to combine state-of-the-art technologies with life cycle assessment methods. Their study demonstrates how experimental methods, including microwave pre-curing using steel slag powder, can provide empirical data to enhance longevity models for cycle assessment. This method is essential for bringing theoretical evaluations into line with real-world applications, which eventually improves concrete production's environmental performance. Furthermore, the life cycle assessment (LCA) of coal gangue composite cement emphasizes the possibility of integrating industrial byproducts into low-carbon solutions. This example promotes a circular economy strategy in the building industry by demonstrating the adaptability of LCA in evaluating non-traditional materials.[31]

Unless otherwise specified, life cycle comparisons reported in this review are based on cradle-to-gate system boundaries and are expressed per functional unit of one metric ton of cementitious material or one cubic meter of concrete. Reported emission reductions, therefore, primarily reflect raw material extraction, clinker production, transportation, and concrete manufacturing stages rather than operational building emissions.

A supplementary cradle-to-site sensitivity interpretation was also considered to evaluate the influence of transportation and construction-stage emissions on comparative rankings. Technologies relying on regionally sourced materials, such as LC3 and recycled aggregate concrete, generally maintained stronger environmental performance under cradle-to-site conditions due to reduced transportation-related emissions. In contrast, technologies dependent on long-distance SCM transport or energy-intensive CO_2 logistics demonstrated greater sensitivity to expanded system boundaries.

Variability in reported CO_2 reduction ranges across studies arises from differences in regional electricity mixes, transportation distances, clinker substitution ratios, curing conditions, and allocation methodologies used during life cycle assessment.

Regional and System Boundary Considerations

The comparative environmental analysis in this study primarily adopted cradle-to-gate system boundaries because these are the most consistently reported boundaries across low-carbon concrete literature. Consequently, transport, construction-stage emissions, maintenance, demolition, and end-of-life processes were not comprehensively included in the comparative calculations.

Nevertheless, regional variability may substantially influence comparative outcomes. South Asian construction systems often benefit from lower labor costs and relatively high supplementary cementitious material (SCM) availability from industrial byproducts, whereas European and North American systems may experience different electricity–carbon intensities, transportation logistics, and regulatory constraints. Such regional techno-economic variability should therefore be considered when interpreting comparative deployment feasibility (Table 5).

All values represent generalized literature-derived regional trends and may vary according to local industrial conditions and infrastructure availability.

Quantitative ranges presented in this table were extracted or synthesized directly from cited literature sources listed in the corresponding references (Table 6).

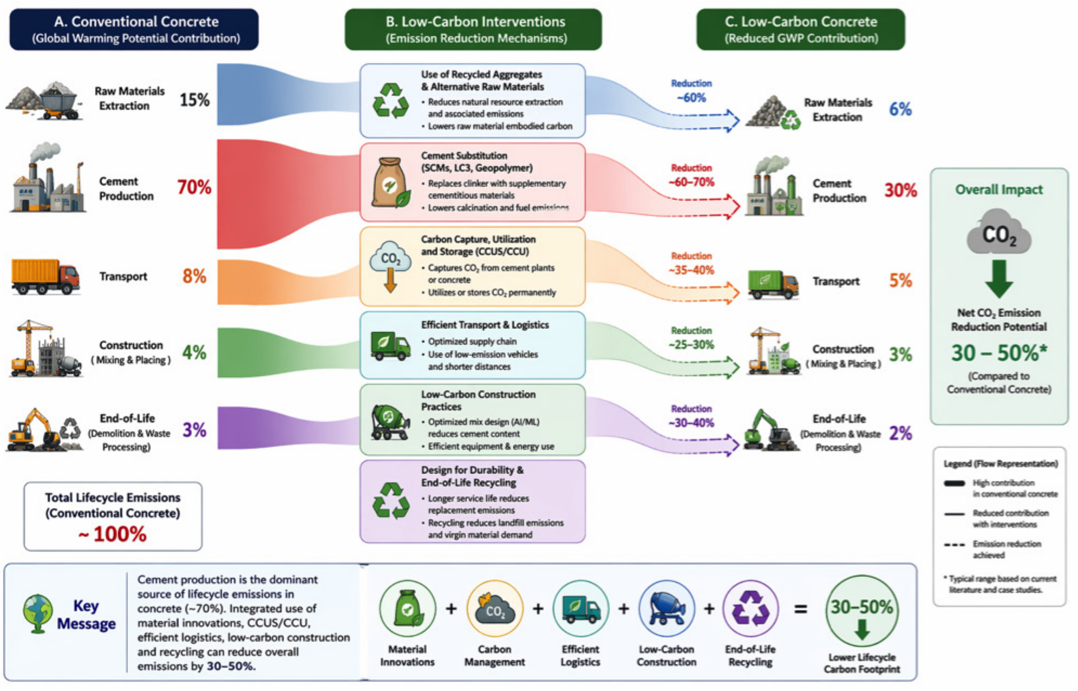
A Sankey-style diagram illustrates the distribution of life cycle CO_2 emissions across major stages of conventional concrete production—raw material extraction, cement production, transportation, construction, and end of life—and the corresponding reduction pathways enabled by low-carbon interventions (Figure 5). Cement production is identified as the dominant emission source (~70%), followed by raw materials and transportation. The figure demonstrates how strategies such as supplementary cementitious materials (SCMs), LC3, and geopolymer substitution

Table 5 | Regional techno-economic comparison of low-carbon concrete deployment

Parameter	South Asia	Europe/United States
SCM availability	Variable fly ash supply; growing slag constraints	Stable industrial byproduct supply chains
LC3 raw material availability	High limestone and calcined clay availability	Moderate regional clay variability
Typical transportation distance	100–300 km	50–150 km
Electricity carbon intensity	Moderate to high	Lower due to renewable integration
Carbon pricing mechanisms	Limited implementation	Established ETS/carbon taxation
Relative CCU feasibility	Moderate due to energy constraints	Higher with low-carbon electricity
Typical low-carbon concrete cost premium	5%–20%	10%–25%
Primary deployment constraint	Logistics and SCM variability	Regulatory approval and cost

Table 6 | Life cycle assessment (LCA) of concrete

Life Cycle Stage	Emission Contribution (%)	Key Activities	Reduction Strategies
Raw material extraction	10–20	Mining limestone, aggregates	Use recycled materials
Cement production	60–80	Clinker production, fuel combustion	SCMs, alternative fuels
Transportation	5–10	Material transport	Local sourcing
Mixing & construction	2–5	Batching, placement	Efficient equipment
Use phase	Low	Maintenance	Durable materials
End-of-life	5–10	Demolition, disposal	Recycling, reuse



Cement production is the dominant source of lifecycle emissions in concrete (~70%). Integrated use of material innovations, CCUS/CCU, efficient logistics, low-carbon construction and recycling can reduce overall emissions by **30–50%**.

Fig 5 | Life cycle carbon flow and reduction pathways in conventional versus low-carbon concrete

significantly reduce clinker-related emissions, while carbon capture, utilization, and storage (CCU) contribute to direct CO_2 sequestration. Additional reductions are achieved through recycled aggregates, efficient logistics, optimized construction practices, and end-of-life recycling. The integrated application of these approaches can reduce overall life cycle emissions by approximately 30%–50% compared to conventional concrete, highlighting the importance of system-level decarbonization strategies.

Economic and Environmental Advantages of Low-Carbon Concrete

Low-carbon concrete is a creative alternative to regular concrete that can drastically cut CO_2 emissions. This environmentally friendly concrete reduces carbon emissions in a number of methods, such as using alternative binders like geopolymer, including industrial byproducts like fly ash or slag, or improving the mix design to lower the amount of clinker. Technological advancements in carbon capture and storage can also enhance its sustainability.

Because low-carbon concrete lowers the carbon footprint associated with cement production—one of the largest industrial generators of CO_2—it is a crucial component of sustainable building plans. This promotes more environmentally friendly building techniques and lessens the effects of climate change. The cost–benefit analysis of low-carbon concrete systems reveals a complex link between initial costs, long-term savings, and environmental effects. The potential financial gains from implementing low-carbon technologies and the economic advantages of managing building waste through carbon trading policies were also investigated through previous studies,[31] demonstrating that using sustainable materials may greatly reduce carbon emissions while enhancing performance in ultra-high-performance fiber-reinforced concrete. This was additionally confirmed, and it was shown that carbon negativity and emission offsetting are possible with biochar-augmented concrete. Meanwhile, innovative material sourcing techniques that can reduce costs while promoting sustainability are highlighted by the economic viability and performance of low-carbon binders manufactured from calcined sediments. When considered collectively, these studies demonstrate the financial and environmental advantages of low-carbon concrete, encouraging its increased use in the construction industry.[32]

Economic Assumptions and Regional Considerations

The economic feasibility of low-carbon concrete depends strongly on regional material availability, transportation logistics, energy sources, and carbon pricing policies. SCM-based systems often remain the most cost-effective due to the use of industrial byproducts such as fly ash and slag; however, supply constraints are increasing as coal-fired power generation and blast furnace steel production decline globally.

In South Asia, particularly in India and Pakistan, transportation costs and inconsistent SCM availability significantly influence project-level feasibility. LC3 presents a promising alternative because calcined clay and limestone are more regionally abundant and less dependent on industrial byproduct supply chains.

For CCU-based systems, economic viability is highly sensitive to CO_2 capture costs, compression, transport distance, and access to renewable energy. Carbon pricing mechanisms such as emissions trading systems and carbon taxation can substantially improve financial competitiveness by internalizing environmental costs.

Comparative regional analysis suggests that SCM-based systems currently remain more economically favorable in Europe and North America due to established industrial byproduct supply chains and stronger carbon pricing policies. In contrast, South Asian regions may face increasing fly ash variability and transportation constraints, making LC3 systems potentially more scalable because of abundant clay and limestone reserves. Additionally, lower renewable electricity penetration in some developing regions may reduce the net climate benefit of energy-intensive CCU systems relative to countries with decarbonized power grids.

Therefore, techno-economic assessment should be region-specific rather than generalized globally, with sensitivity analyses for material cost fluctuations, logistics, and carbon price scenarios.

Challenges and Difficulties With Low-Carbon Concrete Production

There are various technical obstacles in the way of producing low-carbon concrete on a large scale. First, the performance and composition of the mix may be impacted by the requirement for substitute elements, such as additional cementitious materials or recycled aggregates.[33] It is challenging to provide consistency and quality control at scale. Furthermore, incorporating new techniques or technologies, such as carbon capture and storage, necessitates a large infrastructural and financial commitment. To accommodate new compositions, the curing procedure might also need to be modified. In order to overcome these obstacles, advancements in material science, supply chain management, and process optimization are needed, in addition to stringent testing to guarantee that low-carbon concrete satisfies performance requirements while minimizing environmental impact.

For low-carbon concrete to be widely used, regulatory and standards concerns are essential. The approval and implementation of novel concrete formulas may be complicated by regional differences in building rules and standards. Inconsistencies in performance and quality might result from a lack of consistent standards.

The special qualities of low-carbon concrete might not be taken into account by regulations, requiring revisions or new rules.

Standards, Codes, and Certification Pathways

The large-scale adoption of low-carbon concrete depends not only on material performance but also on compliance with existing design codes, certification systems, and regulatory acceptance pathways. International standards such as EN 197-5 for composite cements, ASTM C595 for blended hydraulic cements, and ASTM C1157 for performance-based hydraulic cement specifications provide important frameworks for integrating alternative binders such as LC3- and SCM-based systems into mainstream construction practice.

For structural design applications, ACI 318 acceptance pathways remain critical for validating the use of non-conventional binders in reinforced concrete systems. Performance-based qualification rather than purely prescriptive composition-based limits is increasingly recognized as essential for enabling innovation in low-carbon materials.

Geopolymer concrete and alkali-activated systems still face major standardization barriers due to the absence of universally accepted durability qualification methods and mix design protocols. Current guidance from RILEM Technical Committees emphasizes the need for standardized testing for chloride ingress, sulfate resistance, alkali–silica reaction (ASR), freeze–thaw resistance, carbonation depth, creep, and shrinkage before widespread code adoption can occur.

Similarly, CCU-based concrete requires validation of long-term carbon permanence and durability performance before certification pathways can be fully integrated into national building standards. Alignment with global roadmaps from the IEA, GCCA, and IPCC further supports policy harmonization and industrial adoption.

It is crucial to make sure that low-carbon concrete complies with many regulations and satisfies safety, durability, and performance standards. To properly address these issues, cooperation between legislators, business leaders, and standard organizations is essential.

As the building sector looks for sustainable options, low-carbon concrete is becoming more widely accepted and adopted.[34] Growing environmental restrictions and increased awareness of climate change have led to a growing preference for this environmentally friendly material, which lowers carbon emissions as compared to conventional concrete. The production and uptake of low-carbon concrete are significantly impacted by the supply chain and resource availability. Regular product quality depends on a regular supply of materials like SCMs, which lower carbon footprints.

Managing transportation logistics, obtaining and processing SCMs, and overcoming shortages in the area. Technological developments in recycling and innovations in the procurement of materials can help lessen these problems. In order to scale the production of low-carbon concrete and make it more accessible to a wider market, it is essential to build strong supply chains and enhance resource management. This will aid global sustainability activities.

Despite significant progress, several critical research gaps remain in the field of low-carbon concrete. First, long-term durability data under real environmental exposure conditions are still limited, particularly for geopolymer- and CCU-based systems. Second, the lack of standardized mix design protocols restricts reproducibility and large-scale adoption across different regions. Third, most studies focus on laboratory-scale performance, with insufficient validation at industrial or structural scales. Fourth, life cycle assessment methodologies vary widely in system boundaries and emission factors, leading to inconsistencies in reported environmental benefits. Additionally, economic feasibility analyses are often incomplete, particularly regarding the cost of alkali activators, CO_2 capture infrastructure, and SCM transportation logistics. Finally, the integration of digital tools such as AI-based mix optimization remains underdeveloped and requires robust experimental data sets for reliable predictive modeling. Addressing these gaps is essential for transitioning low-carbon concrete from laboratory innovation to mainstream construction practice.

Practical Policy and Procurement Implications

Recent policy developments may substantially accelerate the adoption of low-carbon concrete technologies:

- EN 197-5 enables broader acceptance of composite and low-clinker cements in Europe.
- ASTM C595 and ASTM C1157 facilitate performance-based specification pathways for blended binders.
- ACI 318 acceptance frameworks increasingly support non-traditional cementitious systems through performance qualification.
- Environmental Product Declaration (EPD)-based procurement allows infrastructure projects to prioritize low-embodied carbon materials during contractor selection.

Together, these mechanisms support near-term industrial implementation by aligning environmental performance with regulatory compliance and procurement incentives.

Integrated Perspective

A critical observation across all low-carbon concrete technologies is that their environmental benefits are often evaluated in isolation, without considering system-level integration. However, real-world decarbonization of the construction sector will require hybrid approaches that combine material substitution, process optimization, and carbon utilization strategies. For example, SCM-based replacements can be combined with CO_2 curing to enhance both strength and sequestration potential, while LC3 systems may be further optimized using industrial byproducts to improve sustainability. This systems-level integration highlights that future progress will depend not only on material innovation but also on coordinated supply chain transformation and policy support mechanisms.

Potential hybrid deployment pathways may further enhance decarbonization efficiency through synergistic integration of complementary technologies. Examples include the following:

- LC3 combined with CO_2 curing for simultaneous clinker reduction and carbon sequestration.
- SCM-based systems integrated with recycled aggregates to improve circular material utilization.
- Geopolymer concrete incorporating industrial by-products and AI-assisted mix optimization.
- RAC systems enhanced with supplementary cementitious materials to improve durability and reduce permeability.

Such hybrid strategies may provide compound environmental benefits exceeding those achievable through isolated material substitution approaches alone.

Future Developments

In an effort to lessen its environmental impact, low-carbon concrete has undergone a revolution thanks to developments in material science and technology. Substitute cementitious materials have been created, such as fly ash, slag, and silica fume, in place of conventional Portland cement, which uses a lot of energy and emits a lot of CO_2. Additionally, carbon capture methods are incorporated, capturing CO_2 while it is being produced. Innovative admixtures and additives improve durability and strength while lowering the requirement for excessive material utilization.[35] Furthermore, self-healing concrete and 3D printing are increasing design lifetime and precision while reducing waste and emissions.[36] The building sector is moving toward more environmentally friendly and carbon-efficient solutions thanks to these technologies.

The future of sustainable industries is being shaped by new developments in carbon capture and low-carbon materials. Direct air capture (DAC) methods, which extract CO_2 directly from the atmosphere, and bioenergy with carbon capture and storage (BECCS), which uses biomass to absorb carbon, are examples of innovations in carbon capture.[37] Furthermore, low-carbon-neutral concrete made with recycled materials and alternative binders, as well as bioplastics made from renewable resources, are becoming increasingly popular. Developments in the use of captured CO_2 to create carbon-negative products, such as building materials and synthetic fuels, are also crucial. These developments are essential for lowering industrial emissions and advancing climate objectives.

To promote the adoption of sustainable behaviors and technology, policy and regulatory frameworks are crucial. To provide financial incentives for cutting emissions, governments can implement carbon pricing mechanisms like carbon taxes and cap-and-trade schemes.[38] Tax credits, grants, and subsidies for renewable energy initiatives and investment in low-carbon solutions are also fueled by carbon capture technologies. Compliance is encouraged by creating clear norms for sustainable practices across industries and setting strict emissions regulations. Innovation is also encouraged by developing green certification schemes and funding research and development.[39] Accelerating the shift to a low-carbon economy requires international cooperation and policy alignment with global climate targets.

The development of low-carbon concrete design depends on digital technologies like artificial intelligence (AI) and the Internet of Things (IoT). AI improves predictive modeling and material optimization, allowing for better concrete mix designs that lower carbon emissions. It determines the optimal ratio of materials to attain both performance and sustainability. IoT sensors, on the other hand, provide real-time monitoring of crucial factors like production energy use and curing conditions. This guarantees effective procedures and the best possible concrete performance. IoT and AI together produce strong, flexible systems for sophisticated data processing and decision-making. AI analyzes the data gathered by IoT sensors, allowing for accurate modifications to enhance concrete quality and reduce its environmental impact.

By evaluating enormous data sets, machine learning (ML) is transforming the prediction of low-carbon concrete performance to find trends and improve mix designs. Conventional approaches depend on laborious laboratory testing, whereas ML compressive strength can be reliably predicted by models like support vector machines (SVMs) and artificial neural networks (ANNs), carbon footprint, robustness, and longevity.[39] These models make use of input factors such as the water-to-binder ratio, additional cementitious ingredients, and curing circumstances. ML improves sustainability by utilizing big data. For a sustainable future, engineers provide actual solutions that are more effective and environmentally beneficial. Graphene quantum dots (GQDs) are nanoscale materials made from graphene that have exceptional qualities like photoluminescence, thermal stability, and excellent electrical conductivity. GQDs improve mechanical and functional performance in concrete and cement composites. By refinement, they increase tensile and compressive strength, and microstructures, and promote efficient hydration.[40] Additionally, their addition increases hardness, durability, and crack resistance. GQDs also have the ability to sense themselves, which makes it possible to evaluate structural health in real time. Their nanoscale dispersion improves the thermal and electrical conductivity of concrete, which aids energy-efficient building. Despite these advantages, in order to properly utilize GQDs in sustainable, high-performance concrete for contemporary infrastructure, issues like cost and scalability must be resolved.

Technology Readiness and EHS Considerations of GQDs

Although graphene quantum dots (GQDs) show significant promise for enhancing mechanical strength, crack resistance, and self-sensing capabilities in cementitious composites, their current technology readiness level (TRL) remains relatively low, primarily at laboratory and pilot scales. Large-scale industrial deployment is constrained by high synthesis costs, limited production scalability, and uncertainty regarding long-term economic feasibility.

Additionally, environmental, health, and safety (EHS) considerations require further investigation, particularly regarding nanoparticle dispersion, occupational exposure during handling, and end-of-life environmental behavior. Standardized safety protocols and life cycle risk assessments are essential before widespread adoption can be recommended. Therefore, GQDs should currently be viewed as a high-potential emerging technology rather than an immediately scalable industrial solution (Table 7).

Policy and Standardization Implications

Accelerated deployment of low-carbon concrete technologies will depend not only on material performance but also on alignment with evolving construction standards and procurement frameworks. Recent developments such as EN 197-5 blended cement provisions, ASTM C595 and ASTM C1157 performance-based specifications, ACI 318 acceptance pathways, and environmental product declaration (EPD)-based procurement strategies may significantly facilitate near-term adoption of alternative binders and supplementary cementitious materials.

Table 7 | Challenges and mitigation strategies for low-carbon concrete

Challenge Type	Specific Issue	Impact	Proposed Solution
Technical	Reduced early strength	Limits applications	Optimize mix design
Material	SCM variability	Inconsistent quality	Standardization
Economic	High initial cost	Slow adoption	Incentives, subsidies
Regulatory	Lack of standards	Approval delays	Update building codes
Supply chain	Limited SCM availability	Scalability issues	Improve logistics
Environmental	CO_2 capture energy demand	Reduces net benefit	Renewable energy integration

Policy incentives, public procurement standards, and carbon-accounting frameworks may therefore play a critical role in scaling commercially viable low-carbon concrete systems over the coming decade.

Concluding Perspective

This review systematically evaluated emerging low-carbon concrete technologies, highlighting their environmental performance, scalability, and industrial feasibility. Based on comparative analysis, SCM-based concrete and LC3 systems emerge as the most immediately scalable and cost-effective solutions, while geopolymer concrete demonstrates the highest theoretical carbon reduction potential but lower industrial readiness. Carbon capture and utilization (CCU)-based concrete remains promising but is currently constrained by energy intensity and infrastructure requirements.

From an overall readiness perspective, the technologies can be ranked as follows: (1) SCM-based systems (highest readiness), (2) LC3, (3) Geopolymer concrete, and (4) CCU-based systems (lowest readiness but high future potential).

To accelerate industrial adoption, several policy interventions are required, including incentives for low-clinker cement production, carbon taxation frameworks, and standardization of alternative binder specifications. Furthermore, public–private partnerships are essential to bridge the gap between laboratory innovation and large-scale deployment.

In conclusion, no single technology provides a complete solution; rather, a hybrid and region-specific deployment strategy is necessary to achieve meaningful decarbonization of the global cement and concrete industry.

Acronym Definitions

- SCM = Supplementary cementitious material
- LC3 = Limestone calcined clay cement
- CCU = Carbon capture and utilization
- TRL = Technology readiness level
- LCA = Life cycle assessment

Data Availability Statement

The comparative data set, normalization framework, radar-chart scoring workbook, weighting parameters, and supplementary extraction tables used in this study have been deposited in an open-access Zenodo repository for transparency and reproducibility.

Repository access (anonymous peer-review version): https://doi.org/10.5281/zenodo.20120462

The repository includes

- Comparative technology data set
- Figure 3 normalization workbook
- Weighting and sensitivity-analysis parameters
- Technology readiness scoring framework
- Supplementary extraction tables
- Figure-generation workflow documentation

All additional supporting information is provided within the Supplementary Materials.

References

1 Müller DB, Liu G, Løvik AN, et al. Carbon emissions of infrastructure development. *Environ Sci Technol*. 2013;47(20):11739–11746. https://doi.org/10.1021/es402618m

2 Fenner AE, Kibert CJ, Woo J, et al. The carbon footprint of buildings: a review of methodologies and applications. *Renew Sustain Energy Rev*. 2018;94:1142–1152. https://doi.org/10.1016/j.rser.2018.07.012

3 Onat NC, Kucukvar M. Carbon footprint of construction industry: a global review and supply chain analysis. *Renew Sustain Energy Rev*. 2020;124:109783. https://doi.org/10.1016/j.rser.2020.109783

4 Fang Z, Yan J, Lu Q, et al. A systematic literature review of carbon footprint decision-making approaches for infrastructure and building projects. *Appl Energy*. 2023;335:120768. https://doi.org/10.1016/j.apenergy.2023.120768

5 Barcelo L, Kline J, Walenta G, Gartner E. Cement and carbon emissions. *Mater Struct*. 2014;47(6):1055–1065. https://doi.org/10.1617/s11527-013-0114-5

6 Schneider M. The cement industry on the way to a low-carbon future. *Cement Concr Res*. 2019;124:105792. https://doi.org/10.1016/j.cemconres.2019.105792

7 Coffetti D, Crotti E, Gazzaniga G, Carrara M, Pastore T, Coppola L. Pathways towards sustainable concrete. *Cement Concr Res*. 2022;154:106718. https://doi.org/10.1016/j.cemconres.2022.106718

8 Hottle T, Hawkins TR, Chiquelin C, et al. Environmental life-cycle assessment of concrete produced in the United States. *J Clean Prod*. 2022;363:131834. https://doi.org/10.1016/j.jclepro.2022.131834

9 Benhelal E, Zahedi G, Shamsaei E, Bahadori A. Global strategies and potentials to curb CO_2 emissions in cement industry. *J Clean Prod*. 2013;51:142–161. https://doi.org/10.1016/j.jclepro.2012.10.049

10 Lee J, Lee T, Jeong J, Jeong J. Sustainability and performance assessment of binary blended low-carbon concrete using supplementary cementitious materials. *J Clean Prod*. 2021;280:124373. https://doi.org/10.1016/j.jclepro.2020.124373

11 Thorne J, Bompa DV, Funari MF, Garcia-Troncoso N. Environmental impact evaluation of low-carbon concrete incorporating fly ash and limestone. *Clean Mater*. 2024;12:100242. https://doi.org/10.1016/j.clema.2024.100242

12 Golafshani EM, Behnood A, Kim T, Ngo T, Kashani A. A framework for low-carbon mix design of recycled aggregate concrete with supplementary cementitious materials using machine learning and optimization algorithms. *Structures*. 2024;61:106143. https://doi.org/10.1016/j.istruc.2024.106143

13 Guo Y, Luo L, Liu T, et al. A review of low-carbon technologies and projects for the global cement industry. *J Environ Sci (China)*. 2024;136:682–697. https://doi.org/10.1016/j.jes.2023.01.021

14 Andrew RM. Global CO_2 emissions from cement production. *Earth Syst Sci Data*. 2018;10(1):195–217. https://doi.org/10.5194/essd-10-195-2018

15 Shah IH, Miller SA, Jiang D, Myers RJ. Cement substitution with secondary materials can reduce annual global CO_2 emissions by up to 1.3 gigatons. *Nat Commun*. 2022;13(1):5758. https://doi.org/10.1038/s41467-022-33289-7

16 Scrivener KL, John VM, Gartner EM. Eco-efficient cements: potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cement Concr Res*. 2018;114:2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

17 Habert G, Miller SA, John VM, et al. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat Rev Earth Environ*. 2020;1(11):559–573. https://doi.org/10.1038/s43017-020-0093-3

18 International Energy Agency. *Technology Roadmap: Low-Carbon Transition in the Cement Industry*. IEA; 2018.

19 Global Cement and Concrete Association. *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete*. GCCA; 2021.

20 Intergovernmental Panel on Climate Change. *Climate Change 2022: Mitigation of Climate Change*. Cambridge University Press; 2022.

21 Meijssen M, Becattini V, Mazzotti M. Integrated carbon capture and utilization in the cement industry: a comparative study.

ACS Sustain Chem Eng. 2024;12(7):2709–2718. https://doi.org/10.1021/acssuschemeng.3c07081

22 Skocek J, Zajac M, Ben Haha M. Carbon capture and utilization by mineralization of cement pastes derived from recycled concrete. *Sci Rep*. 2020;10(1):5614. https://doi.org/10.1038/s41598-020-62503-z

23 Ravikumar D, Keoleian GA, Miller SA, Sick V. Assessing the relative climate impact of carbon utilization for concrete, chemical, and mineral production. *Environ Sci Technol*. 2021;55(17): 12019–12031. https://doi.org/10.1021/acs.est.1c01109

24 Gálvez-Martos JL, Chaliulina R, Medina-Martos E, et al. Eco-efficiency of a novel construction material produced by carbon capture and utilization. *J CO2 Util*. 2021;49:101545. https://doi.org/10.1016/j.jcou.2021.101545

25 Monteiro J, Roussanaly S. CCUS scenarios for the cement industry: is CO_2 utilization feasible? *J CO2 Util*. 2022;61:102015. https://doi.org/10.1016/j.jcou.2022.102015

26 Zunino F, Martirena F, Scrivener K. Limestone calcined clay cements (LC3). *ACI Mater J*. 2021;118(3):49–56. https://doi.org/10.14359/51730422

27 Elmesalami N, Celik K. Engineered geopolymer composite: a low-carbon ultra-high-performance concrete. *Constr Build Mater*. 2022;346:128491. https://doi.org/10.1016/j.conbuildmat.2022.128491

28 Robalo K, Soldado E, Costa H, Carvalho L, do Carmo R, Júlio E. Durability and time-dependent properties of low-cement concrete. *Materials (Basel)*. 2020;13(16):3583. https://doi.org/10.3390/ma13163583

29 Cui K, Liang K, Chang J, Lau D. Investigation of the macro performance, mechanism, and durability of multiscale steel fiber reinforced low-carbon ecological UHPC. *Constr Build Mater*. 2022;327:126921. https://doi.org/10.1016/j.conbuildmat.2022.126921

30 Zhang H, Sarker PK, Xiao L, et al. Durability of low-carbon geopolymer mortar: different responses to cryogenic attack caused by water content and freeze-thaw mediums. *Cement Concr Compos*. 2023;139:105065. https://doi.org/10.1016/j.cemconcomp.2023.105065

31 Wang J, Wang Y, Sun Y, Tingley DD, Zhang Y. Life cycle sustainability assessment of fly ash concrete structures. *Renew Sustain Energy Rev*. 2017;80:1162–1174. https://doi.org/10.1016/j.rser.2017.05.232

32 Liu J, Li J. Economic benefit analysis of the carbon potential of construction waste resource management based on a simulation of carbon trading policy. *Environ Sci Pollut Res Int*. 2023;30(36):85986–86009. https://doi.org/10.1007/s11356-023-28417-9

33 Chen L, Zhang Y, Wang L, et al. Biochar-augmented carbon-negative concrete. *Chem Eng J*. 2022;431:133946. https://doi.org/10.1016/j.cej.2021.133946

34 Roussanaly S, Berghout N, Fout T, et al. Towards improved cost evaluation of carbon capture and storage from industry. *Int J Greenh Gas Control*. 2021;106:103263. https://doi.org/10.1016/j.ijggc.2021.103263

35 Becattini V, Gabrielli P, Antonini C, et al. Carbon dioxide capture, transport and storage supply chains: optimal economic and environmental performance of infrastructure rollout. *Int J Greenh Gas Control*. 2022;117:103635. https://doi.org/10.1016/j.ijggc.2022.103635

36 Juenger MC, Snellings R, Bernal SA. Supplementary cementitious materials: new sources, characterization, and performance insights. *Cement Concr Res*. 2019;122:257–273. https://doi.org/10.1016/j.cemconres.2019.05.008

37 Barbhuiya S, Kanavaris F, Das BB, Idrees M. Decarbonising cement and concrete production: strategies, challenges and pathways for sustainable development. *J Build Eng*. 2024;86:108861. https://doi.org/10.1016/j.jobe.2024.108861

38 Ali T, El Ouni MH, Qureshi MZ, et al. A systematic literature review of AI-based prediction methods for self-compacting, geopolymer, and other eco-friendly concrete types: advancing sustainable concrete. *Constr Build Mater*. 2024;440:137370. https://doi.org/10.1016/j.conbuildmat.2024.137370

39 Dahish HA, Alfawzan MS, Tayeh BA, Abusogi MA, Bakri M. Effect of inclusion of natural pozzolan and silica fume in cement-based mortars on the compressive strength utilizing artificial neural networks and support vector machine. *Case Stud Constr Mater*. 2023;18:e02153. https://doi.org/10.1016/j.cscm.2023.e02153

40 Raj A, Yamkasikorn P, Wangtawesap R, et al. Effect of graphene quantum dots (GQDs) on the mechanical, dynamic, and durability properties of concrete. *Constr Build Mater*. 2024;441:137597. https://doi.org/10.1016/j.conbuildmat.2024.137597