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The Climate Change and Construction Industry: A Battle in 21st Century

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Abstract

As we approach completing the first quarter of the 21st century, we experience the development of Industry 4.0 in many areas. Remarkably, after the mid-2010s, significant changes took place in the operations and production of many sectors. However, the construction industry still falls far behind these speed-up changes as "the construction industry remains climate-unfriendly*". Many reports state that the construction industry is responsible for 38% of annual greenhouse gas emissions globally. As the dominating material, concrete is responsible for 7% of all global carbon emissions. Although environmental considerations have become undeniable in the sector and moves such as Carbon Neutrality, Green Deals, Net-zero-buildings, etc., have emerged, the industry still does not show any radical change as a response. This paper focuses on the construction industry to understand its role in climate change. It aims to clarify how the conventional practice in the sector contributes to carbon emissions and energy consumption from the start of production to life cycle assessment. The paper primarily focuses on the cement production and novelties adopted in order to combat climate change and reviews the approaches to reduce the environmental impact of the industry.

Keywords : Construction industry; Carbon emissions in construction; Building sector; Construction materials.

1. Introduction

Our urbanization practices to date have been rapid, consumptive, short-sighted, and most importantly, focused solely on human needs without considering the damage inflicted on nature. However, with climate change reaching an undeniable scale, we have begun to think more deeply and calculate the damage we inflict on nature. We are starting to consider, albeit belatedly, how we can restore and even heal the damage we have caused. The architecture, engineering and construction (AEC) sectors, which hold a significant share within the triangle of energy consumption, carbon emissions, and raw material usage, have also been the focus of discussions and criticisms in recent years. Indeed, the process that began with eco-friendly climate control technologies continued with the concept of low-carbon buildings, and today it has reached the point of a complete circular transformation of the sector. In 2010, structures across the globe were accountable for 32% of the total energy utilized globally and contributed to 19% of all greenhouse gas emissions. If current patterns persist, the global energy consumption within buildings could potentially increase twofold or even triple by the year 2050. Having said that, by widely adopting optimal practices and technologies, it is possible for energy consumption in buildings to stabilize or decrease by 2050 (CISL, 2014). The construction sector stands out as the largest contributor to greenhouse gas emissions, accounting for a minimum of 37 percent of global emissions. Up until now, the majority of advancements in the sector have focused on reducing the "operational carbon" of buildings – the emissions stemming from heating, cooling, and lighting. These emissions are expected to decrease from 75 percent to 50 percent of the sector in the coming decades. However, efforts to reduce "embodied" carbon emissions from the design, production, and deployment of building materials like cement, steel, and aluminum have fallen significantly behind. The reasons for this are multifaceted and involve numerous stakeholders. Therefore, incentives for decarbonization must enable decision-makers across global material supply chains, encompassing both informal and formal building sectors, from producers to consumers (UNEP, 2023).

As a part of AEC sector, the MEP 2040 Challenge was brought by the Carbon Leadership Forum. MEP stands for mechanical, electrical and plumping systems in buildings and the movement is the biggest supporter of the net-zero carbon achievement by 2040, which targets the operational carbon by 2030 and the embodied carbon by 2040. MEP systems designers have long been optimizing for operational carbon. However, integrating embodied carbon into this focus represents the next frontier in reducing the total carbon emissions linked with the built environment (One Click LCA., n.d.). All stakeholders, including designers, contractors, and engineers, are aware of the importance of minimizing operational energy expenses stemming from fuel usage like oil, natural gas, or electricity. The CO_2 emissions produced through the utilization, management, and upkeep of yearly building operations represent roughly 28% of the total annual global greenhouse gas emissions. Today, mechanical management became more efficient and operational carbon emission got more controllable, therefore a contemporary consciousness began to grow upon the 'embodied carbon', which is considered 'locked-in-place' once a building is built. Accordingly, an environmentalist approach must be taken from the beginning of the design process by choosing the materials causing the least embodied carbon in the building during the constructipn process. The speed of the urban population's growth emerges the speed construction of buildings globally. The estimations show that from now to 2060s, the world population requires to build a New York city every month for 40 years. In addition, if the construction practices do not change, it is also estimated that embodied carbon will be responsible for the half of total building sector's emission between now and 2050s. In developed countries, material and natural sources are often used wasteful, although they display showcases of green buildings, in constrast. In developing countries, this issue is more handicapped since they struggle with rapid urbanisation and large amount of sourcing for building sector. With such consciousness upon 'locked in carbon', a transformation of the conventional practices began to shape around three core principles (Figure 1).

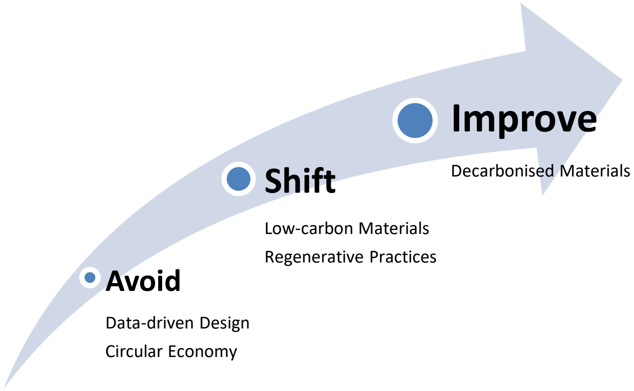

Figure 1. Core principles for transforming the conventional building practices (Developed by Author, UN Environment Programme).

The first principle, **Avoid** implies the utilisation of data-driven design to optimize building design in a way to achieve effective material use and resource allocation without compromising the structural and architectural integrity. This also involves the integration of AI tools through ML and DL approaches which can assist to production of less waste and better prediction for the constrıction management phases. Avoiding from building new contributes to material salvage and reduce demand for new raw materials. In architecture, adaptive reuse values existing structures instead of demolishing them. Through renovation of a building with less material and upgrading it to an energy efficient one is a cost effective move as far as sustainable.

The second principle, **Shift** encompasses sustainable sourcing and points at the shift from conventional high-carbon materials to ethically produced low-carbon materials, including earth-based, bio-based and recycled materials. Innovation of sustainable building materials also is a part of the shift move. Developing engineered timber products, since timber is one of the materials with large volume of byproducts, is a key to design and build the least embodied-carbon buildings.

The third step is **Improve** and as it implies, the main target is to decarbonize the conventional building materials. For example, replacing conventional concrete with geopolymer concrete or with reduced clinker content are highly favorable research topics in the industry along with the large interest of improving technologies for carbon capture and storge (CCS) in cement production, since concrete dominates the construction sector and evolving this materials means evolving the sector by all means. The sympathy for steel in the construction sector has a long past, unlike concrete. Because, steel is widely recyclable and allows for dissassamble and reassemble design practices, which enables longer lifetime use. Current environmentalist approach focuses on green production of steel, which covers hydrogen-based steel production Aluminium follows steel as the most used metal material in the industry. Current studies focuses on recycled aluminium and innovate aluminium alloys that offer same strength, durability and quality of the conventional version. Glass use in buildings is increasing year by year, particularly with the rising number of tall buildings. Glass is highly associated with exploitation of natural sources and high carbon footprint during its manufacturing. Integrating strategies to increase the efficient use of glass material and its recyclable use is a manner of smart design which can be adopted by manufacturers and responsible architects. Glass, as a building material, contributes directly to the energy performance of buildings. Using high performance insulating glass (e.g. double or triple glazing, low emissivity coatings) can directly improve the thermal performance of the building envelop by reducing the demand for heating and cooling the interiors. In the light of these arguments, this paper focuses on the transformation of the construction sector and questions how the sector adapted itself in the fight against the climate change and which strategies it utilizes to decrease its contribution to it. Accordingly, the paper continues with the literature review to highlight the contemporary cement material improvements. It largely focuses on concrete since it is the backbone of the construction industry.

2. Novelty in concrete production

Concrete is fundamental for the construction sector considering it is used not only for buildings, but also for dams, bridges, and power plants etc. To produce concrete, it is required to mix aggregate (60-75%), water (14-20%) and cement (7-15%) in varying percentages depending on the quality and other features wanted and the purpose. Therefore, concrete production exploits natural sources primarily, water and natural aggregates. Concrete production alone is responsible for 7-8 % of the global carbon emission and this occurs during production as well as on-site construction. Cement production is significant source of carbon emission during concrete production process and approximately half of these emissions are generated as by-products of the chemical reactions involved in limestone calcination (Thorne et al., 2024). The high carbon footprint of cement production has accelerated research into developing low-carbon alternatives to conventional concrete. This involves replacing traditional cement binders with more sustainable alternatives. Experimenting new mixture design of concrete is commonly aimed for improving the mechanical properties and durability against the chemical factors. This perspective has widened to include the environmental impact as well. Developing low-carbon alternatives to conventional concrete is crucial for reducing the environmental impact of construction. Producing low carbon concrete is possible in many ways (Table 1).

Table 1. Low-carbon alternatives to conventional concrete (Thorne et al., 2024).

Alternative	Description	Benefits	Challenges
Supplementary Cementitious Materials (SCMs)			
Fly Ash	By-product of coal combustion in power plants, can partially replace cement concrete.	Reduces CO_2 emissions, utilizes industrial waste	Availability dependent on coal industry, potential for heavy metal contamination
Slag	Produced from steel-making process, ground granulated blast-furnace slag (GGBS) can substitute cement	Lowers CO_2 emissions, enhances durability	Limited supply, geographical constraints
Silica Fume	By-product of silicon and ferrosilicon alloy production, enhances strength and durability of concrete	Reduces need for cement, improves concrete properties	Expensive, limited availability
Natural Pozzolans	Volcanic ash and other natural pozzolans Can replace a portion of the cement binder in concrete	Reduces CO_2 emissions, naturally occurring	Variable quality, limited supply in some regions
Geopolymer Concrete	Made by activating aluminosilicate materials (like fly ash or slag) with alkaline solutions.	Significant CO_2 reduction compared to Portland cement.	Requires careful mix design, limited large-scale adoption.
CarbonCure Technology	Involves injecting captured CO_2 into concrete during mixing, forming calcium carbonate.	Reduces overall emissions, improves concrete strength.	Needs infrastructure for CO_2 capture and storage.
Limestone Calcined Clay Cement (LC3)	A blend of limestone, calcined clay, and clinker, reducing the clinker content.	Lowers CO_2 emissions while maintaining performance.	Requires changes in production processes, initial higher costs.
Bio-Based Materials			
Hempcrete	Made from inner woody core of hemp plant mixed with a lime-based binder.	Carbon-sequestering, sustainable, good insulation properties.	Limited structural strength, requires regulatory acceptance.
Mycelium-Based Composites	Utilizes root structure of fungi (mycelium), can be used as lightweight, insulating building materials.	Biodegradable, sustainable, good insulation properties.	Not suitable for structural applications, scalability issues.
Magnesium-Based Cements	Magnesium silicate and other magnesium-based materials that absorb CO_2 as they cure.	Carbon-negative alternative, sustainable.	Higher cost, requires new manufacturing techniques, regulatory hurdles.

Pyroprocessing is a crucial stage in cement manufacturing. Pyroprocessing involves heating raw materials to high temperatures to bring about chemical or physical changes necessary for cement production. It is typically carried out in rotary kilns (Nalobile et al., 2020). The preheated materials undergo calcination, where limestone (calcium carbonate) decomposes into lime (calcium oxide) and CO_2. The calcined materials are then heated to around 1450°C in the kiln, where they form clinker, the main component of cement. The clinker is rapidly cooled to stabilize its structure and preserve its reactivity. The pyroprocessing stage in cement production is the most energy-intensive and significant source of CO_2 emissions, consuming around 88% of the total fuel and 91% of the total energy used in the entire cement production process, also causing a similar weight of carbon emission. Other production stages cause less than 12% energy consumption and carbon emission. Therefore, efforts to improve energy efficiency and reduce emissions in the cement industry should focus primarily on optimizing and innovating within the pyroprocessing stage (Gao et al., 2023). Benhelal et al. (2013) suggested three strategies to prevent large CO_2 emissions occurring from the concrete production:

- Strategy 1: fuel and energy saving,
- Strategy 2: carbon separation and storage,
- Strategy 3: utilizing alternative materials.

Cement manufacturing can be carried out through three main processes: wet, semi-wet, and dry. Each process has different steps for preparing raw materials, and they vary in terms of energy consumption and efficiency (Table 2).

Table 2. Comparison of raw material process in concrete production (Benhelal et al., 2013).

Process	Moisture Content	Pre-heating and Drying	Energy Consumption	Calcination Location
Wet	30-40%	None	High due to energy needed to evapora moisture	Directly in the kiln
Semi-wet	15-20%	Preheated by kiln exhaust gases	Moderate due to partial moisture removal	Partially in preheating stage, then in the kiln
Dry	Low (Dried before kiln)	Dried and preheated befo kiln	Lowest due to efficient use of energy	Mainly in the calciner before the rotary ki

The **wet process** is the least energy-efficient due to the high moisture content of the raw materials, requiring significant energy to evaporate water. The **semi-wet process** improves efficiency by removing some moisture before the raw materials enter the kiln. The **dry process** is the most energy-efficient as it involves pre-drying and preheating the raw materials, with most calcination occurring before the materials enter the rotary kiln. The dry process is the preferred method in modern cement production due to its lower energy consumption and higher efficiency. As seen in Table 2, there is a remarkable difference between energy consumption in wet and dry processes in the production. As part of *Strategy 1*, by shifting from wet process to dry process, it is possible to save up to 50% of energy demand and to reduce carbon emission by 20% (Benhelal et al., 2013). The other energy source in the pyroprocessing is the hot stream emitted after preheating raw material at high temperature. This is called 'waste heat' and energy recovery systems are suggested in the literature. For example, in some countries, e.g. Japan and China, there are plant examples to generate electricity from stream turbines integrated into the cement production plant.

Lately, carbon capture and storage (CCS) research is highly favourable since it is seen as a major opportunity to reduce carbon emission. Post-combustion CO_2 capture and storage (CCS) is an important technology for reducing carbon emissions in the cement production process, as *Stategy 2*. This approach involves capturing CO_2 from the flue gases produced after the combustion of fuels in the kiln and then storing it to prevent its release into the atmosphere. For example, Barker et al. (2009) are one of early research that focused on the use of post-combustion amine scrubbing using monoethanolamine (MEA). The flue gas leaves from the cement process at the raw mill at approximately 110ºC. This must be cooled to approximately 50ºC to meet the ideal temperature for CO_2 absorption with MEA. In addition, hydrochloric acid can be present in small quantities within cement flue gases. However, the presence of any acidic components will reduce the efficiency of the MEA absorption process (Barker et al., 2009). Table 3 provides a structured and detailed summary of the key aspects, methods, benefits, and challenges associated with post-combustion CO_2 capture and storage in the cement production process.

Implementing and developing CCS in the cement industry is a cost-intensive process that demands a stable and long-term investment environment. Key factors include high initial and operational costs, long-term commitment, technological advancements, regulatory frameworks, economic incentives, and public support. A stable investment environment can be fostered through consistent policies, financial mechanisms, collaboration, infrastructure development, and risk management. Ensuring these elements are in place will be crucial for the successful deployment and scalability of CCS technologies in the cement industry, contributing to significant reductions in CO_2 emissions and aiding in the global effort to combat climate change.

Alternative fuels have gained significant traction in various industries, including cement production. With growing concerns about environmental degradation, energy scarcity, and economic viability, the adoption of alternative fuels presents a promising solution. Over the past decade, there has been a notable surge in the utilization of alternative fuels in cement manufacturing processes, as part of *Strategy 3*. This trend is driven by the need to mitigate environmental impacts, reduce reliance on traditional fossil fuels, and address economic challenges associated with energy costs. ubstituting conventional raw materials with alternative ones can have a substantial impact on reducing emissions in cement plants. The properties of raw materials, such as burnability, composition, and fineness, play crucial roles in influencing energy consumption during the pyro-processing stage.

Table 3. Carbon capture and storage (CCS) methods.

Aspect	Detail
Flue Gas Extraction	Capturing CO_2 from the exhaust gases emitted by the cement
CO2 Capture Methods	Chemical Absorption: Uses solvents like amines to absorb CO_2 from flue gases. Physical Adsorption: Uses materials like activated carbon or zeolites to adsorb CO_2. Membrane Separation: Selective membranes allow CO_2 to pass through while blocking other g Cryogenic Distillation: Cools flue gas to very low temperatures to condense and separate CO_2.
CO2 Compression and Purification	CO_2 is compressed to reduce volume and purified to meet specifications for transportation storage.
Transportation	Compressed CO_2 is transported to storage sites via pipelines, truck ships.
Storage Methods	**Geological Storage:** Injects CO_2 into underground formations such as depleted oil/gas fields, saline aquifers, or unmineable coal seams. **Mineral Carbonation:** Reacts CO_2 with minerals to form stable carbonates (currently under research).
Benefits	**Significant Emission Reduction:** Capturing and storing CO_2 can significantly lower the carbon footprint of cement production. **Compatibility with Existing Infrastructure:** Post-combustion capture systems can b retrofitted to existing cement plants. **Supports Carbon Neutral Goals:** Essential for achieving long-term carbon neutrality meeting international climate targets.
Challenges	**High Cost**: CO_2 capture, transportation, and storage are expensive. **Energy Intensity**: Capture processes, especially chemical absorption, require significant energy input, reducing overall plant efficiency. **Storage Security**: Ensuring the long-term security and stability of geological storage sites to prevent CO2 leakage. **Technological Development**: Methods like membrane separation and mineral carbonation require further research to become viable at scale.

By replacing conventional raw materials with suitable alternatives, including by-products from other industries such as slag or sludge, cement plants can significantly decrease their environmental footprint. Utilizing low-carbon content fuels with a high hydrogen-to-carbon (H/C) ratio presents a promising strategy for reducing CO_2 emissions in cement production. Alternative fuels with higher H/C ratios, such as biomass, waste-derived fuels, or hydrogen-rich fuels, offer significant advantages over conventional fossil fuels like coal or petroleum coke. Following outlines how these alternative fuels contribute to economic and environmental achievements in cement plants:

1. **Reduced CO_2 Emissions:** Fuels with high H/C ratios produce fewer CO_2 emissions when burned compared to conventional fossil fuels. This is because they contain less carbon per unit of energy, leading to lower carbon dioxide emissions during combustion.
2. **Energy Efficiency:** Alternative fuels with higher H/C ratios often have higher calorific values, meaning they can generate more energy per unit of fuel input. This increased energy efficiency can lead to lower overall energy consumption in cement kilns, further reducing emissions.
3. **Waste Utilization:** Many alternative fuels used in cement plants are derived from waste materials such as biomass residues, municipal solid waste, or industrial by-products. By using these fuels, cement plants can divert waste from landfills and incineration, contributing to waste management and resource conservation efforts.
4. **Diversification of Energy Sources:** Incorporating a variety of alternative fuels allows cement plants to diversify their energy sources, reducing dependency on traditional fossil fuels. This enhances energy security and resilience to fuel price fluctuations.
5. **Compliance with Regulations:** Utilizing low-carbon alternative fuels aligns with regulatory requirements aimed at reducing greenhouse gas emissions and promoting sustainable practices in the cement industry. Cement plants that adopt these fuels may be better positioned to meet environmental standards and avoid penalties.

By incorporating industrial by-products into cement production, industries can reduce the amount of waste sent to landfills or incinerators, thereby minimizing environmental impact and conserving valuable resources. Integrating industrial by-products into cement production promotes the principles of the circular economy by closing the loop on material flows. Instead of being discarded as waste, these by-products are repurposed as valuable inputs in another industrial process, fostering sustainability and resource stewardship. Fly ash is a prime example of an industrial by-product that holds significant potential for reuse in cement production. It is primarily generated by coal-fired power plants during the combustion of coal. Fly ash contains fine particles that can be collected from the flue gases emitted during combustion. When used as a partial replacement for cement in concrete mixtures, fly ash can improve workability, reduce permeability, and increase resistance to chemical attack, sulfate attack, and alkali-silica reaction (ASR). Additionally, the finer particle size of fly ash can contribute to denser concrete microstructures, resulting in improved strength and durability over the long term. By diverting fly ash from landfills or disposal ponds and using it as a valuable additive in cement and concrete production, industries contribute to waste reduction and promote sustainable practices. By reducing the amount of clinker needed through the use of Cement Kiln Dust (CKD), potassium chloride (KCl) and fly ash, energy consumption in cement manufacturing can be reduced, leading to potential cost savings and improving the overall microstructure of concrete and potentially enhancing its mechanical properties (Youn et al., 2019; Bagheri, et al., 2020).

3. Life Cycle Assessment approach in the construction sector

Life Cycle Assessment (LCA) is a comprehensive and widely-used methodology for quantifying the environmental impacts of products and processes, including the decarbonization potential of replacing cement with industrial by-products like CKD and fly ash in concrete production (Amen, 2021; Amen et al., 2023; Barone, 2023) . LCA evaluates the entire life cycle of a product, from raw material extraction to end-of-life disposal, to provide a holistic view of its environmental performance. LCA in decarbonzaition aims to to assess the reduction in CO_2-equivalent (CO_2-eq.) emissions achieved by substitutions. LCA provides different levels of impact assessment as shown in Table 4, which is known as Life-cycle-impact-assessment (LCIA). Rhaouti et al. (2023) reviewed the frequency of different impact indicators chosen among a collection of papers in Life Cycle Assessment (LCA) studies and found that Global Warming Potential (GWP) is the most commonly chosen impact indicator, reflecting the high priority placed on assessing climate change impacts.

Table 4. Environmental Impact Indicators in LCA Studies.

Environmental Concern	Impact Indicator
Climate Change	Global Warming Potential (GWP)
Resource Use	Non-renewable Energy Use
	Abiotic Depletion (Resources)
	Abiotic Depletion (Fossil Fuels)
Air Quality	Acidification Potential
	Particulate Matter Emission
	Photochemical Oxidation
	Respiratory Organics
Water Quality and Use	Eutrophication Potential
	Water Use
Toxicity	Human Toxicity (Carcinogens)
	Human Toxicity (Non-Carcinogens)
	Ecotoxicity
	Heavy Metals
Ozone Depletion	Ozone Layer Depletion
Land Use and Ecosystems	Land Occupation
Radiation	Ionizing Radiation

GWP calculates the CO_2-eq. emissions for each life cycle stage. The GWP is a measure of how much heat a greenhouse gas traps in the atmosphere over a specific time period, relative to CO2 (Zhang et al., 2014; Setiawan et al., 2021; Ige and Olanrejawu, 2023; Dahanni et al., 2024). Manjunatha et al. (2021) studied the environmental impact of variety of concrete mixtures. Their mixtures formed with ground granulated blast furnace slag (GGBS) and portland pozzolana cement (PPC) have reduced the cement consumption in concrete and CO_2 emission during manufacture. SO_2, NH3 and NHx are the primary causes for terrestrial acidification and it has been reduced by almost 0.157% for utilizing 100% GGBS as a binder in concrete. Georgiades et al. (2023) quantified the CO2-eq. emissions mitigation potentials in Europe until 2050 using prospective life cycle assessment. Their study resulted that the potential CO_2 eq. emissions per kg -eq. emissions reduction from use of alternative fuels (25% reduction between 2020 and 2050) is lower than that achieved through the SCMs scenario 42% reduction between 2020 and 2050). The alternative fuels scenario with the lowest GWP100 values combines hydrogen (providing 40% of the thermal demand, generated through wind power), biomass (providing 50% of the thermal demand), and fossil fuels (providing 10% of the thermal demand), since this scenario utilises renewable energy sources with inherently low CO_2-eq. emissions.

Furthermore, Guo et al. (2023) studied the weight coefficients for various environmental impact categories in a Life Cycle Assessment (LCA) for cement production by incorporating feedback from senior experts and the cement industry. These weights reflect the relative importance of each impact category in the overall assessment (Table 5).

Table 5. Weighted Impact Categories in LCA for Cement Production (Guo et al., 2023).

Impact Category	Weight Coefficient
Abiotic Depletion Potential (ADP)	0.3005
Global Warming Potential (GWP)	0.2663
Human Toxicity Potential (HTP)	0.2502
Acidification Potential (AP)	0.0704
Photochemical Oxidation Potential (POCP)	0.0565
Eutrophication Potential (EP)	0.0326
Land Use (LU)	0.0235

By applying these weight coefficients in LCA, decision-makers in the cement industry can prioritize efforts to reduce environmental impacts in the most critical areas, align with sustainability goals, and improve overall environmental performance (Afara et al., 2024; Amen et al., 2024)

. LCA models for quantifying the embodied emissions of concrete and the operational emissions of buildings is significantly influenced by the selection of the functional unit (FU). The FU is crucial because it defines the basis for comparing environmental impacts and ensures that the assessment accurately reflects the intended functions and performance characteristics of concrete and buildings. Table 6 summarizes different functional units (FUs) used in Life Cycle Assessment (LCA) for concrete and buildings, along with their descriptions and typical applications.

Table 6. Different functional units (FUs) used in Life Cycle Assessment (LCA).

Functional Unit (FU)	Description	Typical Applications
Per Cubic Meter of Concrete (m^3)	Measures environmental impacts per volume of concrete. Suitable for assess material inputs, energy use, and emissions dur the production phase.	Concrete production, comparison of differ concrete mixes
Per Square Meter of Building Floor Area (m^2)	Measures environmental impacts per unit area building floor. Useful for evaluating impa related to construction and operational phase buildings.	Building construction, energy performance buildings
Per Building Lifetime (years)	Measures environmental impacts over the en life span of a building, including constructi use, maintenance, and end-of-life.	Long-term sustainability assessments, build lifecycle studies
Per Ton of Cement (t)	Measures environmental impacts per unit wei of cement produced. Commonly used assessing the production phase of cement.	Cement production, comparison of cement typ
Per Occupant (person)	Measures environmental impacts based on number of building occupants. Useful buildings where occupancy significantly affe operational emissions.	Residential buildings, commercial buildings
Per Functional Unit of Service (e.g., per bed hospitals, per student for schools)	Measures environmental impacts based on specific service provided by the building. Tailo to specific building functions and uses.	Specialized buildings such as hospitals, scho and hotels
Per Service Life (years)	Measures environmental impacts considering durability and expected service life of concr structures.	Infrastructure projects, long-term durabi assessments

However, establishing a comprehensive FU that captures the spatial, temporal, and intensity aspects of cement/concrete and its applications poses a challenge in LCA practice (Teran-Cuadrado et al., 2024). A research by Teran-Cuadrado et al. (2024) approve that concrete mixtures with the highest cement content causes the highest environmental impact. Similarly, a review study by Rhaouti et al. (2023) suggested that limestone calcined clay cement could be the most promising solution to the cement industry, with an average GWP of 517 kgCO_2eq/ton of cement and SCM content of 46%.

4. Conclusions

The implementation of alternative fuels and raw materials in cement production has become an increasingly important strategy for addressing environmental, energy, and economic challenges. By substituting conventional fuels with low-carbon alternatives and incorporating industrial by-products, the cement industry can significantly reduce CO_2 emissions and enhance resource efficiency. Examples such as the use of fly ash and Cement Kiln Dust (CKD) illustrate the dual benefits of minimizing waste and improving the sustainability of cement products.

Life Cycle Assessment (LCA) plays a critical role in quantifying the environmental impacts of these measures, allowing for a comprehensive evaluation of their effectiveness. The selection of an appropriate functional unit (FU) is vital in LCA as it ensures that the assessment captures the full range of functionalities and performance characteristics of concrete and buildings. However, defining a FU that comprehensively encompasses spatial, temporal, and intensity aspects remains a significant challenge.

The weight coefficients determined for various environmental impact categories, such as Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), and Human Toxicity Potential (HTP), provide a structured approach for evaluating the relative importance of each impact in LCA studies. Applying these weights can help prioritize efforts to reduce environmental impacts in the most critical areas.

Moreover, the analysis of impact indicator choices among LCA studies reveals a strong focus on Global Warming Potential (GWP) and Non-renewable Energy Use, reflecting the high priority placed on climate change and energy consumption. Other significant indicators include Acidification Potential, Eutrophication Potential, and Ecotoxicity, highlighting concerns over air and water quality, as well as ecological health.

The consistent use of these impact indicators across multiple studies underscores their relevance in addressing the key environmental challenges associated with cement and concrete production. However, it also suggests areas where increased focus and further research might be beneficial, such as land use, ionizing radiation, and heavy metals, which are less frequently considered but still important.

In conclusion, the combination of innovative material substitutions, robust LCA methodologies, and a comprehensive understanding of environmental impact indicators can significantly advance the sustainability of the cement industry. By continuously improving these practices, the industry can better align with global sustainability goals, reduce its environmental footprint, and contribute to a more sustainable built environment.

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Conflict of Interests

The Author(s) declare(s) that there is no conflict of interest.

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