

# Environmental Impacts of Cement Production and Pathways for Sustainable Solutions

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## Abstract

Cement is a widely used construction material, but its production significantly impacts the environment, contributing 5–8% of global CO<sub>2</sub> emissions and releasing pollutants such as particulate matter, NO<sub>x</sub>, SO<sub>2</sub>, and heavy metals. Cement manufacturing also consumes large amounts of raw materials and energy, generating solid waste, noise, and wastewater. Strategies to reduce these impacts include short-term measures like bag filters and improved mix designs, medium-term use of supplementary cementitious materials (SCMs) such as fly ash, slag, or calcined clay, and long-term solutions like geopolymers and carbon capture technologies. If industry, technology, and policy work together, emissions could be reduced by up to 50%, enabling sustainable construction.

**Keywords:** Cement production, CO<sub>2</sub> emissions, air pollution, Sustainable construction, Geopolymer, Supplementary Cementitious Materials (SCMs), Carbon capture.

## 1. Introduction

Cement is the backbone of modern construction. From homes and highways to skyscrapers and dams, it's everywhere. In fact, more than 4 billion tonnes of cement are produced each year that's about one tonne for every person on Earth. While it plays a vital role in development, the environmental cost is high. The cement-making process involves several energy-heavy steps: mining raw materials, grinding them, heating them in kilns to form clinker, and then grinding that clinker into fine powder. This process not only requires large amounts of fuel and electricity but also emits a range of pollutants. CO<sub>2</sub> is the most concerning the industry is responsible for about 5–7% of global human-made carbon dioxide emissions. Other byproducts include cement kiln dust, wastewater, heavy metals, and noise pollution. Although some efficiency improvements have been made over the years, there's a limit to how much can be achieved because the chemical reaction at the heart of cement production — turning limestone into lime — releases CO<sub>2</sub> by nature. With cities continuing to grow and global urbanization expected to add another 2.5 billion people by 2050, the demand for cement won't slow down. This makes it urgent to find cleaner, smarter ways to produce it. This paper explores the environmental issues linked to cement production and outlines practical, technical, and policy-based steps that can reduce its impact. Concrete, the world's most widely used man-made material, relies fundamentally on cement as its binding agent. Over 4 billion tonnes of cement are produced annually, translating to roughly 1 tonne per person per year. This scale makes cement a cornerstone of modern infrastructure but also a major source of environmental burdens. Cement production involves quarrying,

raw material processing, calcination, clinker production, and final grinding—stages that demand intensive energy and release significant pollutants. Globally, the sector accounts for 5–7% of anthropogenic CO<sub>2</sub> emissions, alongside generating cement kiln dust, noise, wastewater, and heavy metal residues. While technological efficiency has improved in recent decades, further progress is constrained by the chemical process of calcining limestone, inherently releasing CO<sub>2</sub>. The need for sustainable alternatives is urgent, particularly as urbanization is projected to add 2.5 billion people to cities by 2050. This study reviews the environmental impacts of cement production and synthesizes practical, technological, and policy-based solutions to mitigate them.

## 2. Literature Review

Alabado (2024) [1], This recent review provides a comprehensive overview of the environmental issues associated with cement production, including CO<sub>2</sub> emissions, dust, NO<sub>x</sub>, SO<sub>2</sub>, and heavy metals. It also highlights practical short- and long-term solutions such as using bag filters, optimizing raw materials, adopting alternative fuels, and developing low-carbon cement technologies. The paper emphasizes the need for sustainable industrial practices and government regulations to minimize ecological impacts. Habert, Miller, John, (2020) [2], A landmark paper in *Nature Reviews Earth & Environment* that outlines the full environmental footprint of the cement and concrete sector. It discusses multiple decarbonization pathways, including supplementary cementitious materials (SCMs), clinker substitution, carbon capture, and carbon curing. The authors present a system-level approach combining technology, policy, and design innovation to achieve deep emission cuts by mid-century. Andrew, (2018) [3], This paper provides global datasets and analysis showing that cement production contributes approximately 5–8% of global CO<sub>2</sub> emissions. It tracks historical emission trends, regional differences, and the role of industrial growth. The data serves as a reference point for global climate models and policy frameworks targeting the construction industry. Miller, John, Pacca, & Horvath, (2018) [4], The authors model future emission reduction scenarios in the cement industry, suggesting that global CO<sub>2</sub> emissions can be cut by up to 50% through a combination of technological innovation, alternative materials, and carbon capture. The paper evaluates both short-term and long-term strategies under different policies and industrial adoption rates. Turner, and Collins, (2013) [5], This study compares the life-cycle emissions of ordinary Portland cement (OPC) concrete and geopolymer concrete. Thinclads that geopolymer concrete can reduce CO<sub>2</sub> emissions by up to 80%, depending on raw materials and production methods. The paper supports the use of industrial by-products like fly ash and slag as eco-friendly alternatives. Bărbulescu & Hosen (2025) [6], Cement Industry Pollution and Its Impact on the Environment and Population Health: A Review. This recent review summarizes how cement production affects both the environment and public health. It discusses pollutants emitted during manufacturing—such as CO<sub>2</sub>, dust, heavy metals, and their ecological and health consequences. The paper emphasizes the need for stricter regulations and cleaner technologies to reduce environmental and health risks. Scrivener, John & Gartner (2018) [7], Eco-efficient cements: Potential economically viable solutions for a low-CO<sub>2</sub> cement-based materials industry. A foundational study on sustainable cement alternatives. It highlights that the cement industry contributes 5–8% of total global CO<sub>2</sub> emissions. The authors explore strategies for emission reduction through supplementary cementitious materials (SCMs), clinker substitution, and geopolymer cements, which use industrial by-products like fly ash and slag. Andrew (2018) [8], Global CO<sub>2</sub> emissions from cement production. This paper provides

quantitative global data on CO<sub>2</sub> emissions from cement manufacturing from 1928 to 2016. It tracks emission trends over time and links them with industrial growth and policy shifts. The study serves as a key reference for understanding cement's contribution to global greenhouse gas inventories. Habert, d'Espinose de Lacaillerie & Roussel (2011) [9], An environmental evaluation of geopolymer-based concrete production: Reviewing current research trends. This review focuses on geopolymer concretes as a sustainable alternative to traditional Portland cement. It evaluates life-cycle impacts, raw materials, and performance benefits of geopolymer systems. The study concludes that geopolymers can substantially reduce CO<sub>2</sub> emissions, though more research is needed for large-scale adoption. IEA & CSI (2018) [10], Technology Roadmap: Low-Carbon Transition in the Cement Industry. A report by the International Energy Agency (IEA) and Cement Sustainability Initiative (CSI). It outlines pathways for the cement sector to reduce emissions by up to 50% through technologies like carbon capture and storage (CCS), energy efficiency, alternative fuels, and innovative materials. Also discusses the role of policy, investment, and collaboration in achieving a low-carbon transition.



(Source: Google)

**Figure.1:** Close-Up of A Cement Plant with Tower Cranes and Chimneys.

### 3. Justifications

#### 3.1. Significance

Cement production is one of the largest sources of carbon dioxide emissions worldwide, contributing about 7 to 8 percent of global emissions. This makes it an important industry to focus on when working to reduce greenhouse gases. As cities grow and infrastructure expands, the demand for cement continues to rise, making it even more crucial to find ways to produce cement with less environmental impact. Traditional cement manufacturing releases large amounts of CO<sub>2</sub> because it involves heating limestone and burning fossil fuels. Reducing these emissions is necessary to meet climate goals set by international agreements and to limit global warming.

Besides cutting emissions, sustainable cement production helps protect natural resources. Extracting raw materials like limestone, clay, and sand often causes environmental damage, including land degradation and pollution. By using alternatives such as industrial byproducts like fly ash, slag, and calcined clays, the cement industry can reduce the need to quarry new materials. Recycling concrete waste and demolition rubble further reduces the strain on natural resources and helps keep waste out of landfills.

Sustainable cement production also offers social and economic benefits. Cleaner technologies and alternative materials create new business opportunities and help companies meet stricter environmental rules. In addition, adopting greener practices improves the industry's reputation among customers and investors who are increasingly interested in environmental responsibility.

### 3.2. Advantages of the Study

There are many clear benefits to making cement production more sustainable. One of the biggest is reducing greenhouse gas emissions. Using industrial byproducts to replace a portion of clinker—the most carbon-intensive part of cement—can cut CO<sub>2</sub> emissions by up to 40 percent. Improving kiln technology to recover heat and switching from fossil fuels to biomass or waste fuels also lower emissions.

Energy efficiency is another important advantage. Modern grinding equipment consumes less electricity, and when this electricity comes from renewable sources like wind or solar, the environmental impact drops even further. Cement plants also use filters and scrubbers to capture dust and harmful gases, helping to keep air pollution under control.

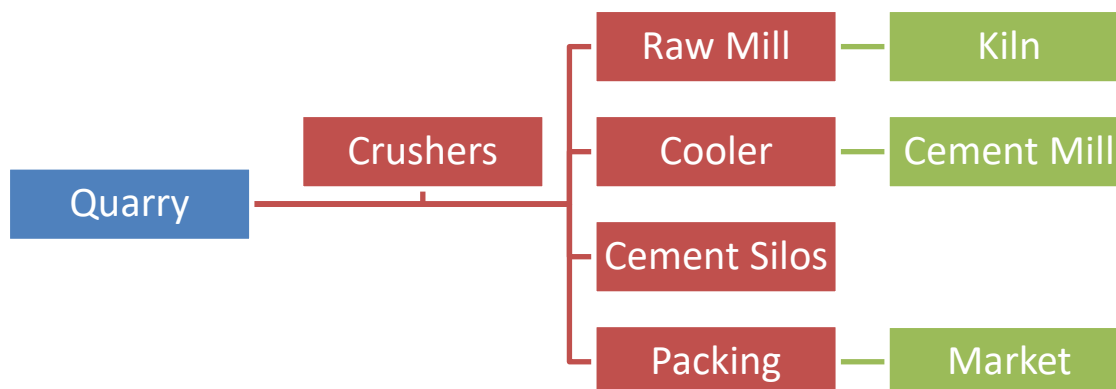
From a performance standpoint, many of the materials used to replace clinker actually make concrete stronger and more durable. This means buildings and infrastructure last longer and need fewer repairs, which reduces overall environmental impacts over their lifespan. New types of binders like geopolymers are being developed that could eventually replace traditional cement altogether, offering much lower carbon footprints.

Sustainable cement production also supports waste reduction. Using waste materials as fuel and recycling concrete reduces landfill waste and lowers the demand for new raw materials. While some sustainable technologies require investment, the long-term savings on energy, materials, and regulatory compliance often make them cost-effective.

### 3.3. Applications

Sustainable cement is widely used across construction projects, from highways and bridges to homes and office buildings. Infrastructure projects benefit from lower-carbon cement blends that still meet performance requirements. In precast concrete products, high-performance mixes made with supplementary materials are common because they combine durability with reduced emissions. Carbon capture technology is also gaining traction. By capturing CO<sub>2</sub> from cement plants and using it to cure concrete, this approach permanently locks carbon into the material while improving its strength. Recycled concrete aggregates are used in new constructions, such as road bases and non-structural concrete, which reduces the need for virgin materials and lowers waste. Water-efficient curing methods help save water, which is especially important in dry regions. Green building programs like LEED recognize the use of sustainable cement, encouraging builders to reduce the environmental impact of their projects. As more builders and developers prioritize green construction, sustainable cement products are becoming essential. The circular economy is another key concept in the industry, where materials are reused and recycled instead of discarded. This approach reduces raw material extraction and emissions while supporting sustainable growth in the built environment.

**Implementation Flowchart for Sustainable Cement Production:**



**Figure.2. Implementation flowchart for sustainable cement production**

**Summary**

Cement is a critical material in global construction, with annual production exceeding 4 billion tonnes. However, its manufacturing process contributes approximately 5–8% of global CO<sub>2</sub> emissions and results in the release of air pollutants such as particulate matter, nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and heavy metals. The process is also resource-intensive, involving significant consumption of raw materials, water, and energy, while generating solid waste and noise pollution. Despite improvements in energy efficiency, the decarbonization of cement production is limited by the inherent CO<sub>2</sub> emissions from limestone calcination. Several mitigation strategies have been identified across the production chain. These include the use of low-carbon raw materials such as fly ash, slag, and calcined clay, energy-efficient grinding systems, kiln optimization, alternative fuels, pollution control technologies, and renewable energy sources. Long-term solutions include the development of alternative binders such as geopolymers and the integration of Carbon Capture, Utilization, and Storage (CCUS) systems. At the construction stage, measures such as high-performance concrete use, aggregate recycling, and circular economy practices help reduce the overall environmental footprint. These approaches offer a practical framework for reducing emissions and resource consumption in the cement sector.

**Discussion**

The environmental impacts of cement production are driven by energy consumption, raw material extraction, and the chemical process of clinker formation. Emission sources include the combustion of fossil fuels and the decomposition of limestone during calcination. Although improvements in energy efficiency and emissions control have been made, further reductions require systemic changes across the supply chain.

Short-term measures such as the installation of filtration systems and real-time emission monitoring contribute to reducing air pollutants. Medium-term strategies, including the use of supplementary cementitious materials and optimization of kiln operations, help lower CO<sub>2</sub> emissions and reduce reliance on clinker. The substitution of fossil fuels with biomass or waste-derived alternatives further decreases carbon intensity. Long-term approaches focus on the development and adoption of low-carbon binders and CCUS technologies, which are essential for

achieving significant emissions reductions.

In addition to production-related strategies, sustainable construction practices and end-of-life recycling play a critical role. Using durable, high-performance concretes reduces material demand over time, while recycling concrete rubble supports resource efficiency and waste reduction. These combined strategies align with global sustainability goals and contribute to climate change mitigation efforts in the construction sector. The integration of technological, industrial, and regulatory actions is necessary for effective implementation and long-term environmental performance improvement in cement production.

### Conclusion

Cement is both a necessity and a challenge. It supports the infrastructure that societies depend on, but it also contributes significantly to environmental damage, especially in terms of greenhouse gas emissions. Despite these challenges, there's a clear path forward. We already have many of the tools we need: better filters, smarter manufacturing methods, alternative materials like fly ash and calcined clay, and even entirely new types of cement. Technologies like carbon capture can play a huge role in long-term decarbonization. If the industry, governments, and researchers work together, emissions can be cut by nearly half — without slowing down construction or development. To meet the demands of a growing population and a warming planet, the cement industry must transform itself — from being a major polluter to becoming a key player in the fight against climate change. Cement production remains a double-edged sword: vital for modern society yet one of the largest contributors to global CO<sub>2</sub> emissions and environmental degradation. Its impacts span air quality deterioration, greenhouse gas emissions, and resource depletion. Nevertheless, a spectrum of solutions exists. Short-term pollution control technologies, medium-term efficiency gains and clinker substitution, and long-term alternatives like carbon capture and geopolymers form a comprehensive roadmap toward sustainability.

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