A COMPREHENSIVE REVIEW OF CEMENT MANUFACTURING, ENVIRONMENTAL IMPACTS AND SUSTAINABLE PRODUCTION PRACTICES

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Abstract*—Cement is one of the most essential construction materials used in the development of infrastructure and modern buildings. However, its manufacturing process is associated with significant environmental challenges, including greenhouse gas emissions, air pollution, high energy consumption, depletion of natural resources and industrial waste generation. The cement industry is considered one of the major contributors to global carbon dioxide (CO_2) emissions, primarily due to limestone calcination and the combustion of fossil fuels during clinker production. This review paper presents a comprehensive study of the cement manufacturing process, its associated environmental impacts and various sustainable production practices adopted to minimise these effects. It examines the major stages of cement manufacturing, including raw material extraction, crushing, grinding, preheating, calcination, clinker formation and cement grinding. Furthermore, it discusses the environmental consequences of cement production, particularly CO_2 emissions, particulate matter, nitrogen oxides (NOx), sulphur oxides (SOx), water consumption and land degradation. The paper also reviews sustainable approaches such as the use of supplementary cementitious materials, alternative fuels, energy-efficient technologies, waste heat recovery, renewable energy and carbon capture, utilisation and storage (CCUS). Special emphasis is given to the potential of low-carbon cement and innovative manufacturing techniques in reducing the environmental footprint of the cement industry. The review highlights the importance of adopting cleaner production methods, resource-efficient technologies and effective environmental management strategies to achieve sustainable cement production. It concludes that integrating technological advancements with sustainable practices can significantly reduce the environmental impacts of cement manufacturing while supporting the growing demand for construction materials and sustainable infrastructure development.

I. INTRODUCTION

Cement is one of the most widely used construction materials in the world and plays a vital role in the development of modern infrastructure, including residential buildings, commercial structures, bridges, roads, dams and other civil engineering projects. It acts as a binding material in concrete and mortar, providing strength, durability and stability to construction works. With rapid urbanisation, industrialisation and population growth, the global demand for cement has increased significantly. Consequently, cement manufacturing has become an essential industrial activity supporting economic growth and infrastructure development. However, the increasing demand for cement has also raised serious environmental concerns due to its energy-intensive manufacturing process and considerable greenhouse gas emissions.

The conventional cement manufacturing process mainly involves the extraction of raw materials such as limestone, clay, silica and iron-bearing materials, followed by crushing, grinding, blending, preheating,

calcination, clinker formation and final grinding with gypsum. Among these stages, clinker production is considered the most energy-intensive and environmentally significant stage. During calcination, limestone (calcium carbonate) decomposes into calcium oxide and carbon dioxide at high temperatures. Additionally, the combustion of fossil fuels required to maintain the high temperatures in rotary kilns contributes further to carbon dioxide emissions. These two processes make cement production a significant contributor to global industrial greenhouse gas emissions.

Apart from carbon dioxide emissions, cement manufacturing generates several other environmental pollutants, including particulate matter (PM), nitrogen oxides (NOx), sulphur oxides (SOx) and other gaseous emissions. These pollutants can deteriorate air quality and contribute to respiratory problems, environmental degradation and climate change. Furthermore, activities such as limestone quarrying, transportation and raw material extraction can result in land degradation, loss of biodiversity, dust generation and increased noise levels. Cement manufacturing also requires considerable quantities of water and energy, making efficient resource management an important concern for the industry.

Considering these environmental challenges, sustainable cement production has become an important area of research and technological development. Several sustainable approaches are being explored to reduce the environmental footprint of cement manufacturing. These include replacing a portion of clinker with supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume and other industrial by-products. The use of alternative fuels, renewable energy sources, energy-efficient kiln systems, waste heat recovery and advanced pollution-control equipment can also contribute to reducing energy consumption and industrial emissions. In addition, emerging technologies such as carbon capture, utilisation and storage (CCUS) offer opportunities to capture carbon dioxide generated during cement production and reduce its release into the atmosphere.

The development of low-carbon and alternative cement materials is another important step towards achieving sustainable construction. Blended cement, geopolymer cement and other innovative cementitious materials have the potential to reduce dependence on conventional clinker-based cement. The adoption of circular economy principles, recycling of industrial waste and efficient utilisation of natural resources can further improve the sustainability of cement manufacturing. However, the implementation of these practices involves challenges related to cost, availability of raw materials, technological development, quality control and large-scale industrial application.

In this context, the present review paper provides a comprehensive overview of cement manufacturing, its major environmental impacts and the sustainable production practices adopted to minimise these effects. It examines the different stages of cement production, identifies major sources of pollution and greenhouse gas emissions, and reviews recent technologies and alternative materials aimed at improving environmental performance. The study also highlights the challenges and future opportunities associated with the transition towards cleaner and more sustainable cement production. Overall, this review aims to emphasise the importance of balancing the growing demand for cement with environmental protection, resource conservation and sustainable infrastructure development.

1.1 EVOLUTION AND HISTORICAL DEVELOPMENT OF CEMENT

The evolution of cement dates back thousands of years, when ancient civilizations used natural materials such as clay, lime, gypsum, and volcanic ash to prepare binding materials for construction. The Egyptians used gypsum and lime-based materials in the construction of pyramids, while the Greeks and Romans developed more advanced hydraulic cement by mixing lime with volcanic ash. The Romans extensively used this material in constructing bridges, aqueducts, roads, and massive structures such as the Pantheon. During the 18th century, significant developments took place in cement technology. In 1756, British engineer John Smeaton developed an improved hydraulic lime for constructing the Eddystone Lighthouse.

Later, in 1824, Joseph Aspdin patented Portland cement in England, marking a major milestone in the history of modern cement production. The name Portland cement was given because the hardened cement resembled Portland stone. During the 19th and 20th centuries, improvements in kiln technology, grinding processes, and chemical composition led to large-scale industrial cement production. The introduction of rotary kilns further improved production efficiency and cement quality. Over time, Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), and Portland Slag Cement (PSC) were developed to meet different construction requirements. Today, cement manufacturing has become an essential part of the global construction industry. However, increasing environmental concerns related to carbon dioxide emissions, energy consumption, and natural resource depletion have encouraged the development of sustainable cement production techniques, alternative raw materials, supplementary cementitious materials, and low-carbon cement technologies.

1.2 PRESENT SCENARIO OF CEMENT MANUFACTURING INDUSTRY

In India, cement production has reached approximately 491.4 million tonnes in FY 2025–26, reflecting an increase of 8.6% compared with the previous financial year. The industry is also moving towards sustainable manufacturing practices through the use of fly ash, ground granulated blast furnace slag (GGBS), alternative fuels, waste heat recovery systems, renewable energy, and low-carbon cement technologies. Modern dry-process technology with preheater and precalciner systems is widely adopted to improve energy efficiency. Despite these improvements, reducing greenhouse gas emissions and minimizing the environmental impact of cement production remain major challenges. Therefore, the present scenario of the cement manufacturing industry highlights the need to balance increasing production demands with environmental protection and sustainable development.

II. LITERATURE REVIEW

1) Chirag Jha and Karthik Reddy Maram, in their study India's Cement Industry, discussed cement manufacturing processes, industry growth, market demand and major cement producers in India. The study also highlighted the importance of green cement, renewable energy and waste heat recovery for sustainable production. However, limited attention was given to detailed environmental impacts and carbon emission reduction technologies.

2) Dr. Ravi B. and Shambhulingappa F. Nallanavar (2022), in their research paper “History & Growth of Cement Industry in India – A Study,” discussed the development and growth of the Indian cement industry. The study highlighted technological advancements, increased production capacity, modernization of cement plants, and the use of industrial waste materials like fly ash and blast furnace slag for sustainable cement production.

3) Shrivastava et al. (2014) studied the challenges of adopting green manufacturing practices in the Indian cement industry. Their research highlighted the importance of energy efficiency, waste recycling, pollution control and sustainable production techniques to reduce environmental impacts.

4) Bărbulescu and Hosen (2025), in their research paper “Cement Industry Pollution and Its Impact on the Environment and Population Health: A Review,” studied the environmental effects of cement manufacturing. They highlighted that cement production causes air, water, soil and noise pollution, leading to global warming, respiratory diseases and ecosystem damage. The study emphasized the need for cleaner technologies and sustainable manufacturing practices to reduce pollution and protect the environment.

5) Chatterjee and Mala (2024) reviewed particulate matter emissions from cement manufacturing in India. The study highlighted that cement production releases harmful dust and gases, causing respiratory diseases, air pollution, and environmental degradation. It also discussed pollution control measures such as bag filters, electrostatic precipitators, and the use of protective equipment to reduce environmental impacts.

6) Zhu et al. (2022) reviewed pollution caused by cement industries and discussed its harmful effects on air, water, soil, and human health. The study highlighted pollution control methods such as filtration, waste recycling, alternative fuels, and Python-based monitoring to promote sustainable cement production.

7) Hasanbeigi, Bhadbhade and Ghosh (2022) studied air pollution caused by the global cement industry. Their research highlighted emissions of SO_2, NOx, particulate matter and other pollutants during cement manufacturing. The study emphasized the need for pollution-control technologies, energy efficiency and cleaner fuels to reduce environmental impacts.

8) Mudgal and Chellasamy (2024), in their research paper "Growth of Indian Cement Industry, Its Environmental Impact and Emerging Alternatives," studied the growth of the Indian cement industry and its environmental effects. The study highlighted CO_2 emissions, air pollution, and resource consumption caused by cement production. It suggested sustainable alternatives such as fly ash-based cement, geopolymer concrete, and low-carbon binders to reduce environmental pollution and promote sustainable construction.

III. CEMENT MANUFACTURING PROCESS

Cement manufacturing is a systematic process in which raw materials such as limestone, clay, silica, and iron ore are converted into cement through various physical and chemical operations. The process mainly involves the extraction of raw materials, crushing, grinding, blending, heating in a rotary kiln, cooling, and final grinding. The modern cement industry mainly uses the dry process because it consumes less energy and is more efficient than the wet process. Extraction of Raw Materials

1.The process begins with the extraction of raw materials such as limestone, clay, shale, silica, and iron ore from quarries. These materials provide the essential chemical components required for cement production.

2. Crushing
The extracted raw materials are transported to crushing units, where large rocks are broken into smaller pieces using crushers. This makes the materials suitable for further processing.

3. Raw Material Grinding
The crushed materials are ground into a fine powder using raw mills. The required proportions of different materials are maintained to obtain the desired chemical composition.

4.The finely ground raw materials are mixed thoroughly in blending silos to achieve a uniform composition. This step ensures consistent quality of the final cement product.

5. Preheating and Precalcination
The raw meal passes through a preheater, where it is heated by hot gases from the kiln. During precalcination, limestone decomposes into calcium oxide and carbon dioxide.

6. Burning in Rotary Kiln

The heated raw material enters a rotary kiln, where it is exposed to temperatures of approximately 1450°C. At this high temperature, chemical reactions take place and small hard nodules called clinker are formed.

7.The hot clinker coming out of the rotary kiln is rapidly cooled using air in a clinker cooler. Cooling helps maintain the required mineral composition and improves clinker quality.

8. Final Grinding
The cooled clinker is mixed with a small quantity of gypsum and other suitable additives. The mixture is finely ground in cement mills to produce cement powder. Gypsum is added to regulate the setting time of cement.

9. Storage and Packaging
The finished cement is stored in large silos to protect it from moisture. Finally, it is packed in bags or transported in bulk to construction sites and distributors.

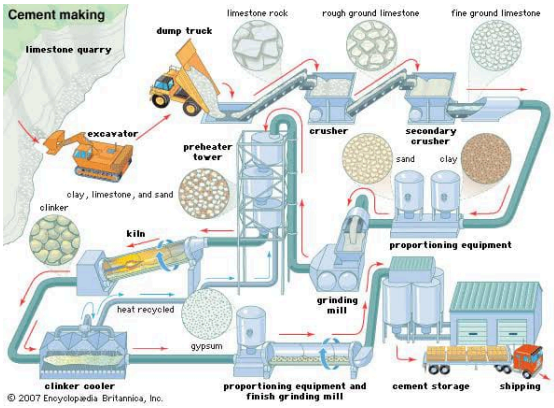

FIG 1: CEMENT MANUFACTURING PROCESS

3.1 ENVIRONMENTAL IMPACT OF CEMENT PRODUCTION

1.Air Pollution: Cement manufacturing releases various air pollutants, including particulate matter, dust, sulphur dioxide (SO_2) and nitrogen oxides (NO_x). These pollutants are mainly generated during raw material handling, kiln operations and fuel combustion. They reduce air quality and may cause respiratory problems.

2. Carbon Dioxide Emissions: Cement production is a significant source of carbon dioxide (CO_2) emissions. CO_2 is released mainly during limestone calcination, where calcium carbonate decomposes into calcium oxide and carbon dioxide, and through the burning of fossil fuels to maintain high kiln temperatures. These emissions contribute to global warming and climate change.

3.High Energy Consumption: Cement manufacturing requires large amounts of thermal and electrical energy for crushing, grinding, material transportation and clinker production. The extensive use of coal, petroleum coke and other fossil fuels increases energy demand and greenhouse gas emissions.

4. Water Pollution: Water is used in cement plants for cooling, equipment cleaning and dust suppression. Improper discharge of wastewater containing suspended solids, chemicals and other contaminants can affect nearby water bodies and soil quality.

5.Land Degradation: Limestone and other raw materials are extracted through quarrying activities. Continuous mining changes the natural landscape, removes vegetation, destroys habitats and can cause soil erosion.

6. Noise Pollution: Heavy machinery, crushers, grinding mills, compressors and transportation vehicles generate high noise levels. Continuous exposure to industrial noise can affect workers and nearby communities.

7.Solid Waste Generation: Cement manufacturing produces solid wastes such as kiln dust, rejected materials and packaging waste. Improper disposal of these materials can create environmental problems and increase land pollution.

8. Impact on Biodiversity: Quarrying, land clearing and industrial activities disturb natural ecosystems. These activities can destroy habitats, reduce vegetation cover and affect the survival of local plant and animal species.

3.2 PARTICULATE MATTER EMISSION

Particulate matter can be defined as a fusion of particles which can be solid in nature and aerosol (liquid droplets). Some examples of PM are dust, soot, carbon particles, fly ash, bottom ash, slag, black filter dust, smoke, fume, flue gases, dolochar, scraps, etc. Based on the aerodynamic diameter, PM can be classified into three types; coarse particle, fine particle and ultrafine particle. PM of aerodynamic diameter less than 10m (2.5-10m) falls under the coarse particle category and is designated as PM10. PM of aerodynamic diameter less than 2.5m(0.1-2.5m) is considered as fine particle, designated by PM2.5. The ultrafine particles are those of aerodynamic diameter less than 0.1m represented as PM0.1. The different size of particles can enter upto different levels in the human body. PM10 particles are filtered out in the proximal airway causing slight irritation in skin only [8, 30]. PM2.5 particles enters into the peripheral airways owing to its smaller size but are stopped from entering the systemic circulation whereas PM0.1 particles are very toxic in nature as they get introduced into the systemic circulation causing toxic effects in the body. Particulate matter also comprises of poisonous metals and toxic compounds like lead, barium, nickel, chromium, etc. all of which have harmful health implications. The average PM2.5 level in India is 40-50 g/m3 whereas the prescribed limit is of 10 g/m3.

As the cement industry grows, the concentration of particulate matter in the atmosphere by direct as well as fugitive emissions from stocked materials increase . Different procedures in cement production like, quarrying, drilling, blasting, hauling, crushing, fuel preparation, grinding of the cement clinker, packaging and transport leads to the release of particulate matter, PM10 and PM2.5. Blasting of rocks produces dust particles which get distributed in the surrounding area, making it toxic . Flue gases are the most usual waste released from mostly all cement manufacturing plants . The cement kiln dust (CKD) which is composed of burnt, partially burnt and unburnt substances is produced during pyro-processing in the cement kiln . The particle size of CKD ranges from 0-5m which approximately the clay size to a size greater than 50 m which is approximately the silt size . Even though the CKD produced during the process is reused, its adverse impact is seen once it is dispersed in air.

Approximately 175 tons of fly ash is generated per day, of which 75 tons are from the Waste Heat Recovery (WHR) Boiler used during the calcination and clinker cooling step of cement production. An average of 10

to 12 tons of bottom ash also produced daily by the cement plants . The CPCB of India has formulated a specific particulate emissions limit which is equal to 250 mgNm−3 for the cement plants of India having a capacity of more than 200 tons per day (TPD). It is noted that a greater rigid standard of maximum 150 mgNm-3 was applicable for bigger plants on a case-to-case basis. After considering the above situation, the particulate concentration of the rotary kiln stack emission was found to be marginally exceeding the standard of 750 mg Nm3 promulgated by CPCB. As per the World Health Organization (WHO) guidelines, if we cut down the PM concentration from 70 to 20 g/m3, the air pollution causing death can be reduced to approximately 15%.

3.4 GREEN CEMENT TECHNOLOGY

Green cement technology refers to the development and use of environmentally friendly cement and concrete manufacturing methods that reduce carbon dioxide (CO_2) emissions, energy consumption, and the use of natural resources.

1.Alternative raw materials
Industrial waste materials such as fly ash, blast furnace slag, silica fume, and other supplementary cementitious materials are used as partial replacements for conventional cement raw materials. This reduces the consumption of limestone and other natural resources.

2.Geopolymer cement
Geopolymer cement is produced using aluminosilicate-rich materials such as fly ash and GGBS, activated by alkaline solutions. It can significantly reduce CO_2 emissions compared with conventional Portland cement, depending on the materials and production process.

3.Low-carbon cement
Low-carbon cement is manufactured by reducing clinker content and replacing a portion of clinker with materials such as fly ash, limestone, and slag. Since clinker production is a major source of cement-related emissions, reducing its quantity helps lower the carbon footprint.

4.Carbon capture and storage (CCS)
This technology captures CO_2 released during cement manufacturing and stores it underground or directs it towards suitable industrial uses. It helps reduce direct emissions from cement plants.

5.Waste heat recovery
Waste heat from cement kilns is recovered and used to generate electricity. This reduces dependence on external energy sources and improves energy efficiency.

6.Alternative fuels
Cement industries use suitable waste-derived fuels, biomass, and other alternative fuels instead of conventional fossil fuels such as coal. This helps conserve non-renewable resources.

7.Carbon curing technology
In this technology, CO_2 is introduced into concrete during the curing process. Some of the CO_2 reacts with cementitious materials and becomes chemically bound, improving carbon utilization and potentially enhancing concrete properties.

IV. CONCLUSION

The cement industry plays a vital role in infrastructure development and economic growth; however, its manufacturing process contributes significantly to environmental pollution, energy consumption, and global carbon dioxide emissions. This review highlights the major stages of cement manufacturing and examines their environmental impacts, including greenhouse gas emissions, air pollution, depletion of natural resources, and industrial waste generation.

The study emphasizes the importance of adopting sustainable production practices to minimize these environmental problems. The use of alternative raw materials, supplementary cementitious materials, low-carbon cement, geopolymer technology, waste heat recovery, renewable energy, and carbon capture systems can help reduce the carbon footprint of cement production. Furthermore, proper waste management, energy-efficient equipment, and advanced manufacturing technologies can improve resource utilization and environmental performance.

It can be concluded that achieving sustainable cement production requires continuous technological development, effective environmental regulations, industrial collaboration, and increased awareness. Although the transition towards green cement technologies involves certain economic and technical challenges, their long-term environmental and economic benefits are significant. Therefore, adopting innovative and sustainable manufacturing practices is essential for developing a low-carbon cement industry and supporting environmentally responsible infrastructure development in the future.

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