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Innovations in Cement Production: The Road to Sustainability and A Circular Economy

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Abstract: After water, cement is the most frequently used material on the planet, and the cement industry is critical to any country's economic prosperity. When mixed with water, it produces concrete, which serves as the foundation for buildings, roads, dams, and bridges. According to studies, the cement sector accounts for approximately 8% of global warming carbon dioxide emissions, far more than global carbon emissions from aviation, for example. In this context, the cement industry needs to implement major innovations to ensure sustainability, energy efficiency, and a lower carbon footprint. The scientific publication discusses the most current advances in cement manufacturing, with a focus on methods and technology for achieving sustainability and integrating the cement sector into the circular economy. The study examines the relationship between annual worldwide carbon dioxide emissions and annual global emissions from cement production. The correlation shows that carbon dioxide emissions from cement production have a significant impact on annual worldwide carbon dioxide emissions, emphasising the critical need to apply contemporary, sustainable solutions in this industry.

Keywords: Cement, CO_2, Innovations, Sustainability, Circularity.

Introduction

Cement is an essential construction material that has the potential to greatly contribute to the growing demand for infrastructure due to the increasing global population (GCCA, 2022). According to Grigorova and Koprev the need for raw materials is a prerequisite for their demand on the market and hence for investigations and mining operations. Exploration and mining activities, including sediments mining, are faced with the challenge to ensure both the need for raw materials for the industry and to preserve the fragile ecological balance (Grigorova & Koprev, 2018). Cement production is widely recognised as a significant source of global greenhouse gas emissions (GHGs) (Worrell et al, 2001). It contributes to 7-8% of the total human-caused Greenhouse Gas (GHG) emissions worldwide (Busch et al., 2022).

CO_2 emissions, being a prominent greenhouse gas, provide a substantial contribution to the overall greenhouse effect on a worldwide scale. In 2019, the cement industry released 2.4 gigatonnes (Gt) of carbon dioxide (CO_2), accounting for 26% of total industrial emissions, as reported by the International Energy Agency (IEA, 2020a). Therefore, it is imperative to give high importance to the implementation of low-carbon solutions in the cement business. Cement is manufactured in over 90% of countries and regions worldwide, resulting in a total global production of 4.1 gigatonnes (Gt) in 2019.

The manufacturing of one tonne of cement, on average, emits 0.5-0.6 tonnes of CO_2. The quantity of carbon dioxide released is influenced by several factors, such as the clinker-to-cement ratio, the manufacturing technique, heat recovery methods, and the specific raw materials and fuels employed (Plaza et al., 2020). The reduction of CO_2 emissions from cement production presents challenges primarily because approximately 50% to 60% of CO_2 is produced during the decomposition of limestone (CaCO3) into lime (CaO) (Benhelal et al., 2021). Approximately 30%–40% more carbon dioxide (CO_2) is generated from the combustion of fossil fuels

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and the indirect discharge of emissions from power generation. The International Energy Agency (IEA) predicts that worldwide carbon dioxide (CO_2) emissions from cement production will decline from 2.4 gigatons (Gt) in 2019 to 0.2 Gt in 2070, based on the sustainable development scenario (SDS).

This reduction is expected to come from a 35% decrease in CO_2 emissions due to reduced demand for cement and a 14% decrease resulting from a lower ratio of clinker to cement. These initiatives are already fully developed and will have a significant impact by 2030. By 2070, CCUS is projected to eliminate over 60% of the total CO_2 emissions, and its function will commence after 2030.

In 2021, China produced 2.36 billion metric tonnes of cement, which represented 56% of global production (DC, 2009). In 2020, the cement industry consumed 175 million tonnes of coal (Wei, 2022). The cement sector generated around 1.375 billion tonnes of carbon emissions, representing over 13.5% of the total emissions in the country (Xinhuanet, 2022). The cement sector has experienced considerable changes in air pollutant emission levels due to the implementation of stricter air pollutant emission limits. Hence, it is crucial to compile a precise emissions inventory for the cement industry.

Various techniques have been identified to reduce the greenhouse gas (GHG) emissions of the cement industry. The initial strategy is the material efficiency plan, which involves enhancing the quality of cement to decrease the required amounts for maintaining its performance. This is also seen as a significant aspect for mitigating climate change. It is advisable to contemplate reducing the amount of cement used in that particular context. Nevertheless, the worldwide increase in population and economic progress indicate that the demand for concrete, and consequently for cement, will continue to rise on a global scale instead of declining.

Method

A comprehensive literature review was conducted to gather existing knowledge on sustainable practices in cement production. Key sources included peer-reviewed journals, industry reports, government publications and conference papers. Search terms included "sustainable cement production," "carbon capture in cement industry," "alternative raw materials for cement," and "circular economy in construction". The relationship between cement production and global CO_2 emissions was analyzed using statistical methods. This involved quantitative analysis of emission data from industry reports and correlation analysis to determine the impact of cement production on overall global CO_2 emissions.

Results and Discussion

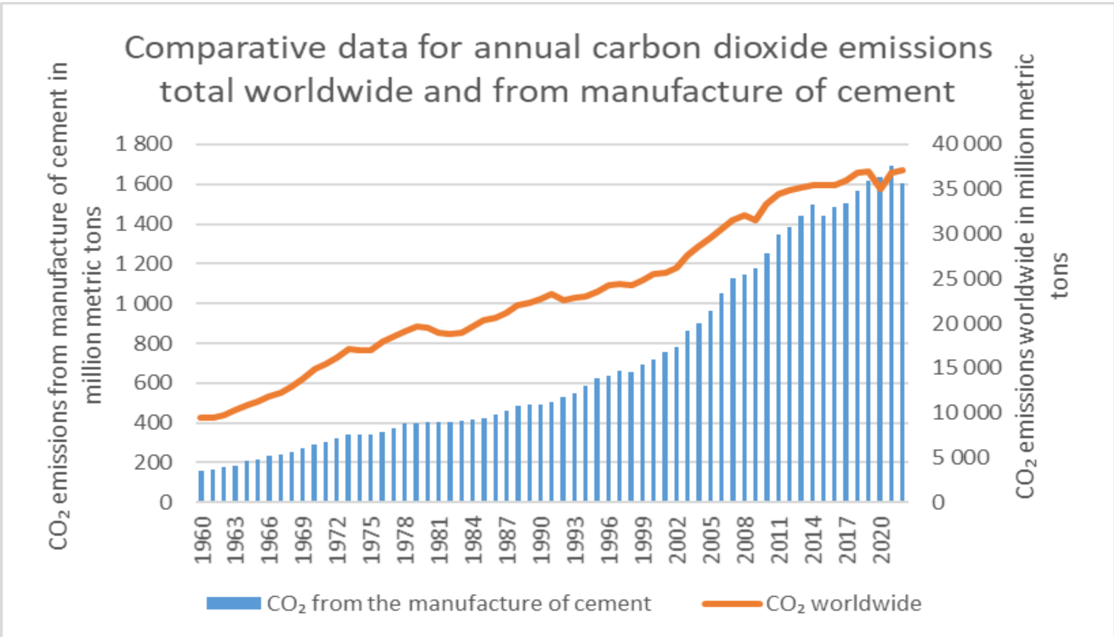

Figure 1. Comparative data for annual carbon dioxide emissions total worldwide and from manufacture of cement

The research in this publication focuses on the comparison between total carbon emissions on a global scale and the carbon emissions caused by cement production. Total Carbon Emissions include all sources of carbon dioxide emissions globally, such as fossil fuel combustion, deforestation, industrial processes and more. Cement Production Emissions specifically refer to carbon dioxide emissions resulting from the production of cement, a significant industrial source of carbon emissions due to the calcination process and energy use. Figure 1 illustrates their development for the period 1960–2022.

Pearson's correlation coefficient was used to determine the linear correlation between the two data sets. Figure 2 demonstrates that carbon dioxide emissions from cement production have a significant impact on annual global carbon dioxide emissions. The equation y=17.078x+11274 describes this dependence. This practically means that an increase in cement production by 1 million metric tonnes will result in an increase in annual carbon dioxide emissions worldwide by more than 17 million metric tonnes, highlighting the urgent need to apply modern purification technologies in this industry. The coefficient of determination, R2, indicates the accuracy of the resulting regression model. Its maximum value can be 1, and the resulting model has been shown to be very accurate.

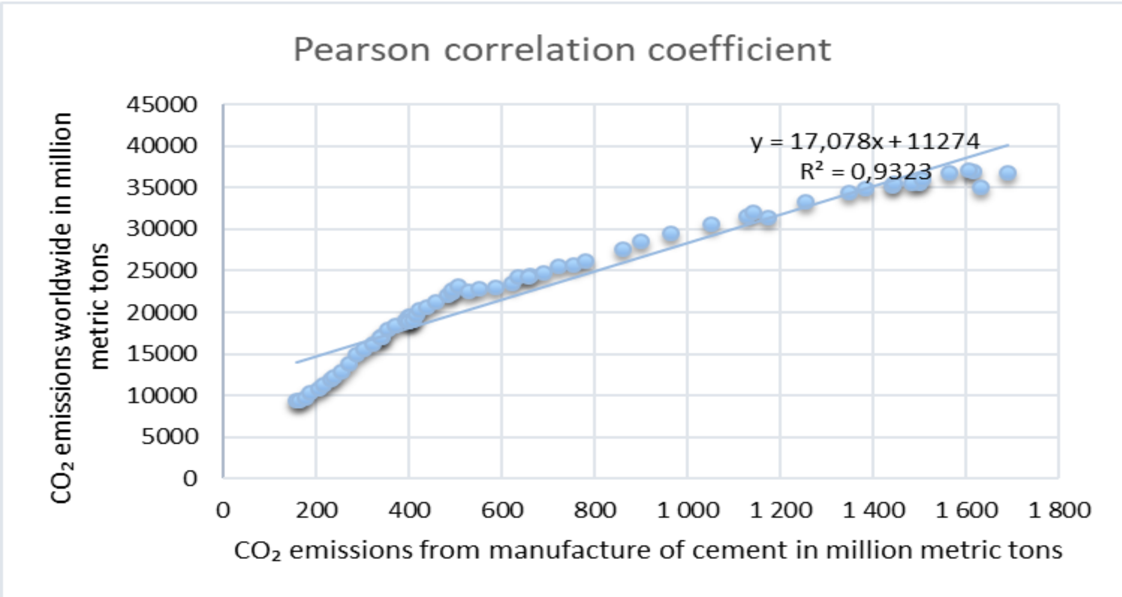

Figure 2. Pearson correlation between annual carbon dioxide emissions total worldwide and the manufacture of cement

The correlation is also evident in population growth, which leads to a higher demand for infrastructure and housing, consequently resulting in increased consumption of construction materials such as cement. The increase in cement usage can be attributed to urban development, industrialisation, and residential construction. As urban areas expand, the demand for additional structures, highways, bridges, and other infrastructure developments also increases.

Principles of Circular Economy in Cement Production

The circular economy model emphasizes sustainability, resource efficiency, waste reduction, and the continual use of resources. In the context of cement production, adopting circular economy principles involves rethinking traditional practices to minimize environmental impact and promote sustainable development. This section explores the key principles of circular economy as they apply to cement production, supported by relevant literature and case studies.

Resource Efficiency

By maximising the utilisation of alternate raw materials, such as industrial by-products like fly ash, slag, and silica fume, the dependence on primary resources can be greatly diminished. Geopolymer cements, which make use of discarded materials, demonstrate this concept.

Waste Minimization

By recycling concrete and utilising demolition waste as aggregate in the creation of new concrete, the amount of trash is reduced and valuable natural resources are conserved (Aleksandrova et al., 2019, Dimov et al., 2020). Smart crushers are advanced technologies that enable the efficient separation and recycling of different components of concrete.

Energy Recovery

Integrating waste heat recovery systems in cement factories enables the capture and reuse of energy, hence enhancing the total energy efficiency. Alternative fuels, such as biomass and fuels obtained from waste, decrease reliance on fossil fuels and decrease carbon emissions.

Product Longevity

Enhancing the longevity and durability of concrete decreases the necessity for frequent repairs and replacements, therefore preserving resources and minimising the environmental footprint over the lifespan of the product.

The Innovations in Cement Production

Low-Carbon Clinker Substitutes

The production of conventional Portland cement clinker significantly contributes to CO_2 emissions due to the high-temperature calcination process required to transform limestone into lime. To address this environmental challenge, several low-carbon clinker substitutes have been developed to reduce carbon emissions associated with cement manufacturing by utilizing alternative materials and methods.

Belite-rich clinkers are a notable example of this innovation. Composed primarily of dicalcium silicate, belite forms at lower kiln temperatures compared to alite, the main component of traditional Portland cement. The production of belite-rich clinkers typically occurs at temperatures around 1250-1350°C, as opposed to 1450°C for alite-rich clinkers. This lower production temperature leads to decreased energy consumption and reduced CO_2 emissions (Buchwald et al., 2019). Additionally, cements with high belite content exhibit superior long-term strength development, although they may demonstrate slower initial strength gain, which can be a disadvantage in applications requiring rapid setting (Gartner, 2004).

Calcium sulfoaluminate (CSA) cements represent another significant advancement in low-carbon alternatives. The production of CSA cements involves mixing bauxite, limestone, and gypsum, with ye'elimite being the primary component of CSA clinker. During hydration, ye'elimite reacts with gypsum to form ettringite and monosulfate, which enhance the cement's strength. CSA cements generate lower CO_2 emissions during production due to reduced limestone content and typically lower calcination temperatures, usually around 1250°C. These cements also set quickly and exhibit high initial strength, making them suitable for fast-track construction projects while demonstrating excellent resistance to sulfate attack (Shi et al., 2011). However, the reliance on specific raw materials, such as bauxite, can pose challenges related to availability and cost (Wang et al., 2020).

Magnesium-based cements, including magnesium oxychloride and magnesium oxysulfate cements, utilize magnesium compounds instead of calcium compounds. A noteworthy variant is magnesium silicate hydrate (MSH) cement, which has the ability to absorb CO_2 during the curing process. This property allows magnesium-based cements to capture and sequester CO_2, thereby reducing net emissions. Additionally, these cements can be produced at lower temperatures compared to traditional Portland cement, leading to energy savings and decreased CO_2 emissions (Meyer, 2009). However, the durability and long-term stability of magnesium-based cements can be compromised in humid environments, and the raw materials required can be more expensive and less accessible than those used for conventional Portland cement (Powers, 2018).

Alkali-activated materials (AAMs), which include geopolymers, are created by activating aluminosilicate materials, such as fly ash or slag, with alkaline solutions. This process eliminates the need for high-temperature calcination, resulting in significantly reduced CO_2 emissions during production (Davidovits, 1994). AAMs often utilize industrial by-products, which minimizes waste and reduces the demand for virgin raw materials. Furthermore, AAM products demonstrate exceptional durability, including resistance to chemical attacks and high-temperature stability. However, the handling of strong alkaline solutions can present safety challenges, and the lack of standardized production methods can hinder wider acceptance (Van Jaarsveld et al., 2002).

In summary, low-carbon clinker substitutes offer viable solutions for reducing the carbon footprint of cement production. Each alternative presents unique advantages and challenges, and their adoption will depend on regional material availability, cost considerations, and specific application requirements.

Utilization of Industrial By-Products

The utilization of industrial by-products in cement production is a critical strategy for enhancing sustainability and reducing environmental impact. Incorporating materials such as fly ash, slag, and silica fume not only minimizes waste but also improves the performance characteristics of cement (Koprev et al., 2007).

Fly ash, a by-product of coal combustion in power plants, has gained significant attention for its pozzolanic properties. When used as a partial substitute for Portland cement, fly ash can enhance the durability and workability of concrete while reducing overall CO_2 emissions associated with cement production. Studies have shown that incorporating fly ash can lead to improved resistance to sulfate attack and reduced permeability in concrete, contributing to longer service life and reduced maintenance costs (Mehta & Monteiro, 2014).

Similarly, ground granulated blast furnace slag (GGBFS), a by-product from the steel manufacturing process, serves as an effective supplementary cementitious material. The use of slag in cement not only recycles industrial waste but also contributes to the production of low-carbon cements. Slag-based cements exhibit excellent mechanical properties and durability, making them suitable for a variety of construction applications. The hydration products formed with slag lead to increased strength development over time, further enhancing the longevity of concrete structures (Bentz & Stutzman, 2015, Hristova, 2022).

Silica fume, produced during the production of silicon metal or ferrosilicon alloys, is another valuable by-product that enhances the properties of cement and concrete. Its high silica content and fineness improve the density and strength of concrete, making it particularly effective in high-performance applications. The inclusion of silica fume can significantly increase compressive strength and reduce the permeability of concrete, thereby enhancing its durability against environmental stresses (Hooton & Bickley, 2006).
The incorporation of these industrial by-products not only contributes to the circular economy by diverting waste from landfills but also helps in the production of more environmentally friendly cements. By utilizing such materials, the cement industry can significantly reduce its carbon footprint while maintaining or even enhancing the performance of cement and concrete products (Scrivener et al., 2018).

In summary, the utilization of industrial by-products in cement production offers a promising avenue for achieving sustainability goals. By integrating materials like fly ash, slag, and silica fume, the cement industry can promote resource efficiency, reduce environmental impact, and enhance the overall quality of cement and concrete.

Energy Efficiency

Energy efficiency is a crucial aspect of modern cement production, significantly impacting both operational costs and environmental sustainability. The cement industry is inherently energy-intensive due to the high temperatures required for clinker production, making the optimization of energy usage a priority. One effective strategy for enhancing energy efficiency is the implementation of waste heat recovery systems. These systems capture excess heat generated during the manufacturing process, converting it into usable energy for various applications within the plant. By utilizing waste heat, cement producers can reduce their reliance on external energy sources and lower overall production costs (Zhang et al., 2018).

Advanced kiln technologies also play a vital role in improving energy efficiency in cement manufacturing. Innovations such as multi-channel burners and pre-calcination techniques enable more efficient fuel combustion and better thermal management within the kiln. These advancements not only enhance energy efficiency but also contribute to reduced CO_2 emissions. For instance, the use of pre-calcination allows for a portion of the limestone to be calcined before entering the kiln, which can lower the energy requirements and increase the overall efficiency of the process (Hendriks et al., 2018).

Additionally, optimizing the operation of existing equipment through automation and process control systems can further enhance energy efficiency. By employing real-time monitoring and data analytics, cement plants can fine-tune their operations to minimize energy consumption while maintaining product quality. This integration of digital technologies enables manufacturers to make informed decisions and adopt best practices in energy management (Mourtzis et al., 2020).

Overall, the focus on energy efficiency in cement production not only aids in reducing operational costs but also aligns with the industry's sustainability goals. By implementing waste heat recovery systems, adopting advanced kiln technologies, and optimizing operational processes, cement manufacturers can significantly lower their energy consumption and carbon emissions, contributing to a more sustainable future for the industry.

Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) is an essential technology for mitigating CO_2 emissions from the cement industry, which is one of the largest industrial sources of greenhouse gases. CCS involves capturing carbon dioxide emissions produced during cement manufacturing and securely storing them to prevent their release into the atmosphere. This process is crucial for achieving climate targets and transitioning towards a low-carbon economy.

One prominent method of CCS is post-combustion capture, where CO_2 is separated from the flue gases after combustion has occurred. This approach utilizes various technologies, such as chemical absorption, to effectively capture CO_2 emissions from cement plants. Research indicates that integrating post-combustion capture systems can significantly reduce overall emissions while maintaining production efficiency (Bui et al., 2018).

Another innovative method within CCS is oxy-fuel combustion, which involves burning fossil fuels in a mixture of oxygen and recycled flue gas instead of air. This process results in a concentrated stream of CO_2, making it easier to capture and store. Oxy-fuel combustion has demonstrated promising results in reducing CO_2 emissions in various industrial applications, including cement production (Zhang et al., 2019). By utilizing this technology, cement manufacturers can potentially achieve higher capture rates while minimizing energy penalties associated with CO_2 capture.

Implementing CCS in the cement industry not only supports emission reduction goals but also aligns with broader sustainability initiatives. By capturing and storing CO_2, cement producers can significantly lower their carbon footprint while maintaining competitiveness in a market increasingly focused on environmental responsibility (IPCC, 2021). Despite the challenges associated with the deployment of CCS, such as high capital costs and the need for extensive infrastructure, ongoing research and development efforts are paving the way for its wider adoption in the cement sector.

In summary, carbon capture and storage is a critical component in the strategy to decarbonize cement production. Through methods like post-combustion capture and oxy-fuel combustion, the cement industry can significantly reduce its greenhouse gas emissions and contribute to global climate goals.

Alternative Fuels

The integration of alternative fuels in cement production is increasingly recognized as a vital strategy for reducing carbon emissions and promoting sustainability. Biomass fuels, such as agricultural residues and wood chips, are particularly significant due to their renewable nature. These materials originate from plant and animal matter, contributing to a carbon-neutral lifecycle. When utilized in cement kilns, biomass fuels release CO_2 that was previously absorbed by plants during growth, thereby maintaining a closed carbon cycle. This approach contrasts sharply with fossil fuels, which release long-sequestered carbon, thereby exacerbating atmospheric CO_2 levels (Gartner, 2004).

Agricultural residues, including straw, husks, and other by-products, can be effectively repurposed as fuel sources in cement manufacturing. This practice not only lowers the carbon footprint of the production process but also provides an environmentally friendly disposal method for agricultural waste. Additionally, wood chips and forestry by-products serve as valuable energy inputs, further diversifying the fuel mix within the industry (Scrivener et al., 2018).

Waste-derived fuels are equally important in advancing sustainable practices in cement production. Refuse-derived fuel (RDF), which is composed of processed municipal solid waste, significantly aids in diverting waste from landfills while providing a reliable fuel source. The incorporation of RDF into cement production processes enhances energy recovery and reduces dependency on conventional fossil fuels (Worrell et al., 2001). Tire-derived fuel (TDF), produced from shredded tires, is another effective alternative that supports both waste management and energy generation. The utilization of TDF helps cement manufacturers secure a sustainable fuel supply while simultaneously addressing waste disposal challenges (Zhang et al., 2019).

The adoption of these alternative fuels is not only an environmentally responsible choice but also aligns with the principles of the circular economy. By repurposing waste and renewable materials, the cement industry can lower greenhouse gas emissions and improve resource efficiency. This transition represents a strategic move that enhances the resilience and competitiveness of the industry in an evolving market landscape, ultimately contributing to more sustainable cement manufacturing practices.

Digital Technologies

The cement business is being revolutionised by digital technologies, which are improving efficiency, cutting costs, and fostering sustainability. Artificial intelligence (AI) and machine learning (ML) are being more and more used into cement manufacturing processes to enhance operations and enhance decision-making. These technologies facilitate predictive maintenance, wherein algorithms examine past data to identify equipment breakdowns in advance, thereby reducing downtime and operational disturbances. Cement factories can achieve energy consumption optimisation, waste reduction, and improved product quality by utilising artificial intelligence (AI) and machine learning (ML) technologies. This can be accomplished by the use of real-time monitoring and adaptive control systems (Bashir et al., 2020).

The Internet of Things (IoT) is essential for modernising cement production, alongside AI and ML. The Internet of Things (IoT) devices enable the gathering of extensive quantities of data from different phases of the production process, offering valuable insights that can result in enhanced operational efficiency. Embedded sensors in machinery and infrastructure have the capability to monitor performance characteristics in real time. This allows firms to make well-informed decisions using precise and fast information. The connectivity not only improves the visibility of operations but also enables preventive maintenance approaches, resulting in cost reduction and productivity enhancement (Li et al., 2018).

The integration of artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT) has a synergistic impact that enables cement makers to adopt intelligent production systems. For example, the use of AI-powered predictive analytics can enhance the efficiency of the supply chain by accurately predicting demand trends and making necessary adjustments to production schedules. This capacity is especially crucial for effectively managing resources and minimising surplus inventories, which can aid in achieving sustainability objectives (Wang et al., 2020).

Furthermore, the use of these digital technology enables more effective environmental management. Cement plants can achieve substantial reductions in carbon emissions and energy usage by optimising their manufacturing processes and resource utilisation. Aligning with sustainability objectives not only ensures compliance with regulations but also strengthens the competitive edge of enterprises in a dynamic market (Mourtzis et al., 2020).

To summarise, the cement business is being transformed by the implementation of digital technologies such as artificial intelligence, machine learning, and the Internet of Things. These advancements enhance the effectiveness of operations, facilitate preventative maintenance, and encourage environmentally-friendly practices. As the sector increasingly adopts these technologies, there is great potential for improved productivity and decreased environmental impact.

Conclusion

Transitioning to a circular economy in cement production is vital for reducing the industry's environmental impact and aligning with global sustainability goals. Innovations in raw materials, energy efficiency, carbon capture, and recycling provide feasible pathways for achieving this transition. The publication highlights the urgent need to implement modern purification technologies in the cement industry. The publication describes the innovative approaches in the field, namely Low-Carbon Clinker Substitutes, Utilization of Industrial By-products, Energy Efficiency, Carbon Capture and Storage.

By embracing circular economy principles, the cement industry can significantly reduce CO_2 emissions, conserve natural resources, and create a more sustainable future. The path to a sustainable and circular cement industry is paved with innovative technologies and practices that reduce carbon emissions, enhance energy efficiency, and promote the use of alternative materials and fuels. While significant progress has been made, continued efforts are necessary to fully realize the potential of these advancements. By embracing these innovations and integrating them into a cohesive strategy, the cement industry can play a pivotal role in achieving global sustainability goals and mitigating the impact of climate change. The transition to a greener future is not only feasible but imperative for the long-term prosperity of both the industry and the planet.
Continued research, supportive policies, and industry collaboration are essential to drive this transformation.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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