

A REVIEW ON LIFE CYCLE ENVIRONMENTAL IMPACT ASSESMENT OF ORDINARY PORTLAND CEMENT PRODUCTION IN SOUTH AFRICA: MITIGATION STRATEGIES AND SUSTAINABLE PRACTICES

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ABSTRACT

In South Africa, a bag of Ordinary Portland Cement (OPC) does not just build houses, it quietly damages the environment too. The production chain is heavy on energy use, very fossil-fuel hungry, and this review paper walks through the whole life cycle of OPC to see what that really means in terms of greenhouse gas emissions, energy consumption, resource depletion and toxicity. Recent studies report that every 1 kg of OPC manufactured release about 0.993 kg of CO₂ equivalent, and around 98.8% of that is actually real CO₂. The clinker-making stage are basically the main primary contributor here. It is the moment in the story where most of the emissions happen. On top of that, the process deepens resource shortage, since roughly 0.139 kg of oil equivalent is used for every kilogram of cement produced. Toxic releases, including 1,4-Dichlorobenzene equivalents, add another dark layer to the plot, posing serious environmental and health risks, with end-point analysis suggesting a massive potential damage: more than 55,000 human life cases threatened each year and about 133 species at risk. The economic side is not so calm either, with a possible marginal price increase of about ZAR 6.2 billion linked to resource depletion alone. So, the story this review tells is quite clear: the South African cement industry is in urgent need of more holistic environmental assessments. A stronger mitigation approach is needed to push down the environmental burden of OPC production, for example by bringing in alternative materials and more effective energy-saving practices. The overall findings are expected to guide policy makers, industry people and researchers who are trying, maybe slowly but seriously, to move South African cement production toward something that actually looks like sustainable.

Keywords: *Portland Cement; Life Cycle Assessment; Environmental Impact.*

1. INTRODUCTION

The construction sector plays a massive role in shaping the environment, sometimes in good ways, sometimes not so much. Cement production sits right at the center of this story, acting as one of the biggest sources of carbon emissions and heavy energy use (Ige & Olanrewaju, 2023; Sbahieh et al., 2025). In South Africa, the demand for Ordinary Portland Cement has kept rising almost stubbornly largely because underground mining operations now rely more on cemented paste backfill (Zhang et al., 2023). But this growth comes with a cost. A serious one. The more OPC we make, the more environmental pressure we create, since its production is incredibly energy-intensive.

So, understanding the full life cycle of OPC from digging raw materials out of the ground to the final bag leaving the factory is absolutely necessary if South Africa wants meaningful solutions (Ige et al., 2022). This review therefore aims to explore practical mitigation strategies and sustainable options tailored to the South African context, trying to soften OPC's heavy environmental footprint, especially its greenhouse gas emissions and resource depletion issues (Firoozi et al., 2025; Liu et al., 2023). And since the global cement industry alone accounts for roughly 27% of total direct CO₂ emissions, the question becomes obvious: how can South Africa shift toward carbon neutrality? (Dahanni et al., 2023; Khaiyum et al., 2023).

Answering that requires looking closely sometimes uncomfortably at current production methods, experimenting with alternative raw materials, and adopting high-efficiency technologies that match worldwide decarbonization goals. This review focuses exactly on that: understanding South Africa's cement production through life cycle assessments, identifying environmental hotspots, and evaluating possible mitigation strategies that might actually work.

The reality is harsh. Cement kilns operate at 1300–1450 °C, and that massive energy demand seriously boosts the carbon intensity of the process (Uratani & Griffiths, 2023). The two biggest emission sources are well-known: burning fossil fuels to heat rotary kilns and the chemical calcination reaction inside clinker production (Antunes et al., 2021). Before 2013, OPC production alone contributed nearly 5–7% of global anthropogenic CO₂ emissions, driven mainly by these exact processes (Batuecas et al., 2021). Not surprisingly, this places the industry at the heart of sustainability discussions worldwide (Generowicz & Kulczycka, 2025).

About half of the emissions come directly from calcination, another 40% from pyro-processing, and the final 10% from raw material mining and transportation (Althoey et al., 2023). Reducing these layers of emissions requires innovation new clinker technologies, strong carbon-capture systems, and serious policy interventions (Antunes et al., 2021; Dagnachew et al., 2021). And again, cement kilns' extreme energy needs continue to intensify the sector's total environmental burden (Dahanni et al., 2023).

This makes it urgent no, unavoidable to review the environmental impact of OPC production in South Africa so that effective mitigation strategies can be implemented (Santamouris & Vasilakopoulou, 2021). Decarbonizing cement production requires advanced strategies and bold steps (Oguntola & Simske, 2023) (Kumar et al., 2025). Cement alone accounts for roughly 8% of global emissions, mostly tied to limestone calcination, which forms about 80% of clinker's raw material (Durastanti & Moretti, 2020; Qasim et al., 2025). As a result, making one ton of clinker releases about 0.83 tons of CO₂, and producing one ton of OPC releases around 0.54 tons about 5–8% of global greenhouse gases (Antunes et al., 2021).

Given these numbers, the industry is under increasing pressure especially in South Africa's energy-intensive economy to adopt safer, cleaner production pathways (Statham et al., 2014; Suarez-Riera et al., 2024). Innovation, new technology, and policy frameworks are essential (Ercan et al., 2023; Guo et al., 2021).

Therefore, this review aims to provide a comprehensive analysis of the literature on the life cycle impact of OPC production in South Africa, pointing out key environmental hotspots and evaluating how well current mitigation strategies actually work (Valente et al., 2021). This is a necessary step

toward building a sustainable cement industry aligned with national and global climate ambitions (Althoey et al., 2023; Ishak & Hashim, 2014)

Table 1: Composition of different concrete samples for [cubic meters](#) (Adapted from Monkman et al., 2022).

Concrete	Mix proportioning (kg/m ³)								
	Cement	FA	GGBS	SF	MK	Water	CA	FAG	HP
Cement	400	–	–	–	–	239	498	1154	–
FA	320	80	–	–	–	240	484	1122	–
GGBS	280	–	120	–	–	236	999	659	–
SF	280	–	–	70	–	210	963.8	782.3	1.42
MK	324	–	–	–	36	180	1160	681	–

2. LITERATURE REVIEW

This review pulls together insights from many studies and tries to form a clearer picture almost like assembling a puzzle about the environmental challenges tied to cement production, especially in South Africa’s industrial setting (Akintayo et al., 2024). A lot of the important studies use a cradle-to-gate boundary. It’s a mouthful, but basically it tracks everything from raw material extraction to the cement plant gate, giving a fuller story of what really happens behind the scenes (Ige et al., 2022). And honestly, these assessments matter because they expose the life cycle stages that hit the environment the hardest, which then helps guide smarter, more targeted interventions (Akintayo et al., 2024).

The cement industry, as we already know, is a big global CO₂ emitter around 5% of the total anthropogenic emissions mostly because of calcination and the burning of fuel inside kilns (Durastanti & Moretti, 2020; Ige et al., 2022). And in places like Saldanha Bay, South Africa, where industrial operations consume huge amounts of energy, the cement sector’s contribution becomes even heavier, almost unavoidable (Un-Habitat, 2011). This makes it very clear that South Africa must adopt transformative technologies and strong policy frameworks that push the sector towards decarbonization, in line with global net-zero plans (Türkiye’s 2053 Long-Term Climate Strategy, 2023). To do that, renewable energy use in the sector needs to go up. Like seriously up. And policy tools such as limiting clinker ratios in public procurement may be needed too (Türkiye’s 2053 Long-Term Climate Strategy, 2023).

Energy is another big piece of the story. Increasing renewable energy in the cement production chain can significantly reduce reliance on fossil fuels (Khaiyum et al., 2023). These changes support wider efforts aimed at enhancing building energy efficiency and reducing emissions across the entire construction sector part of the global push toward low-carbon living (Ke et al., 2023). Achieving net-zero emissions will require a combination of approaches: improving fuel efficiency, cutting clinker ratios, using more supplementary cementitious materials, and developing alternative binders like geopolymers (Raveendran & Vasugi, 2025).

Waste-derived binders, like those from steel slag or magnesium slag, are gaining attention too because they do two things at once: utilize industrial waste and sequester CO₂ (Huang et al., 2025). But achieving net-zero isn’t simple hard-to-abate sectors like cement need both advanced technology and comprehensive policy frameworks to pull it off (Türkiye’s 2053 Long-Term Climate Strategy, 2023) (For this, exploring low-CO₂ technologies such as alternative clinker, supplementary cementitious

materials, and CCUS systems becomes essential (Barbhuiya et al., 2024). Novel ideas like alkali-activated cements, calcium looping, and even bio-inspired materials are part of this roadmap (Barbhuiya et al., 2024).

At optimal contents (usually 1–2 wt.%), biochar improves compressive and flexural strength, durability, and even shrinkage resistance (Lin et al., 2023; Osman et al., 2023). Its porous structure supports internal curing, boosts hydration, and helps create a denser cement matrix (Khan et al., 2022; Patel et al., 2025). Studies show that certain types of biochar can increase splitting tensile strength and fracture energy while reducing permeability (Osman et al., 2023). But the performance varies depending on the feedstock, pyrolysis temperature, and particle size, meaning the “perfect mix” is still under research (Suarez-Riera et al., 2023). Higher biochar dosages sometimes reduce compressive strength or workability, so balance is everything (Khan et al., 2022; Osman et al., 2023).

Overall, biochar’s role remains promising but complex. It shows real potential for improving sustainable construction and carbon mitigation, though more efficient and cost-effective technologies are still needed to fully unlock its benefits (Ye et al., 2025).

In midpoint environmental impact studies, flows are grouped by category around 18 in total. These categories help simplify complex interactions by linking production stages like clinker formation, raw material use, electricity usage, fuel combustion, and transportation to specific environmental impacts. Figure 2, for instance, illustrates how these five processes each contribute to multiple impact categories, with clinker production unsurprisingly dominating due to calcination and fuel burning.

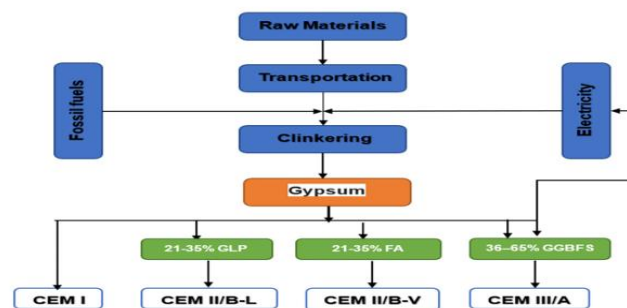


Figure 1: System boundary of portland cement production in South Africa (Adapted from Ige & Olanrewaju, 2023).

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Developing lower-carbon cement alternatives and integrating recycled materials into concrete are also promising ideas, offering ways to shrink both embodied energy and the overall carbon footprint of construction materials (Barbhuiya et al., 2024; Firoozi et al., 2025). The cement industry consumes massive raw materials and energy, so any reduction matters (Salas et al., 2015). Substituting part of the cement with supplementary cementitious materials say fly ash can cut global warming potential by up to 25% (Tran et al., 2025). Calcined clays, slag, and other alternatives broaden these options even further (Kumar et al., 2025). There's even research showing that biochar, added as a fine aggregate replacement, can create carbon-negative concrete, reducing emissions by roughly -60 kg CO₂ per ton (Sun et al., 2025). And geopolymers cements, which use industrial by-products, appear as another strong candidate for cutting embodied carbon (Khaiyum et al., 2023) (Firoozi et al., 2025).

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Carbon capture technologies also play a central role. They can suppress emissions from both calcination and combustion, offering a deep decarbonization path that almost feels like the industry's necessary lifeline (Suarez-Riera et al., 2024). Circular economy ideas are gaining traction too, promoting full-cycle solutions that reduce environmental impacts by using waste streams more efficiently (Althoey et al., 2023) (Barbhuiya et al., 2024). Using fly ash, slag, and limestone to replace portions of cement can cut emissions by up to 40% while still maintaining structural performance (Jessa & Ajidahun, 2024). Meanwhile, carbonation curing technology lowers CO₂ emissions by about 15% during production, adding another meaningful option to the sustainability toolkit (Tran et al., 2025).

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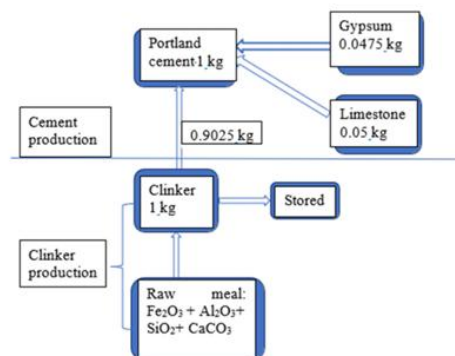


Figure 2: Material flow diagram for the production of 1 kg of Portland cement (Adapted from Akintayo et al., 2024).

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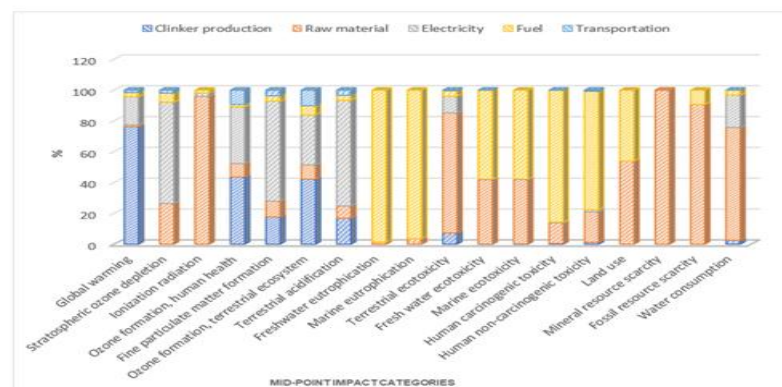


Figure 3. Contribution of five production processes to impact categories (Adapted from Akintayo et al., 2024).

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3. DISCUSSION

This discussion also dives deeper into how biochar actually behaves inside construction materials. Kind of like following its journey, from waste to something more useful (Khan et al., 2022; Osman et al., 2022, 2023). When biochar made from agricultural waste gets blended into cementitious mixes, it does more than just sit there. It becomes active. It provides a real pathway for carbon sequestration while boosting important mechanical features like compressive and flexural strength, toughness, and even thermal stability (Khan et al., 2022). Some studies tell a pretty interesting story: finely ground biochar, added in the right amounts, can seriously improve flexural strength. But push it too far, and the benefits start fading away (Osman et al., 2023).

Biochar also grabs CO₂. Literally. One study showed a 6% CO₂ uptake after 28 days of accelerated curing with just 10 wt.% biochar plus a 24.2% jump in compressive strength, which is honestly impressive (Kushwah et al., 2024). And because biochar is so porous, it carries tiny reservoirs of water. These act like "water-pockets" during curing, releasing moisture slowly and improving hydration, making the cement matrix tighter and stronger (Patel et al., 2025).

Still, there are cautions. While biochar usually increases mechanical strength, too much of it can actually reduce compressive strength. It's a balance issue. This is why some researchers suggest high-pressure compression methods for particleboard-like applications where higher proportions are used (Sun et al., 2025). The enhanced surface area and incredibly small particle size also help. They fill gaps between aggregates, intensifying the formation of cement hydrates, giving the concrete a beneficial filler effect and an overall denser structure (Khan et al., 2022).

Optimal ranges matter a lot here. Usually 1–2 wt.% works best, giving noticeable improvements in compressive and flexural strength. There's even evidence showing that adding 2% wood sawdust biochar increases splitting tensile strength significantly (Biochar for Agronomy... n.d.; Lin et al., 2023). More detailed findings show that specimens incorporating 0.8% and 1% softwood biomass biochar pyrolyzed at 800 °C had higher flexural strength and fracture energy compared to regular cement composites (Osman et al., 2022). Internal curing from water stored in biochar pores further enhances compressive and splitting strengths over time (Ling et al., 2023).

But again, dosage is critical. Biochar amounts above 2% tend to reduce hardened density and may lower ductility. Its inherent brittleness can even lead to microcrack formation if not managed well (Akinyemi & Adesina, 2020; Osman et al., 2022). So, the story remains clear: biochar is powerful, but only when balanced carefully within the mix.

still a critical need to fine-tune things like particle size, dosage levels, and the right pyrolysis conditions to unlock biochar's full potential without running into its weaknesses (Khan et al., 2022; Ling et al., 2023).

Future studies must dig deeper into life cycle assessments of biochar-modified concrete within the South African context. This isn't optional it's essential for understanding the actual environmental footprint across different applications. Such insights would give policymakers and industry leaders stronger tools to build proper standards for biochar use in construction. Something South Africa urgently needs. More research into long-term durability under the region's unique climate conditions is also important, because real-world environments can be harsh and unpredictable (Osman et al., 2022). And different feedstocks will behave differently too, meaning they need to be studied carefully across multiple South African climate zones.

Exploring nano biochar could be the next big leap. These ultra-fine materials may reshape the microstructure of cement composites, reduce reliance on Portland cement, and ultimately shrink embodied carbon even further (Akinyemi & Adesina, 2020). But research about economic feasibility is also needed. Biochar production from local waste streams must be affordable, scalable, and sustainable for widespread adoption to really take off in the construction industry. Understanding the physical and chemical interactions between various biochar sources and cement components is another essential piece without this, the full picture remains incomplete (Akinyemi & Adesina, 2020).

More studies focusing on long-term durability and performance will strengthen confidence in biochar-based composites and help push them further into mainstream construction (Akinyemi & Adesina, 2020). And importantly, biochar isn't just a mechanical enhancer. It can replace traditional aggregates, lower weight, provide thermal insulation, and even pull CO₂ straight from the air turning buildings into carbon-storing structures (Osman et al., 2022). This dual benefit makes biochar a serious contender for helping decarbonize the built environment (Osman et al., 2023).

5. DECLARATION OF USE OF AI

The authors declare that ChatGPT (version 5.2), an AI-based language model developed by OpenAI, was used during the preparation of this manuscript for the purpose of improving grammar, language clarity, and overall readability. The AI tool was not used in the research design, data collection, analysis, interpretation of results, or generation of scientific content.

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