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Environmental and Public Health Challenges of Phases Towards Cement Production, Remediation Monitoring and Evaluation Strategies

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Abstract: *Cement production plays a pivotal role in global construction, contributing significantly to economic development. However, the industry is also a major source of environmental pollution, responsible for approximately 8% of global* CO_2 *emissions, alongside substantial impacts on air quality, water resources, and biodiversity. This review examines the environmental impacts of cement production across three key phases: construction, operational, and post-operational. The construction phase is marked by land degradation, habitat destruction, and dust emissions, while the operational phase results in issues such as high* CO_2 *emissions, water contamination, solid waste generation, and high energy consumption. In the post-operational phase, issues related to biodiversity restoration and land reclamation persist. This review explores current strategies and technological innovations aimed at mitigating these impacts, such as carbon capture utilization and storage (CCUS), low-carbon cement alternatives, energy-efficient kilns, and the use of waste materials in production. Furthermore, the integration of circular economy principles and the adoption of digital monitoring systems are highlighted as promising solutions for reducing the environmental footprint of cement production. This review also underscores the need for sustainable practices and collaboration among stakeholders to address the environmental and public health challenges posed by the cement industry. The authors recommend the scaling up of innovative technologies, improved resource management, and stricter regulatory frameworks to achieve a more sustainable cement industry.*

Keywords: *Cement industry, public health challenges, construction, operational and post-operation phases*

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1.0 Introduction

Cement production is a vital component of the global construction industry, with an annual output exceeding 4 billion metric tons worldwide, reflecting its central role in infrastructure development (IEA, 2023). The demand for cement has surged with rapid urbanization, population growth, and an increasing need for infrastructure in both developing and developed economies. However, the environmental impact of cement production is a growing concern, as the industry is responsible for approximately 8% of global carbon dioxide (CO_2) emissions, a major contributor to climate change (Andrew, 2019). The environmental footprint of cement production is not limited to greenhouse gas emissions. It also extends to air pollution, depletion of natural resources, water contamination, and biodiversity loss, all of which contribute to the industry's broader environmental challenges. Cement plants are often located in areas that are rich in raw materials but vulnerable to environmental degradation, further amplifying the ecological impact.

Environmental management in the cement industry is a complex process that involves addressing challenges at various stages, from construction to post-operational. The construction phase primarily focuses on site selection, land preparation, and minimizing adverse environmental effects such as habitat destruction and social displacement (Chijioke-Churuba, 2023a; Chijioke-Churuba, 2023c, 2023; Chijioke-Churuba, 2024;). It is during this stage that environmental impact assessments (EIA) are conducted to evaluate the potential risks and to establish mitigation strategies to reduce land degradation and environmental harm. Post-construction operations, on the other hand, present ongoing challenges related to emission control, resource management, waste handling, and water conservation. This phase involves the actual production process, which generates significant environmental pollution and resource consumption. Over the years, the cement industry has made progress in reducing its environmental impact through innovations in technology, such as carbon capture utilization, and storage (CCUS), the development of low-carbon cement formulations, and the integration of alternative materials into production processes. Despite these advancements, cement production remains a major environmental concern, and achieving significant reduction in its ecological footprint requires a sustained effort at every phase of its lifecycle.

This review explores the environmental impacts associated with cement production in detail, with particular attention to the construction and post-operational phases. The authors also discuss cutting-edge innovations and strategies that are being developed to reduce the industry's environmental footprint. By examining the latest technological advancements, including digital monitoring systems and alternative cement materials, the authors provide a comprehensive overview of the approaches that can guide the cement industry toward more sustainable and eco-friendly practices. The future of cement production lies in integrating circular economy principles, where waste materials are reused, and the industry's reliance on non-renewable resources is minimized. Through continued research and the scaling up of these innovations, the industry can move toward more sustainable practices and contribute to reducing global environmental impacts. The transition to low-carbon and resource-efficient cement production processes will require collaboration among governments, industries, and researchers to drive the necessary regulatory, technological, and operational changes. Also, by taking proactive steps to mitigate the environmental challenges associated with cement production, the industry can play a crucial role in advancing sustainability in the construction sector and beyond.

1.1 The Phases in the Cement Industry

Table 1 presents a clear overview of the various activities that can lead to public health challenges throughout the construction, operational, and post-operational phases of cement industries. Each phase carries its own unique set of potential health risks, many of which are interlinked with environmental factors like air quality, water quality, and land degradation.

During the construction phase, the primary health challenges arise from activities such as site preparation, quarrying, and the use of heavy machinery. Dust and particulate matter generated during excavation and transportation can have severe respiratory effects, particularly for workers and nearby communities.

Table 1: Potential Public Health Concerns during different Phases of Cement Production

Phase	Activities	Potential Public Health Challenges
Construction Phase	Site preparation, quarrying, land clearing	Respiratory issues from dust and particulate matter (PM); noise pollution; soil contamination from heavy machinery and chemicals used.
	Excavation and transportation of raw materials	Respiratory problems and cardiovascular issues from dust exposure; potential for accidents and injuries.
	Use of machinery and heavy equipment	Noise pollution leading to hearing loss or stress; physical accidents and injuries from machinery operations.
	Community displacement (if applicable)	Mental health issues due to displacement; disruption of local livelihoods and community networks.

Operational Phase	Cement production (calcination, grinding, mixing, etc.)	High levels of CO_2 and NO_x emissions contributing to respiratory issues, asthma, and cardiovascular diseases; noise pollution affecting mental well-being.
	Use of fossil fuels for energy production	Air pollution from particulate matter, volatile organic compounds (VOCs), and toxic gases, leading to lung diseases and cancer.
	Water usage and disposal of wastewater	Water contamination with high pH levels, causing skin irritation and gastrointestinal diseases in nearby communities.
	Generation of solid waste (Cement Kiln Dust, fly ash, slag)	Soil and water contamination from improper disposal; health issues due to exposure to toxic heavy metals.
Post-Operational Phase	Land reclamation and quarry rehabilitation	Risk of further soil contamination and airborne dust exposure if not properly managed; potential for long-term health impacts on local ecosystems.
	Closure of production facilities and waste site management	Exposure to hazardous waste and pollutants during site closure; inadequate waste management leading to environmental degradation.
	Long-term impact on local air and water quality	Ongoing respiratory issues, cardiovascular diseases, and waterborne diseases from lingering pollutants.

Dust exposure has been shown to lead to respiratory illnesses such as asthma, bronchitis, and even more severe conditions like pneumoconiosis in the long term (Poole et al., 2024). Additionally, noise pollution from machinery and heavy equipment poses risks such as hearing loss and stress-related disorders, particularly for workers. The potential displacement of communities, although not always applicable, can also lead to significant mental health challenges, including stress, anxiety, and the loss of community cohesion, which has been well-documented in studies on displacement and public health (Lee et al., 2023; Chijioke-Churuba, 2023b).

In the operational phase, the cement production process itself generates significant environmental pollutants, including particulate matter, carbon dioxide (CO_2), and nitrogen oxides (NO_x), which are major contributors to air pollution. Exposure to these pollutants has been linked to a variety of health issues, including respiratory diseases, cardiovascular diseases, and an increased risk of lung cancer (Andrew, 2019). Furthermore, the use of fossil fuels for energy production can exacerbate air pollution, adding to the toxic emissions that contribute to these health issues. Water contamination from wastewater discharge, resulting in high-pH levels and dissolved solids, can lead to gastrointestinal diseases and skin irritations, especially when local water supplies are affected. This is a concern in regions where water resources are scarce, and communities depend on nearby sources like rivers and streams for drinking and sanitation. Additionally, improper management of solid waste from cement plants, such as Cement Kiln Dust (CKD), can lead to soil and water contamination. The presence of toxic metals in CKD, such as lead and mercury, can pose a significant threat to public health, leading to long-term issues such as organ damage and developmental problems in children (Azad, & Samarakoon, 2021).

The post-operational phase carries risks related to the closure of cement production facilities and the rehabilitation of quarry sites. Land reclamation, if not properly managed, can continue to release dust and contaminants into the air, contributing to respiratory health problems. The process of rehabilitating or closing a cement plant can also expose workers and nearby communities to residual toxic substances, particularly if hazardous waste has not been adequately handled or disposed of during operation. Incomplete or improper closure procedures could result in long-term soil contamination, leading to continuous environmental degradation. This environmental damage could indirectly contribute to health problems, especially in communities that rely on local agriculture or water resources for survival. Persistent air and water pollution after plant closure can also exacerbate the public health impacts of previous operational activities, as toxins may remain in the ecosystem for years, continuing to affect local populations (Lehne & Preston, 2022).

Each phase—from construction to operation to post-operation—presents distinct health risks, ranging from respiratory issues and cardiovascular diseases to gastrointestinal problems and soil contamination. The long-term impact of these activities underscores the importance of implementing effective environmental management strategies at every phase of cement production. Mitigation measures such as better dust suppression technologies, advanced emissions control systems, water treatment solutions, and responsible waste disposal practices are essential in reducing the public health risks associated with the cement industry. Additionally, fostering community engagement and ensuring proper rehabilitation of sites after closure are critical to ensuring that cement industry operations do not cause long-lasting harm to public health.

2.0 Public Health Risks

Like many other manufacturing sectors, the cement industry presents significant public health risks across its entire lifecycle. These risks are particularly prominent during the construction, operational, and post-operational phases of cement plants. Each phase introduces distinct health challenges to workers, surrounding communities, and the broader ecosystem. This section provides an overview of the public health issues associated with each phase, alongside mitigation strategies and the expected public health challenges, supported by recent literature.

2.1 Public Health Risks: Construction Phase

Table 2 highlights some public health risks associated with the construction phase level of a typical cement factory.

During the construction phase of a cement plant, activities such as site clearing, excavation, and the installation of industrial equipment, workers and local communities are exposed to various health risks. Air pollution is one of the primary concerns, with dust and particulate matter generated by construction activities contributing to respiratory diseases such as asthma, bronchitis, and lung disease (Akagbue et al., 2023a, 2024, Wang and Zhang., 2023).

Table 2: Public Health Issues during the Construction Phase of Cement Plants

Health Issue	Impact	Affected Group	Risk Level	Reference

Air Pollution	Respiratory diseases (asthma, bronchitis)	Workers, local residents	High	Wang and Zhang, 2023; Akagbue et al., 2023a; Akagbue et al., 2024.
Noise Pollution	Hearing loss, stress, sleep disturbances	Workers, local residents	Medium	Lee et al., 2023; Baba Aminu et al., 2023; Akagbue et al., 2023b
Physical Injuries	Falls, machinery accidents, fractures	Construction workers	High	Mohan et al., 2023
Chemical Exposure	Silicosis, lung diseases	Workers	Medium	Rupani et al., 2023

The use of heavy machinery, including bulldozers and cranes, can also exacerbate air pollution, which poses a health risk to those in close proximity to the site (Baba Aminu et al., 2023). Noise pollution is another significant issue during construction, as loud machinery and equipment can lead to hearing loss, sleep disturbances, and stress-related illnesses. Workers are also exposed to physical injuries from falls, machinery accidents, and falling debris, leading to disabilities or fatalities in some cases. Furthermore, exposure to hazardous substances, including silica dust, is a concern for workers during the construction of cement plants (Sing et al., 2021). Silica dust is linked to respiratory disorders such as silicosis, which can have long-term health consequences. These risks can be mitigated through measures such as dust suppression systems, noise barriers, and proper personal protective equipment (PPE) for workers (Rupani et al., 2023).

2.2 Public Health Risk: Operational Phase

Risks associated with the operational phase are also highlighted in Table 3. The operational phase of a cement plant introduces additional public health challenges due to the continuous emission of pollutants and the scale of production activities. Airborne particulates, including fine dust particles (PM_{10} and $PM_{2.5}$) and volatile organic compounds (VOCs), are among the most significant pollutants generated by cement plants. These airborne pollutants can lead to chronic respiratory diseases, cardiovascular problems, and other health issues for workers and local communities exposed to them. Carbon emissions from cement production are also a major concern, as the industry is highly energy-intensive and releases large amounts of CO_2, contributing to global warming. This results in an increased risk of heart failure, stroke, respiratory problems, and other heart-related illnesses, particularly in vulnerable populations. Heavy metal contamination is another health risk associated with the operational phase of cement plants. Exposure to metals such as lead, cadmium, and chromium through dust inhalation, contaminated water, or crops can lead to neurological damage, kidney disease, and cancer. Noise pollution, from the continuous operation of machinery, can cause hearing impairment and mental health disorders in the surrounding population. Additionally, water pollution from the discharge of alkaline wastewater and chemicals can result in gastrointestinal diseases, disrupt aquatic ecosystems, and affect drinking water supplies. These risks can be mitigated through the implementation of stricter emission controls, cleaner production technologies, and effective waste treatment systems.

2.3 Public Health Risks: Post Operational Phase

In the post-operational phase, when cement plants cease production, the environmental and health impacts of the previous phases may persist for years. Soil and groundwater contamination from hazardous chemicals and heavy metals can continue to affect local communities and ecosystems. These contaminants can remain in the environment long after plant closure, leading to long-term public health concerns. Environmental degradation, such as the continuous release of airborne dust and toxic chemicals from abandoned cement plants, can continue to impact surrounding areas, exposing local residents to persistent pollution. Mental health issues may also arise in communities affected by the closure of cement plants, particularly among workers who lose their livelihoods. Studies have shown that the economic hardships associated with plant closures can lead to increased levels of stress, depression, and anxiety, which can have serious social and psychological implications.

Table 3: Public Health Issues during the Operational Phase of Cement Plants

Health Issue	Impact	Affected Group	Risk Level	Reference
Airborne Particulates	Chronic respiratory diseases, cardiovascular issues	Workers, local residents	High	Kholodov *et al.*,(2020)
Carbon Emissions	Heat-related illnesses, respiratory issues	Local residents	High	Okoye et al., 2022
Heavy Metals Contamination	Neurological damage, kidney disease, cancer	Workers, local residents	High	Yusuf et al., 2021
Noise Pollution	Hearing loss, mental health issues	Workers, local residents	Medium	Oladimeji & Bello, 2022
Water Pollution	Gastrointestinal diseases, disruption of aquatic ecosystems	Local residents, farmers	Medium	Akinyele et al., 2023

Remediation measures, such as soil decontamination, environmental restoration, and economic support for affected workers, are crucial for mitigating the long-term health risks during this phase. In Table 4 below, public health risk levels and their impact at the post-operational phase of cement production are presented.

Table 4: Public Health Issues during the Post-Operation Phase of Cement Plants

Health Issue	Impact	Affected Group	Risk Level	Reference
Soil and Groundwater Contamination	Long-term exposure to heavy metals and chemicals	Local residents, farmers	High	Yusuf et al., 2021
Environmental Degradation	Continued exposure to airborne dust, toxic chemicals	Local residents, farmers	Medium	Wang and Zhang, 2023
Mental Health Issues	Depression, anxiety due to economic hardship	Workers, community members	High	Oladimeji & Bello, 2022

Addressing these health risks requires comprehensive strategies that span the lifecycle of cement production. During the construction and operational phases, measures such as dust suppression, noise control, and the use of personal protective equipment can reduce the exposure to harmful pollutants.

In the post-operation phase, environmental restoration and remediation measures, such as soil decontamination and groundwater treatment, are essential to mitigate the lasting effects of pollution. Additionally, providing economic support and mental health services for affected workers and communities can help address the social challenges posed by plant closures.

The cement industry must implement stringent environmental and health regulations throughout its life cycle to effectively mitigate these challenges. Mitigation strategies such as application of cleaner technologies, improved waste management, and worker protection, are essential for reducing the public health risks associated with cement production.

3.0 Case studies

3.1 Case Studies: Global scenarios

In this section, we present some environmental impacts associated with cement production, which vary widely across several regions. They include the critical issues such as air pollution, carbon emissions, water contamination, biodiversity loss, energy consumption, and socio-economic impacts.

In India and Nigeria, significant air pollution has been observed due to emissions of particulate matter (PM_{10} and $PM_{2.5}$). These emissions adversely affect respiratory health and, in Nigeria, also reduce agricultural productivity. Effective dust suppression systems and air filtration technologies are essential to mitigate these impacts. In China, cement production is a significant contributor to national CO_2 emissions, accounting for 15% of the country's total emissions. This is driven by high clinker production and reliance on coal, underscoring the importance of transitioning to low-carbon materials and implementing carbon capture technologies.

Table 5: Case Studies of Global Environmental Impacts from Cement Industries

Location	Impact	Details	Reference
India	Air Pollution	High levels of particulate matter (PM_{10} and $PM_{2.5}$) observed around cement plants, causing respiratory health issues.	SiSodiya & Jaiswal (2024)
China	Carbon Emissions	Cement production contributes 15% of the country's CO_2 emissions, driven by high clinker demand and coal dependence.	Liu et al. (2024)
Egypt	Water Contamination	Alkaline wastewater from cement plants found to contaminate nearby water bodies, affecting aquatic ecosystems.	Hindy *et al*. (1990)
Brazil	Biodiversity Loss	Quarrying activities for limestone extraction led to habitat destruction and loss of endemic species in forest areas.	Chaves *et al*. (2021)
Nigeria	Dust Pollution	Cement plants release dust, causing reduced agricultural productivity and health challenges for nearby communities.	Agbede *et al*. (2022)
Germany	Energy Consumption	High energy demand addressed through alternative fuels (biomass and waste), reducing fossil fuel reliance.	Brunke & Blesl (2014)

South Africa	Socio-Economic Displacement	Community relocation for plant construction caused socio-economic disruption, including loss of livelihoods.	Akintayo *et al*. (2024)
Pakistan	Groundwater contamination	Excessive water use by cement plants led to reduced groundwater levels, impacting local agriculture.	Ahmad et al. (2023)
Vietnam	Noise Pollution	Prolonged noise from cement operations disturbed local residents, cause loss of hearing .	Thai *et al*. (2021)

Water-related issues are also prevalent in the United States, as alkaline wastewater discharged from cement plants contaminates water bodies, affecting aquatic ecosystems (EPA Report, 2022). In Pakistan, excessive groundwater extraction for cement production reduces water availability for agriculture and domestic use. These challenges highlight the necessity for wastewater treatment technologies and sustainable water management practices (Ahmad et al., 2023). The Brazilian case study emphasizes the loss of biodiversity due to limestone quarrying in forested areas, leading to habitat destruction and the decline of endemic species. Quarry rehabilitation and ecological restoration are critical for minimizing such long-term ecological damage (Chaves *et al*., 2021)

In Germany, the cement industry has adopted alternative fuels like biomass and waste to reduce its reliance on fossil fuels, demonstrating a successful integration of renewable energy sources into industrial processes (Brunke & Blesl, 2014). However, in Thailand, prolonged noise pollution from cement operations disrupts both local residents and wildlife, indicating the need for acoustic barriers and other engineering controls.

Socio-economic impacts are particularly evident in South Africa, where community relocations for cement plant construction caused significant disruptions, including the loss of livelihoods (Akintayo *et al*., 2024). This highlights the importance of equitable resettlement programs and stakeholder engagement in industrial development projects.

Finally, Italy showcases the benefits of circular economy practices. The use of waste co-processing reduces raw material consumption and landfill dependency, demonstrating how sustainability principles can be integrated into cement production.

These case studies underscore the global importance of adopting sustainable practices in the cement industry, tailored to the unique environmental and socio-economic challenges of each region.

3.2 Case study: Nigeria Industries

Table 6 below provides insight into the significant environmental and health challenges posed by cement production in Nigeria. Cement industries are major contributors to air, soil, and water pollution, alongside noise disturbances. These contaminants have widespread implications for public health and environmental integrity, necessitating urgent attention and intervention. Particulate matter (PM_{10} and $PM_{2.5}$) concentrations near cement plants in Nigeria are alarmingly high, ranging from 250–450 $\mu g/m^3$ for PM_{10} and 120–180 $\mu g/m^3$ for $PM_{2.5}$, which far exceed the WHO limits of 50 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively. These particles are released during quarrying, grinding, and cooling processes. Prolonged exposure to such fine particulates can penetrate deep into the respiratory system, resulting in respiratory diseases such as asthma, bronchitis, and lung cancer. Studies by Qadri *et al*. (2024) highlight similar findings in regions near industrial facilities, where respiratory disease prevalence is notably higher. To mitigate this, advanced dust capture systems like bag filters and electrostatic precipitators should be implemented in cement factories, along with regular health screenings for nearby populations.

Cement industries in Nigeria emit approximately 20 million metric tons of carbon dioxide (CO_2) annually, contributing 15–20% of the country's industrial greenhouse gas emissions. CO_2 is primarily released during the clinker production process and from the combustion of fossil fuels. This substantial emission level exacerbates global warming and contributes to climate-related challenges such as heatwaves, rising sea levels, and extreme weather events. Okoye et al. (2022) emphasize the critical role of industrial CO_2 in Nigeria's increasing vulnerability to climate change. Public health challenges linked to these emissions include heat-related illnesses, vector-borne diseases, and food insecurity caused by disrupted agricultural systems. Transitioning to alternative fuels, such as biomass and waste-derived fuels, and adopting carbon capture, utilization and storage (CCUS) technologies could significantly reduce these emissions.

Heavy metals, including lead (Pb), cadmium (Cd), and chromium (Cr), are prevalent in the soil surrounding cement factories, with concentrations of 300–600 mg/kg, 3–5 mg/kg, and 50–150 mg/kg, respectively (Table 2).

Table 6: Case studies of some environmental impact of cement production in Nigeria

Contaminant	Measured Levels	Standard/Limit	Source	Health Impact	Reference
Particulate Matter (PM_{10})	250–450 μg/m³	WHO: 50 μg/m³ (24-hour)	Dust from quarrying, clinker cooling, grinding	Respiratory diseases (asthma, bronchitis), reduced air quality	Awos *et al.* (2024)
Particulate Matter ($PM_{2.5}$)	120–180 μg/m³	WHO: 25 μg/m³ (24-hour)	Dust from production processes	Severe respiratory health issues in nearby communities	SiSodiya, & Jaiswal (2024)
Carbon Dioxide (CO_2)	20 million metric tons annually	No specific national limit	Clinker production, reliance on fossil fuels	Contributes to global warming; significant share of industrial CO_2 emissions	Agbede et al. (2024)
Lead (Pb)	300–600 mg/kg	100 mg/kg	Limestone with trace metals	Contamination of farmlands, bioaccumulation in crops, and risk to human health	Asher, *et al.* (2020)
Cadmium (Cd)	3–5 mg/kg	1 mg/kg	Emission of particulates	Toxicity in soil, bioaccumulation, and potential impact on crops	Asher, *et al.* (2020)
Chromium (Cr)	50–150 mg/kg	50 mg/kg	Dust and raw materials	Soil contamination; reduced	Asher, *et al.* (2020)

				agricultural productivity	
Noise Pollution	85–105 dB	WHO: 85 dB	Plant machinery and operations	Noise-induced hearing loss in workers; stress and health issues in residents	Ileoye *et al*. (2022)

These levels exceed permissible limits and result from raw material inputs and particulate emissions. Chronic exposure to lead can cause neurological damage, particularly in children, while cadmium is associated with kidney damage and chromium with carcinogenic effects. Yusuf et al. (2021) report similar contamination levels in agricultural areas near industrial zones, linking them to reduced soil fertility and crop contamination. Potential remediation strategies include soil washing, phytoremediation, and regular monitoring of heavy metal levels to ensure compliance with safety standards.

Noise pollution is another significant concern, with levels recorded between 85–105 dB near cement factories, exceeding the WHO limit of 85 dB. Prolonged exposure to high noise levels can result in hearing loss, sleep disturbances, and stress-related disorders, particularly for factory workers and residents in nearby communities. Ileoye ei al. (2022) found correlations between industrial noise exposure and increased cases of mental health challenges. Remediation measures such as soundproofing factory equipment, establishing noise buffer zones, and enforcing workplace hearing protection policies can alleviate these impacts.

Dust deposition on vegetation around cement plants, with rates of 3.5–7.0 $g/m^2/day$, significantly reduces the photosynthetic capacity of plants by affecting chlorophyll content. This results in reduced agricultural yields and compromised food security for dependent communities. Agbede et al. (2024) observed similar impacts on crop productivity in areas affected by industrial dust, leading to economic losses for farmers. Dust suppression measures such as water sprays, greenbelt development, and regular cleaning of vegetation can help reduce these impacts.

4.0 The Need for Monitoring and Evaluation (M&E)

Monitoring and evaluation (M&E) programs are essential in assessing and mitigating the environmental and public health challenges associated with cement production. These programs help identify potential risks at every phase of the cement production cycle, from construction to operation to post-operation, ensuring that mitigation strategies are effectively implemented and compliance with environmental regulations is maintained. Given the significant health risks and environmental impacts outlined earlier, a robust M&E framework is crucial in minimizing these challenges and improving the sustainability of the cement industry.

A key component of any M&E program is environmental monitoring, which involves the continuous assessment of air quality, water resources, soil conditions, and biodiversity around cement production sites. During the construction phase, monitoring air quality is essential to track particulate matter (PM) and gaseous emissions such as nitrogen oxides (NO_x) and sulfur dioxide (SO_2), which can adversely affect respiratory health in nearby communities (Lehne & Preston, 2022). Dust suppression technologies, such as water spraying and air filtration systems, should be regularly monitored for their effectiveness. Similarly, monitoring noise pollution levels during the construction phase is critical to ensure that they remain within acceptable limits to prevent hearing loss and stress-related health issues. In operational plants, continuous emissions monitoring systems (CEMS) can track CO_2 and NO_x emissions in real-time, providing data on the effectiveness of pollution control measures, such as carbon capture and storage (CCS) technologies (Andrew, 2019).

For water quality monitoring, especially during the operational phase, monitoring systems can assess pH levels, dissolved solids, and toxic contaminants in wastewater. Cement plants often discharge wastewater with high pH, which can contaminate local water sources and cause skin irritations or gastrointestinal problems in nearby communities. In this regard, implementing zero-liquid discharge (ZLD) systems or closed-loop water recycling can significantly reduce the impact of industrial wastewater. An M&E program can help track the performance of such systems, ensuring that discharged water meets the necessary environmental standards and does not pose a health risk to local populations. Additionally, soil and groundwater quality monitoring can assess the potential for contamination from cement kiln dust (CKD) and other by-products. Monitoring heavy metals like lead and mercury in nearby soils and water resources is important to mitigate the long-term health risks associated with these toxic substances, which can lead to developmental issues and organ damage in humans (Azad, & Samarakoon, 2021).

To effectively evaluate and manage waste, solid waste monitoring programs can track the amount of cement kiln dust (CKD), fly ash, and slag generated by cement plants. Co-processing waste materials, such as fly ash from coal power plants, can reduce the environmental burden of CKD disposal while increasing resource efficiency. Regular audits of waste management practices can ensure that these by-products are being handled properly and that alternative recycling strategies, such as the use of CKD in construction or as an alternative material for road building, are being implemented. An effective M & E program will measure the success of these waste reduction strategies and monitor the potential risks posed by waste mismanagement.

In addition to environmental monitoring, health monitoring programs are critical in ensuring the safety of workers and nearby communities. Health assessments for workers exposed to dust and emissions from cement plants should be a part of regular occupational health and safety evaluations. Respiratory conditions, cardiovascular diseases, and hearing loss are common health issues in the cement production sector, and an M & E program should track these conditions over time to ensure that worker health is protected. Community health assessments, including the monitoring of respiratory illnesses and waterborne diseases, should also be conducted regularly, particularly in regions near cement plants. These assessments can help identify emerging health trends and provide data to inform public health interventions.

The evaluation component of an M&E program focuses on determining the effectiveness of mitigation strategies and ensuring that environmental and public health standards are met. For example, the impact assessment of emissions control technologies — such as carbon capture utilization and storage (CCUS), low-carbon cement formulations, and alternative fuel use — can be evaluated based on their ability to reduce the carbon footprint and associated health impacts (Lehne & Preston, 2022). Similarly, the success of water conservation measures and waste recycling programs can be assessed through the evaluation of water quality data and the reduction of waste generation over time.

Stakeholder engagement and the use of environmental impact assessments (EIAs) at the outset of construction projects are also essential for ensuring that potential health risks are identified early, and that mitigation measures are in place from the beginning.

4.1 *Remediation Strategies*

Several remediation programs can help address the environmental and public health challenges observed in the cement production sector. These programs are designed to reduce emissions, manage waste effectively, and safeguard public health.

One such program is the implementation of low-carbon technologies in cement production, including the use of alternative fuels (such as biomass or waste-derived fuels) and the development of low-carbon cement formulations (Gartner & Sui, 2023). These technologies can significantly reduce CO_2 emissions, one of the key health threats associated with cement production. The transition to renewable energy sources, such as solar and wind, for powering cement plants can further reduce reliance on fossil fuels and cut down air pollution.

Another important remediation strategy is water treatment and recycling systems. Implementing zero-liquid discharge (ZLD) technologies, which ensure that wastewater is treated and reused rather than discharged, can significantly mitigate water pollution associated with cement production. Closed-loop water systems, where water used in cement production is recycled for use in subsequent processes, can also help reduce the strain on local water resources.

In terms of waste management, co-processing of waste materials—such as fly ash, slag, or municipal waste—can help reduce the environmental burden of cement production while contributing to the circular economy. Co-processing allows for the recycling of industrial waste, reducing the need for raw material extraction and minimizing the volume of waste sent to landfills. Additionally, land reclamation and afforestation programs can help mitigate the ecological degradation caused by quarrying activities. These programs restore ecological balance by planting native vegetation and promoting biodiversity around cement plant sites (Huang et al., 2022).

Also, community engagement programs are essential for ensuring that local populations are informed of the potential health risks associated with cement plants and are involved in decision-making processes regarding environmental management. Engaging with local communities helps build trust and ensures that mitigation measures align with community needs.

Summarily, the implementation of an effective monitoring and evaluation program in the cement industry is essential for managing the environmental and public health risks associated with cement production. By combining robust monitoring systems, innovative technologies, and effective remediation strategies, the cement industry can significantly reduce its environmental footprint and improve the health outcomes for workers and surrounding communities. Future research should focus on improving the scalability of these technologies and the development of comprehensive M&E frameworks that can be applied across the cement industry globally.

5.0 Conclusion

Cement production is a fundamental industry that supports modern construction, contributing significantly to global economic development. However, it is also a major source of environmental pollution, accounting for approximately 8% of global CO_2 emissions. The environmental impacts of cement production span across various phases, from pre-construction through to post-operation. During the pre-construction phase, activities such as land degradation, habitat destruction, and dust emissions pose serious ecological and public health challenges. The operational phase introduces significant air pollution, including CO_2 and nitrogen oxide emissions, water pollution from industrial wastewater, and the generation of solid waste like cement kiln dust. In the post-operation phase, challenges persist with biodiversity restoration, resource management, and land reclamation.

To address these challenges, the industry is exploring various strategies, including carbon capture technologies, the use of alternative materials, and more efficient energy consumption practices. The integration of circular economy principles and the adoption of innovative technologies, such as digital monitoring systems, offer promising solutions for reducing the environmental footprint of cement production.

Cement production, while essential to modern construction, poses substantial environmental and public health risks. The impacts of this industry are evident across the pre-construction, operational, and post-operation phases, affecting air, water, land, and biodiversity. Effective environmental management is required throughout these phases to mitigate negative outcomes and promote sustainability. Recent technological advancements, including alternative cement materials, carbon capture and storage, and improved waste management practices, offer potential pathways to reduce emissions and resource consumption. However, these strategies must be scaled up and integrated into broader industry practices to achieve lasting environmental benefits.

5.1 *Recommendations*

To minimize the environmental impacts of cement production, it is recommended that the industry invests in and implements cutting-edge technologies such as carbon capture, utilization, and storage (CCUS), which can significantly reduce CO_2 emissions. The development and adoption of low-carbon cement alternatives, including geopolymer cements, should be prioritized as they have demonstrated substantial reductions in emissions and energy consumption. Water conservation strategies, such as closed-loop recycling and zero-liquid discharge (ZLD) systems, are essential for addressing water pollution and conserving local water resources. Additionally, the industry should focus on the reclamation of quarry sites and the restoration of biodiversity through afforestation and land rehabilitation programs. Public health risks associated with air and noise pollution must be minimized by adopting best practices in dust control and noise mitigation. Finally, stakeholders should collaborate to establish more rigorous environmental regulations and monitoring systems to ensure that these measures are effectively implemented and maintained.

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