

Review

Emissions and Impacts of the Cement Industry Sector Through a Review of Mitigation Technologies and Ecological Risks

Jordana Georgin ¹, Dison S. P. Franco ^{1,*}, Claudete Gindri Ramos ¹ and Nouredine El Messaoudi ^{2,*}

¹ Department of Civil and Environmental, Universidad de La Costa, CUC, Calle 58 # 55–66, Barranquilla 080002, Colombia; jordana.georgin89@gmail.com (J.G.); cgindri@cuc.edu.co (C.G.R.)

² Department of Chemistry, College of Science, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11623, Saudi Arabia

* Correspondence: francodison@gmail.com (D.S.P.F.); nelmessoudi@imamu.edu.sa (N.E.M.)

Abstract

This study reviewed 187 articles based on systematic review guidelines to evaluate pollution controls through a novel analytical multimedia framework that bridges air, water, soil, and acoustic compartments, alongside emerging digital and circular economy paradigms. With 5–7% of worldwide CO₂ emissions originating in the cement industry, fugitive particulate matter constitutes more than 90% of a plant's emissions. The results show that the cement sector has considerable potential for decarbonization, though highly context-dependent. Under optimal conditions, clinker substitution coupled with alternative fuels could reduce direct emissions by up to 50% and total energy usage by 44%, constrained by regional material availability. Fully integrated carbon capture systems (TRL 7–9) could reduce exhaust emissions by up to 90%, contingent upon overcoming significant energy penalties. Engineering controls in dry-process mills reduced daily occupational noise exposure from 102.9 to 88.3 dB(A). Regarding soil pollution, cement kiln dust increased the unconfined compressive strength of native soils up to 9.9 times for geotechnical stabilization. In water management, hybrid biological systems removed 94.5% of particulate matter and reduced oxygen demand by over 87%, while advanced biomonitoring decreased effluent toxicity by over 90%. The significance of this study lies in overcoming traditional siloed assessments by introducing a holistic multimedia framework that maps biogeochemical interconnectivity alongside Industry 4.0 paradigms. Ultimately, this review provides a vital sociotechnical road map for stakeholders to align localized ecological risk mitigation with stringent 2026 global market mechanisms, such as the carbon border adjustment mechanism and mandatory environmental, social and governance disclosures, ensuring both industrial competitiveness and environmental stewardship.

Keywords: cement industry; pollution mitigation; CCUS; environmental remediation; sustainability



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1. Introduction

The cement industry, one of the most energy-intensive industrial sectors in the world, significantly contributes to environmental deterioration worldwide, with far-reaching effects on ecosystems and human health [1–3]. The manufacture of clinker is the primary cause of this impact, and the calcination of limestone alone is responsible for 5–7% of the world's carbon dioxide (CO₂) emissions [4–6]. Along with carbon, significant volumes of sulfur dioxide (SO₂), nitrogen oxides (NO_x), heavy metals, and particulate matter (PM) are

released throughout the manufacturing process. These pollutants contaminate the air, soil, and water, endangering the local population [7]. Because CO₂ is produced at every stage of the clinker production process, including the chemical breakdown of calcium carbonate and the burning of fossil fuels required to attain high temperatures in the kilns, the industry contributes significantly to air pollution. While the oxidation of sulfur compounds found in fuels and raw materials produces SO₂, this combustion process is also the primary source of NO_x emissions. These chemicals cause acid rain, which further deteriorates regional infrastructure and biodiversity, when they are released into the atmosphere [8,9]. Additionally, PM poses a significant operational difficulty: over 90% of all emissions from cement plants are fugitive dust produced during raw material extraction, transportation, and processing [10–14].

Along with the problems of fuel combustion and greenhouse gas (GHG) emissions, noise pollution caused by cement factory operations is receiving more attention, especially in metropolitan areas [6]. Workers may experience severe hearing damage, including noise-induced hearing loss, as a result of the high-intensity acoustic environments created by heavy machinery operating continuously, such as crushers, kilns, and mills. More effective mitigation techniques within the sector are required because prolonged exposure to high noise levels is connected to wider negative impacts on human health, such as hypertension, increased stress, and cognitive tiredness, in addition to physical harm. If proper noise control measures are not implemented, the noise produced by the cement industry's operations also negatively affects the adjacent population [15–20]. Another environmental challenge experienced by the business is soil and groundwater contamination due to the presence of cement kiln dust (CKD). The composition of CKD is defined by its alkaline nature and concentration of several heavy metals derived from the clinkerization process [21–23]. As it is extremely fine in nature, CKD can spread from its dumping grounds and settle in the nearby ecosystem in the absence of effective handling procedures [24]. Studies have shown that improper handling allows CKD to migrate into groundwater resource resources and a soil profile that leads to chronic contamination and land quality reduction [25].

Pollution of water sources by cement manufacturing processes has historically been documented as a critical environmental issue due to the need for large quantities of water for raw material processing and cooling in plants [26,27]. The high loads of suspended solids, dissolved salts and heavy metals like lead (Pb) and zinc (Zn) contained in industrial wastewater may be far above legal safety limits when discharged into adjacent bodies such as lakes or rivers [24,28,29]. Besides the degradation of the physical and chemical properties of water by increased turbidity and change in pH, there is constant threat to the diversity of aquatic species posed by the pollutions [24,30]. Long term, a certain concentration of these toxins accumulates in organisms through bioconcentration and subsequent biomagnification in the food web, thus causing damage to aquatic organisms and potentially the local water supply used in agriculture or for potable purposes. Effects of cement manufacture on the environment do not exist in isolated compartments, as there are interlinked processes occurring. Atmospheric deposition is defined as the process whereby elements in atmospheric emissions (like PM, NO_x, SO₂, and traces of heavy metals) are transferred from gas or aerosol phase into terrestrial and aquatic reservoirs. Far from the site of emission, these deposition flows initiate secondary contaminant cycles that affect soil and water quality and chemistry. The disposal or improper management of wastes from industry in general (in particular CKD) is a great danger to the environment. CKD can be subject to chemical leaching and physical movement by precipitation when disposed of or stored inappropriately. These hydrogeological processes act as carriers that transport contaminants of higher concentration from relatively immobile solid wastes into mobile forms that leach into the ground and surface waters. They thus provide a recurring

mechanism of land and water degradation based on the dynamic interaction of rainfall with solid waste.

To ensure effective and comprehensive regulation of environmental impacts, there is a need for an analytical multimedia tool that simultaneously considers air, water, and soil. Through these analyses, “collateral benefits,” whereby technological interventions for reducing a key emission also yield external advantages, can be identified. For example, increases in kiln efficiency and energy intensity reduce not only carbon intensity but also noise pollution and impacts on occupational and public health. There is an urgent need to develop and implement appropriate solutions that will help ameliorate such environmental disbenefits and meet the goals of the sustainable development goals (SDGs), especially in view of the anticipated increase in cement consumption in developing economies [30,31].

While previous reviews have predominantly isolated specific environmental compartments, focusing almost exclusively on CO₂ decarbonization pathways or singular dust mitigation tactics, this study introduces a comprehensive multimedia, cross-compartment analytical framework. The novelty of this review lies in three main dimensions, as follows. (1) Biogeochemical interconnectivity: it synthesizes the cascading effects of pollutants across air, soil, and water (atmospheric deposition of heavy metals and subsequent cement kiln dust leaching into aquifers), moving beyond siloed environmental assessments. (2) Integration of Industry 4.0 and circular symbiosis: it critically evaluates how digital twins, AI-driven predictive emission monitoring, and industrial symbiosis act as transversal levers for multi-pollutant mitigation and resource recovery. (3) Contemporary governance and market mechanisms: it aligns technical mitigation with the latest global regulatory landscapes, including carbon border adjustment mechanisms (CBAMs), mandatory ESG/TCFD disclosures, and dynamic life cycle assessments (LCAs). By bridging the gap between localized ecological risks and globalized carbon-market policies, this review provides a holistic, sociotechnical road map that transcends traditional technological compilations.

The primary purpose of this review is to evaluate the state-of-the-art technologies currently in use to reduce pollution from the cement industry while identifying critical research gaps and sociotechnical barriers impeding the transition to sustainable manufacturing. Methodologically, this study employed a systematic literature review following PRISMA guidelines, analyzing 187 peer-reviewed articles from the Web of Science Core Collection. This rigorous systematic approach ensures reproducibility and minimizes selection bias compared to traditional narrative reviews. The research content encompasses a comprehensive assessment of decarbonization options (CCUS, clinker substitution, alternative fuels), noise attenuation measures, soil and water remediation techniques, and the integration of digital and circular economy paradigms. By bridging the gap between localized ecological risks and globalized carbon-market policies, this review provides stakeholders with a holistic, sociotechnical road map to create more resilient environmental governance programs that reconcile industrial productivity with ecological preservation.

2. Methodology

We conducted a systematic literature review in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Figure 1). We conducted the initial search exclusively via the WoS Core Collection. The search strategy yielded 435 records. Since the search was restricted to a single database, cross-database duplication was not applicable. Additionally, the built-in deduplication tools of the WoS platform (based on DOI and title matching) were applied prior to export, confirming that all 435 records were unique. Therefore, 0 duplicates were removed, leaving 435 articles for title and abstract screening. A total of 175 studies were included from our systematic search. In addition, 12 articles from other resources (cross-reference search, manual search)

were added as being highly pertinent for the advancement remediation and adsorption technologies discussed in this work. Hence, there were 187 articles added to our qualitative review in order to constitute the final references used in this paper.

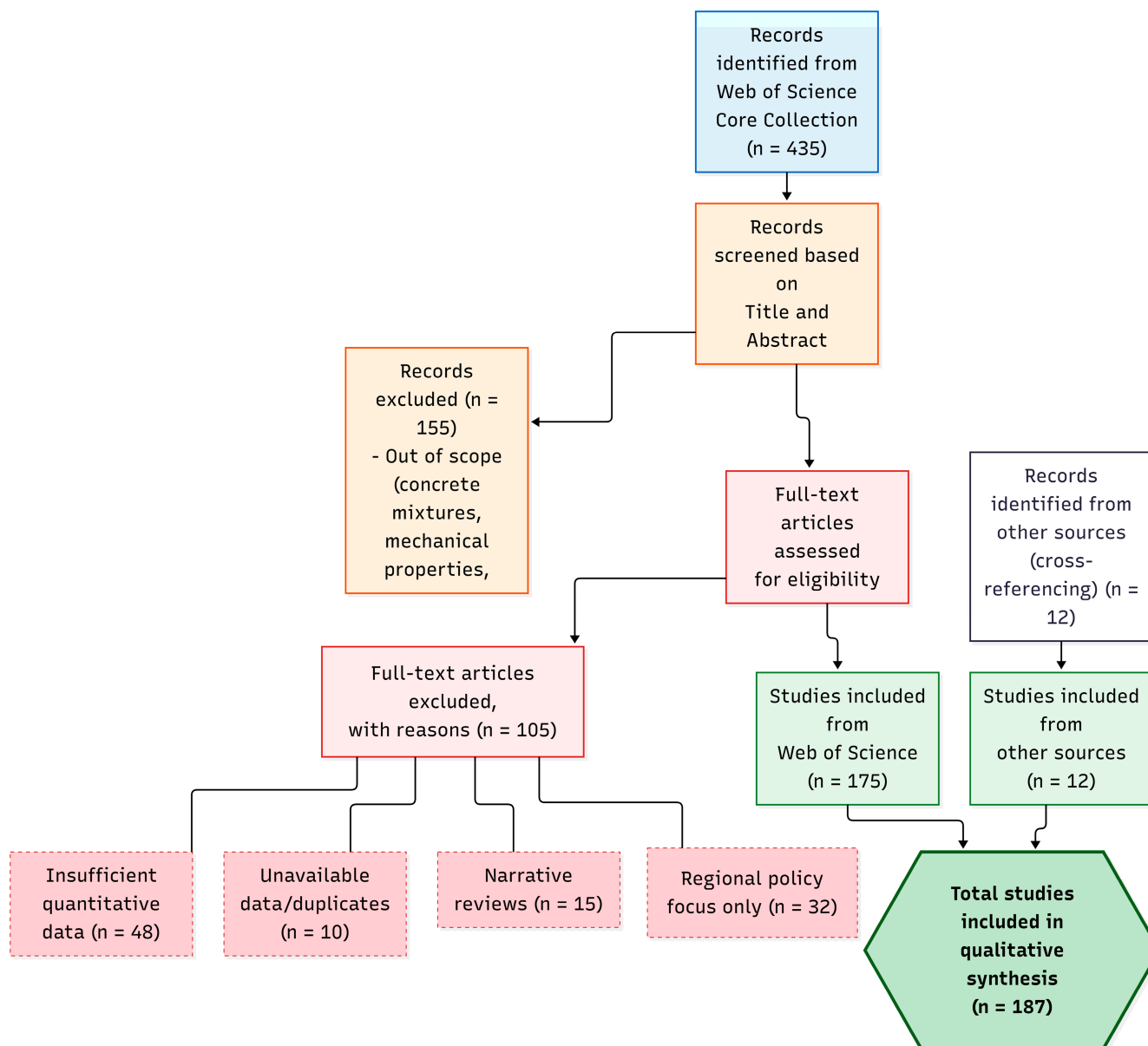


Figure 1. PRISMA flowchart illustrating the systematic selection process of studies on mitigation technologies and ecological risks in the cement industry.

2.1. Search Strategy and Identification

The search was conducted using a comprehensive Boolean string combining keywords related to the cement industry, pollution, and mitigation: (“cement industry” or “cement production” or “clinker”) and (“pollution” or “emissions” or “effluents” or “particulate matter” or “noise” or “soil contamination” or “water pollution”) and (“mitigation” OR “remediation” or “capture” or “treatment” or “abatement”). Additionally, the built-in deduplication tools of the WoS platform were applied prior to export, confirming that all 435 records were unique. Therefore, 0 duplicates were removed, leaving 435 articles for title and abstract screening.

2.2. Screening and Eligibility Criteria

Titles and abstracts were independently evaluated against predefined inclusion and exclusion criteria. Studies were excluded if they focused exclusively on the mechanical behaviors of concrete mixtures, geopolymers, or other cements without appraising the environmental impacts or mitigation technologies of cement production. This initial screening excluded 155 articles. The full text of the remaining 280 articles was then assessed for eligibility. Of these, 105 were excluded due to: (i) deficiency in quantified environmental impact data ($n = 48$); (ii) consideration of exclusively regional policies without dealing with actionable mitigation technologies ($n = 32$); (iii) lack of a systematic or empirical approach ($n = 15$); and (iv) missing or incomplete data ($n = 10$). Consequently, 175 studies were included through the systematic search.

2.3. Data Extraction and Qualitative Synthesis

In addition to the systematic search, 12 highly pertinent articles from other resources (identified via cross-reference and manual searches) were added to capture foundational advancements in remediation and adsorption technologies. Hence, a total of 187 articles were included in the final qualitative review. Data extraction was performed using a standardized form capturing author(s), year, geographic context, type of pollution (air, water, soil, noise), mitigation technology evaluated, quantitative performance metrics (e.g., emission reduction percentages, removal efficiencies), and identified limitations or barriers. The extracted data were then synthesized using a thematic analysis approach, categorizing the mitigation strategies into distinct environmental compartments and cross-cutting governance frameworks, which formed the basis for the novel analytical multimedia framework proposed in this review.

3. Techniques for Lowering CO₂ Emissions in the Production of Cement

Reducing CO₂, the primary cause of anthropogenic climate change, is the biggest obstacle to decarbonizing the cement business. Developing effective mitigation solutions necessitates a multidisciplinary approach, because CO₂ emissions are inherent to both the chemical breakdown of limestone and the burning of fuels at high temperatures [32,33]. As a result, contemporary research has produced a wide variety of technological approaches, from the use of sophisticated carbon capture systems to the adoption of alternative raw materials, each of which offers distinct trade-offs in terms of industrial scalability and efficiency. The primary methods for lowering CO₂ emissions in cement production, such as carbon capture and energy efficiency, are displayed in Table 1.

Table 1. Key strategies for mitigating CO₂ emissions in the cement sector, including energy efficiency, carbon capture systems, and production technologies.

Strategy	Description	CO ₂ Reduction Mechanism	Advantages	Limitations/Challenges
Decrease in the clinker factor	Additional cementitious materials (blast furnace slag, fly ash, calcined clays, limestone filler) can partially substitute clinker.	Lowers kiln energy usage and emissions related to limestone calcination.	Direct emission reduction (up to 30–50%) is a proven technology.	Certain supplementary cementitious materials (SCMs) have limited availability, and regulatory compliance is required.

Table 1. *Cont.*

Strategy	Description	CO ₂ Reduction Mechanism	Advantages	Limitations/Challenges
Utilizing alternative fuels	Substituting industrial waste, biomass, or refuse-derived fuels (RDFs) for fossil fuels.	Encourages the recovery of energy from waste and lowers emissions from fossil fuels.	Both fuel prices and net carbon emissions are decreased.	Variations in waste content and the requirement to regulate emissions into the atmosphere.
Kiln energy efficiency	Updating multi-stage preheaters, pre-calciners, and rotary kilns.	Decreases the amount of specific thermal energy used per ton of clinker.	Substantial decrease in indirect emissions and energy expenses.	Modernizing outdated plants requires large initial expenditure.
Waste heat recovery (WHR)	Producing electricity by using the heat from furnace exhaust gases.	Lowers indirect emissions by lowering the demand for electricity from the power system.	Improves the process's overall energy efficiency.	The size of the plant and the furnace's thermal profile determine efficiency.
Renewable energy sources and electrification	Utilizing renewable energy sources (solar, wind, and hydropower) to power auxiliary industrial steps.	Lowers the indirect emissions that come with producing electricity.	Helps the energy chain become less carbon-intensive.	Technological constraints on the thermal process's full electrification.
Carbon capture and storage (CCS)	Geological storage and CO ₂ capture from furnace exhaust gasses.	Before releasing CO ₂ into the atmosphere, remove it straight from the gas stream.	High potential for mitigation (up to 90% of emissions).	High running costs and the requirement for infrastructure for storage and transportation.
Carbon capture and utilization (CCU)	Construction materials, mineral carbonation, and synthetic fuels are all made from the captured CO ₂ .	Transforms CO ₂ into products with added value.	A circular carbon economy is possible.	There are issues with industrial scale, and the market is still small.
Novel varieties of carbon-free cement	Creation of substitute binders, such as belitic cements, geopolymers, and LC ³ cement.	Lowers the requirement for calcination emissions and clinker.	Substantial long-term potential for CO ₂ reduction.	The necessity of structural performance validation and regulatory obstacles.
Process optimization and digitization	Advanced control and artificial intelligence are used to optimize the production process.	Lowers energy usage and increases operating efficiency.	Lowers operating expenses and raises output.	Industrial system integration and digital infrastructure are necessary.

3.1. Technologies for Carbon Capture, Usage, and Storage

One of the most researched methods for reducing CO₂ emissions in the cement industry is carbon capture utilization and storage (CCUS), which involves capturing flue gas emissions for later industrial use or geological sequestration [34,35]. Post-combustion capture systems have been shown in numerous studies to significantly lower cement plants' carbon footprints [36–41]. The industry is increasingly concentrating on valorization to

offset the expenses, even though sequestration is still an essential part of this infrastructure. For instance, researchers have looked into how well CO₂ can be extracted straight from furnace exhaust gases and then transported to subterranean storage facilities [42]. Chemical solvents, mostly amines, have been shown to be quite successful in this area for CO₂ absorption [43–46]. However, the significant energy penalty needed for solvent regeneration and operational weaknesses, such as solvent deterioration over time and rapid corrosion of the containment infrastructure, prevent solvent-based capture from being widely used [47,48]. It is important to contextualize that while post-combustion and oxyfuel systems demonstrate a theoretical capture potential of up to 90% (TRL 7–9), achieving this maximum efficiency at an industrial plant scale requires massive infrastructure modifications. The actual capture rate is highly sensitive to flue gas composition, and the associated energy penalty (often reducing net plant efficiency by 10–15%) remains a primary source of uncertainty for widespread commercial deployment.

Oxyfuel combustion, which burns fossil fuels in an atmosphere of concentrated oxygen rather than ambient air, is one alternative that is being researched [49]. This technique streamlines the separation process by creating a combustion gas stream that is nearly entirely made up of CO₂ and water vapor. However, the energy-intensive nature of producing high-purity oxygen is a significant barrier to commercialization [50–52]. The switch from traditional air combustion to oxy-combustion systems was further investigated by researchers [53]. The practicality of partial CO₂ capture (60–75%) versus total capture (90–99%) was evaluated in their analysis, and it was noted that implementation would necessitate major structural changes to current plant components, including the calciner and rotary kiln. Their work has confirmed oxyfuel has high capture potential, but also brought to light significant drawbacks, namely the increased electricity use, the operational difficulties to stop ambient air ingress, and the potential risk to clinker quality from changes to the kiln's thermal regime.

Applying CCUS to the cement industry presents unique physicochemical and logistical challenges that fundamentally distinguish it from power generation or steel production. Unlike coal-fired power plants, where flue gas is relatively homogeneous, cement kiln exhaust presents a uniquely hostile environment for carbon capture systems. The flue gas contains extreme dust loading (raw meal and clinker dust), high moisture, and trace impurities such as SO_x, NO_x, and alkali bypass dust. These contaminants severely accelerate the degradation of amine solvents, cause rapid fouling of absorption columns, and increase corrosion rates, thereby driving up operational expenditure (OPEX) and maintenance frequency. Furthermore, the cement production process is inherently dual-natured: approximately 60% of the CO₂ emissions originate from the endothermic chemical calcination of limestone, while 40% stems from fossil fuel combustion. Consequently, CCUS systems must be thermally integrated directly with the calciner to capture the high-purity process CO₂ stream without disrupting the critical thermal profile required for clinker mineralogy. Finally, from an infrastructural standpoint, cement plants are geographically dispersed and often located in remote areas adjacent to limestone quarries. This geographic fragmentation complicates the development of centralized CO₂ transport networks (pipelines) to saline aquifers or utilization hubs, significantly reducing the economies of scale typically assumed in centralized power-plant CCUS models.

While many advantages are promised, a key barrier to widespread industrial use of carbon capture technology remains its relatively high cost and high energy usage [54]. Hence, an effective research focus should be placed on improving capture efficiency and reducing both capital and operating costs [55,56]. An effective source–sink matching method has been developed to aid the widespread application of CCUS in the large cement sector in China [57]. This methodology considers the carbon–energy–water linkage while

assessing the spatial proximity of carbon-emitting sources and practical geological storage sites, and determined that by using carbon-energy-water storage in the cement sector, CO₂ can be reduced by 238.2–715 million tons based on different scenarios. However, the investment required is substantial, ranging from CNY79.4 to CNY269.5 billion, and sufficiency of water and energy at the local level required still needs attention [58].

Besides the possibility of storage, captured CO₂ can be utilized to generate both economic benefits and environmental benefits. For example, CO₂ can be directly incorporated into the production process of concrete or transformed to synthetic carbonates used as a building material. This technology is used to reduce the carbon footprint of the cement industry and simultaneously produce a stronger product. It works through mineralizing and incorporating CO₂ into concrete. Many industry leaders are now employing these mineralizing technologies during the production process to produce green building materials. When directly incorporated into the mixing cycle, these technologies can reduce the net emissions associated with infrastructure production. Enhanced oil recovery is another important use: this technique increases the amount of crude oil that can be extracted by injecting collected CO₂ into already-existing oil reservoirs. Through a circular economy framework, EOR is one of the most concentrated commercial uses for captured carbon, opening up a key avenue for industrial emissions to be recycled for the benefit of the cement and energy sectors [59–61]. However, the effectiveness of the plant's first capture step is crucial to the success of these use and storage techniques.

Despite these opportunities, economic viability and the logistical gap between present utilization rates and the massive amount of CO₂ produced by the industry still hinder large-scale application [56]. While it has been demonstrated that long-term sequestration in saline aquifers and depleted oil fields lowers atmospheric CO₂ [62,63], researchers highlight ongoing worries about possible breaches and these storage facilities' long-term structural integrity [64]. Experts have suggested an integrated carbon capture and utilization (I-CCU) strategy to reduce storage concerns (Figure 2) [65].

They investigated the usage of electrolysis-derived H₂ to convert captured CO₂ into methanol and indicated that although I-CCU involves a closed carbon economy, its high electricity consumption and high cost of electrolysis and capture still remain major challenges for its industrial deployment, comparing it with the business-as-usual model and standard CCS model. Analyses on the costs for carbon capture utilization and storage (CCUS) technology were performed in several studies [66–68]. Cost analysis of CCUS in Shanxi province focused on the improvement of the CCUS system with the use of a mixed integer linear programming model [66] to minimize the total annual cost associated with CCUS operations and CO₂ emission mitigation. They concluded that the cheapest route using CCUS technology would be the synthesis of urea from CO₂. With the utilization of CO₂, it was possible to reach a reduction in emissions higher than 50%, but at the minimum possible cost. The least profitable route was found to be the cultivation of microalgae, while CO₂-EECB (energy-efficient concrete blocks with CO₂) and cement curing could be cost-effective.

Researchers are analyzing the net present value (NPV), energy return on investment, and carbon return on investment of China's first carbon capture, storage, and utilization enhanced oil recovery project (CCUS-EOR), which has a capacity of one million tons [67]. Overall economic viability was demonstrated by the project's NPV of USD 56.09 million, internal rate of return of 13.4%, and payback period of 8.34 years. The authors point out that with an economic viability limit of USD 81.52 a barrel, profitability is susceptible to changes in oil prices. In contrast, the authors of another study take a more comprehensive view of CCUS in relation to China's decarbonization agenda, especially in the steel sector [68]. They stress the importance of CCUS in China's shift to a low-carbon

economy, but they also draw attention to the high upfront, ongoing, and maintenance costs of widespread implementation. On the other hand, these researchers pinpoint particular CCUS designs and technologies that might be profitable [66,67]. Another set of academics contends that increased infrastructure, technological innovation, and a complete legislative framework backed by market mechanisms and government action are necessary for widespread industrial adoption [68]. All of these studies stress the need to increase cost-effectiveness and guarantee long-term financial sustainability while highlighting the prospects and difficulties related to the implementation of CCUS technologies for industrial CO₂ mitigation.

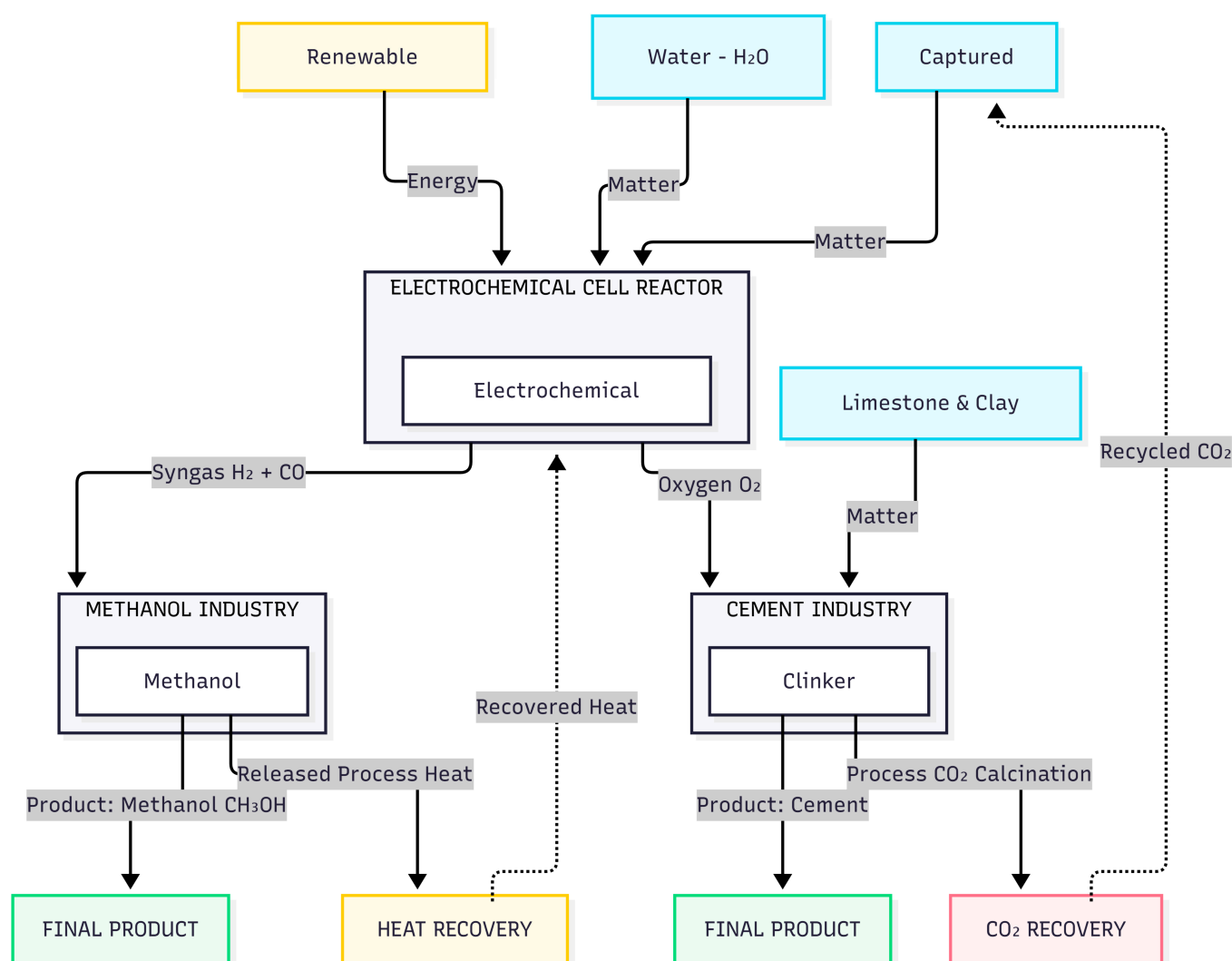


Figure 2. Process flow diagram of the integrated carbon capture and utilization (I-CCU) system in the cement industry, illustrating mass and energy balance relationships, including renewable electricity and H₂O inputs, O₂ supply for oxy-combustion, CO₂ capture, and H₂/CO₂ conversion to methanol.

3.2. Material Substitution and Energy Efficiency

Utilizing alternative fuels is acknowledged as a successful strategy for lowering GHG emissions from the production of cement, frequently in conjunction with carbon capture systems [69–75]. In an effort to lessen the carbon footprint, the industry—which traditionally utilized coal and fossil fuels—is progressively moving toward the use of biomass and fuels derived from waste materials and residues of industrial manufacturing [72,74,76,77]. Biomass is considered to be a carbon-neutral energy source, as the carbon absorbed during the growth process potentially offsets the CO₂ emission after combustion [78–81]. Sev-

eral works thus investigated the utilization of biomass as a fuel alternative for cement production. In fact, in one study it was concluded that a significant reduction in carbon footprint was achieved by substituting biomass and waste-derived fuels for fossil fuels in cement production [74]. Biomass ash properties offer an alternative decarbonization pathway beyond direct combustion. For instance, Rahman and collaborators [72] demonstrated that woody biomass, which is rich in bark, possesses ideal characteristics for clinker formation. Despite the aforementioned benefits, issues regarding biomass supply chains are still prevalent: the chain requires a consistent raw material supply and preprocessing to assure stable combustion [79,82]. Based on several findings, food-versus-fuel conflicts and the enormous use of land for bioenergy development frequently affect the sustainability and feasibility of biomass development [83,84].

Waste-derived fuel such as sewage sludge (SS), tire-derived fuel, RDF, and plastics have provided a “double solution” for both waste management and substitution of fossil fuel. Biomass and SS should generally be dried or pelletized to increase its energy density and kiln performance. It has been shown from environmental assessment that it can reduce both NO_x and SO_x emissions simultaneously, while CO_2 emission reduction between 15% and 30% can be achieved if the usage of waste-derived fuel can be maximized. However, there are still significant hurdles, as follows. (a) It is possible to have variations in chemical constituents and moisture content. The properties can adversely affect the quality of clinker, resulting in the variation of kiln temperature. (b) Harmful pollutants such as dioxins and heavy metals can be emitted when certain waste-derived fuel and biomass are combusted. Strict emission control and advanced filtering processes are required in order to protect the health of the community [85,86]. High cost, locality of raw materials, and diversified environmental regulations are obstacles for the full-scale use of waste-derived fuel in a large cement plant [13]. For example, hazardous materials are subject to problems of hazardous chemical combustion for the use of waste-derived fuel, and it can also be possible that there is not enough biomass fuel available for large cement plants to use.

In terms of holding material quality and processing practices to conventional standards while simultaneously reducing the environmental impact via adopting nonconventional fuel and materials, the literature shows that new methods are still being explored in the development of new cement processes [87,88]. According to recent research, sewage sludge can be effectively used as a secondary fuel, a NO_x -reducing agent in denitrification of NO_x , reducing NO_x emissions to a certain level without deteriorating cement quality [87]. However, a slight retardation of cement curing was noticed and attributed to trace elements in sludge. Another study examined other SCMs, focusing on ashes of biomass burned using wood chips and *Miscanthus* straw as fuel [88]. The study found that ashes produced at the bottom of the furnace and those from burning *Miscanthus* straw improved both the workability and compressive strength of the cementitious matrix. However, ash collected at baghouse filters and electrostatic precipitators yielded significantly lower mechanical strength, due to the fact that large quantities of soluble potassium salt greatly increased the water demand. A key finding of this study is the great need for detailed characterization of ash chemical composition, especially concerning trace metal concentrations. One study successfully immobilized heavy metal pollutants like Zn and Cd into a cement matrix [88]. The former research emphasizes the benefits of pollution (NO_x) reduction [87], and the latter concentrates on improvement of properties for cement, as shown by testing biomass ashes. Finally, both studies confirm the crucial need for effective pretreatments and control tests on alternative resource use in cement production.

3.3. Utilizing Alternative Fuels

Alternative fuels and materials can reduce overall GHGs, but CP approaches that improve overall efficiency of the entire cement production chain (from extraction to final clinker cooling) must still be implemented in order to provide a sustainable long-term approach. The reduction in clinker content of cements by the partial replacement of conventional clinker with SCMs such as fly ash, GGBFS, or calcined clays can lead to a large reduction in the carbon intensity of the cement industry [89]. Using blended cements reduces the direct emissions from limestone calcination because the ratio of clinker to cement is smaller. Several studies reported that the mechanical properties and durability of blended cements are either similar or better than traditional Portland cements [90,91]. Nevertheless, other papers point to a lack of availability of adequate SCMs regionally and a risk of low homogeneity due to possible variation in the chemical characteristics of the SCM. Alongside the concept of material substitution, there is an equally important body of literature concerning energy-efficiency technologies for industry decarbonization. The research in this area strongly supports that heat recovery is a widely scalable mitigation technology, since the cement production process is already extremely energy-intensive [92]. The technologies for energy efficiency can thus include a WHR system that decreases reliance on external sources by utilizing the heat of the clinker coolers and kiln exit gas for electricity generation [93].

Additionally, an evaluation of WHR performance using simulation of different organic Rankine cycle system configurations and drying plants (Figure 3) showed that the conversion efficiency of thermal to electrical power generation using toluene is more efficient than the others considered [94]. Although economic studies concede high capital costs, the return of this investment due to the decrease in energy costs and CO₂ emissions at the global scale as the cement industry goes greener are likely to pay off. Decoupling of the cement industry from fossils through external sources can also be reached by integrating renewable energy, for example, solar and wind power in a cement plant [8]. Several recent reports on the sector concluded that coupling of renewable power production with the previously cited material substitution (replacing clinker by materials derived from waste) could lead to an overall decrease in energy use of 44% and CO₂ emissions by 50% [95]. However, these figures represent theoretical maxima observed in highly optimized, integrated models. In practice, the actual reduction at the plant scale is subject to high uncertainty, as it depends heavily on the regional and seasonal availability of high-quality SCMs (such as fly ash or slag) and the specific baseline energy matrix of the individual facility.

Empirical analyses, on the other hand, have shown that the economic feasibility of an integrated system depends greatly on the specific plant configuration and local availability of energy sources, unlike in model-based studies, where optimal scenarios are usually assumed [8]. Since there is not a single mitigation option suitable in every case, in general, the literature suggests the importance of flexibility, case specificity, and consistent research and development [96].

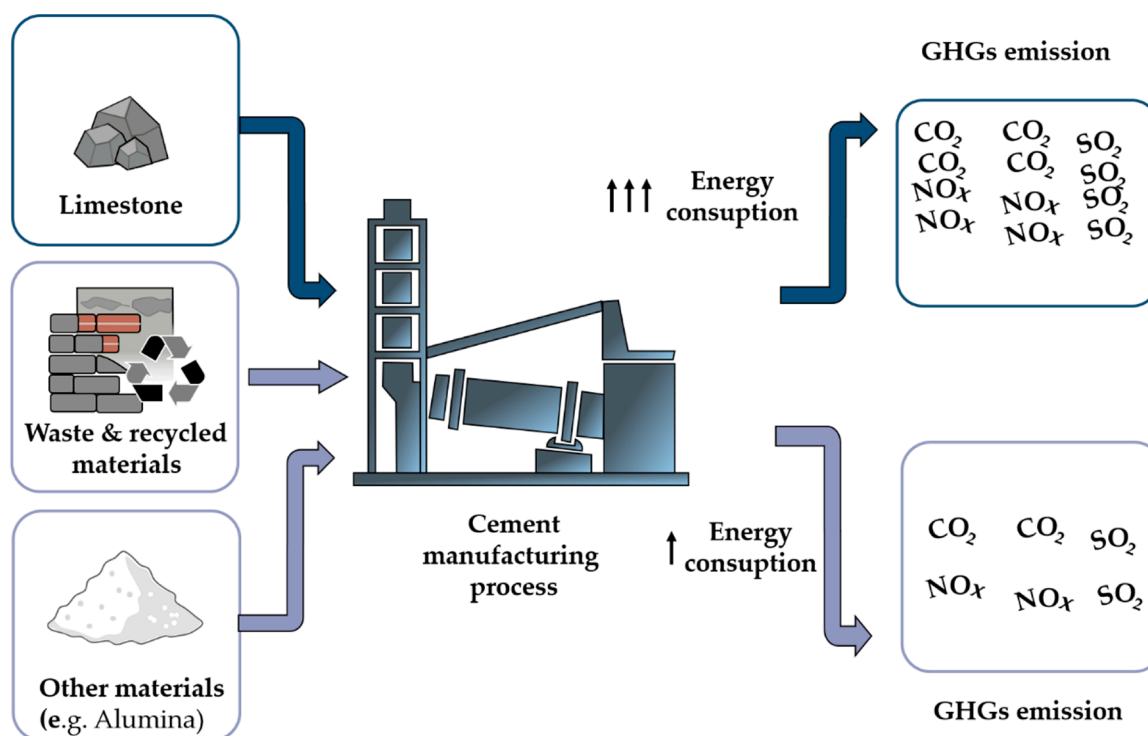


Figure 3. Techniques for material substitution to lower energy use and GHG emissions during the production of cement.

3.4. Switch to Green Cement

The development of “green cement” technologies that are focused on new raw materials and low-energy production methods provides a promising way to tackle the carbon footprint issue of industry [97]. The emphasis is mainly on alkali-activated cements and new binder materials, for example, geopolymers, and so this type of technology does not rely on calcining limestone (which causes CO₂ emissions) [98,99]. Some of these green cement technologies are already available commercially. A range of new cement materials include chemicals that convert captured industrial CO₂ emissions to form a binding agent, thereby locking CO₂ into cement material forever, and have been implemented in industrial applications. An example for the next kind of technology is the production of geopolymer cement, which is a sustainable building material with lower embodied CO₂ and is increasingly being used in construction instead of traditional Portland cement. In the production of geopolymer cement, use is made of by-products from industrial processes (fly ash, slag). However, the use of these technologies is not widespread, and despite the growing trend towards greener cement materials and an increasing requirement for this, it continues to be a challenge. The main reasons are their higher price and poorly developed supply chain for green cement production. However, the pressure for alternative low-carbon materials is building, especially in areas where governments have introduced rigid emission controls and encourage environmentally friendly construction methods. Green cement materials are now specified in “certified sustainable building” projects for certain strict levels of performance to be reached. Despite the above reasons, Portland cement continues to dominate the market due to its well-established price and infrastructure for distribution.

The performance and microstructural evolution of these alternative binders are intrinsically linked to precursor chemistry and the choice of alkaline activator. For instance, the mechanical properties and stabilization mechanisms of slag/fly ash-based geopolymers are highly sensitive to the modulation of initial CaO/Al₂O₃ and SiO₂/Al₂O₃ molar ratios, which dictate the formation and cross-linking of the aluminosilicate gel network [100].

Furthermore, when these geopolymetric systems are applied to stabilize waste clays or contaminated soils, the underlying clay mineralogy profoundly influences the microscopic strength and the synergistic interactions between the activator and the solid phases [101]. Understanding these precursor–activator–mineralogy interactions is crucial for tailoring the mix to specific industrial or geotechnical applications.

In certified and green buildings, they are being increasingly used for meeting the strict standards for environmental performance. This is because of their better cost performance and mature value chain, though traditional cement still holds a dominant position [102]. Recent research identified various pathways that could potentially reduce the carbon footprint. Reactive belite-rich Portland cement shows a moderate emission reduction potential of 10%, but is compatible with the existing Portland cement production infrastructure. It is estimated that belite–ye’elimite–ferrite cement reduces CO emissions by about 24%, as it requires a lower temperature to sinter and consumes less limestone. Better emission reduction potential can be seen for calcium cold-sintered cement: it may achieve up to 37% CO emission reduction using carbonation curing, which is capable of sequestering CO. A breakthrough pathway has been identified as magnesium oxide-based material system: it can produce carbon-negative concrete by sequestering more CO during its service life. Alongside this assessment, an evaluation of the limitations—both technological and economic—preventing the wider use of alternative binders like geopolymers, supersulfated cement, CSA cement, and CAC has been made [103]. CAC cement achieves high early strength, but can lose a large percentage of its strength over time in the presence of moisture and weathering due to conversion. While CSA cement achieves a low carbon footprint and high durability, it relies on the use of bauxite, resulting in high production costs. Even with considerable potential for large carbon reduction and a strong place in the circular economy, geopolymer cement production cannot yet benefit from low-cost production, and scale-up costs associated with liquid alkali activator systems remain a significant barrier. Furthermore, the transition from laboratory-scale synthesis to field-scale validation is still in its infancy. Long-term durability under real-world environmental exposure (e.g., freeze–thaw cycles, wet–dry cycling) and the potential leaching risk of trace elements or residual alkalinity from the geopolymer matrix into surrounding ecosystems must be rigorously quantified. While geopolymerization can encapsulate certain contaminants, long-term leaching behavior under varying hydrological conditions requires standardized testing. Currently, the lack of unified international standards (e.g., comprehensive EN or ASTM codes dedicated specifically to geopolymer binders) and the scarcity of large-scale, field-validated case studies hinder the widespread regulatory acceptance and commercial scalability of these alternative binders. As technologies still in commercialization infancy, they have clear and promising paths towards major carbon reduction in cement [104]. Several industry stakeholders are actively researching the integration of alternative cements into schemes incorporating renewables and waste-derived fuels, but issues with large capital expenditure (CAPEX) and unsolved technical issues currently prevent scaling up to commercial usage.

4. Techniques for Lowering Noise Pollution in the Production of Cement

While reducing CO₂ emissions is the main focus for the cement industry, the cement manufacturing process creates a variety of local environmental contaminants that also affect the well-being of people and the quality of the local environment. The total environmental burden placed on areas neighboring cement manufacturing sites is the cumulative effect of various physical impacts of industrial operations, local pollution (both on land and in water), and airborne contaminants, both as particulate and gaseous pollutants. Therefore, reducing efforts, such as fuel switching, process improvements, and technology upgrading,

impact GHG emissions as well as these local impacts in parallel. Within the context of such pollution, noise pollution is a factor that is significant, but also often a neglected environmental exposure. In industrial cement areas, acoustic pollution is frequently found along with other pollutants of air, water, and soil. Noise pollution creates cumulative environmental stress, and therefore this section shifts the focus away from a global climate consideration to examining noise as one aspect of the local environmental problem associated with cement production. Table 2 below lists the main noise sources and abatement measures in the cement production sector.

Table 2. Primary noise sources in the cement industry, mitigation strategies, and environmental and occupational benefits.

Noise Source in the Cement Industry	Description of the Process/Equipment	Mitigation Measures	Impact of Implementation	Environmental and Occupational Benefits
Limestone crushers	Tools used to break up the limestone that was first taken out of the quarry.	Acoustic barriers, structural insulation, acoustic enclosure installation, and routine maintenance.	Noise levels near the crusher plant have significantly decreased.	Better working conditions and less of an influence on neighboring towns from noise.
Raw material and cement mills	Equipment used to mill clinker and raw materials.	Low-noise internal linings, vibration dampers, and an acoustic enclosure.	Reduction of noise produced during grinding, both airborne and structural.	Lower exposure to noise at work and adherence to environmental regulations.
Exhausts and industrial fans	Utilized in filtering systems, furnace gas exhaust, and pneumatic conveying.	Silencer installation, speed control, and pipe acoustic insulation.	Decrease in airflow-related vibrations and aerodynamic noise.	Decrease in airflow-related vibrations and aerodynamic noise.
Preheating system and rotary kiln	Thermal system that is in charge of clinker generation and limestone calcination.	Acoustic barriers, mechanical upkeep, acoustic insulation, and operational optimization.	Decrease in furnace rotation-related vibrations and structural noise.	Decreased extended exposure to noise and increased workplace safety.
Material handling systems and conveyor belts	Raw materials and intermediate products are continuously transported throughout the plant.	Preventive maintenance, the use of low-noise rollers, belt alignment, and partial enclosure.	Lowering the noise produced by friction and mechanical vibrations.	Lowering the production area's constant noise.
Air compressors	Utilized in industrial instrumentation and pneumatic systems.	Installation in soundproof rooms, usage of silencers, and frequent maintenance.	Substantial decrease in compressor-generated high-intensity noise.	Enhancing workplace acoustic comfort.
Mobile machinery (trucks, loaders)	Utilized in materials handling, internal transportation, and mining.	Operational control, acoustic barriers, engine maintenance, and optimum routes.	Decrease in sporadic noise and sound transmission around the plant.	Less of an influence on surrounding communities and workplaces due to noise.

Table 2. *Cont.*

Noise Source in the Cement Industry	Description of the Process/Equipment	Mitigation Measures	Impact of Implementation	Environmental and Occupational Benefits
Bag filters and ventilation systems	PM control equipment.	Silencer installation, acoustic insulation, and duct and valve upkeep.	Reduction of the air flow and pulse caused by the filtration process.	Adherence to industrial noise regulations.

4.1. Technological Approaches to Reducing Noise

Production facilities are the main locations where sound insulation, absorption, and directed noise diversion techniques are used to reduce the acoustic effects of cement manufacturing [16]. These precautions are intended to shield nearby residential areas and on-site employees from the high-decibel levels typical of heavy industry. Researchers thoroughly examined noise reduction techniques for vital machinery, such as compressors, furnace burners, crushers, and mills, which can produce sound pressure levels (SPLs) of up to 106 dB(A) [105]. Several proactive engineering controls are suggested by the study, as follows. Source encapsulation and damping: acoustic emissions can be reduced by up to 10 dB(A) by placing rubber linings on ball mills and enclosing noisy machinery in sound-proof enclosures. Vibration control: massive, high-inertia foundations are advised to reduce mechanical vibrations from huge mills that would otherwise spread across the factory floor, and structural design is crucial to noise reduction. Operational isolation: cumulative exposure is greatly decreased by implementing segregated control rooms and modifying the plant layout to separate high-noise-intensity zones from high-traffic worker areas.

To prevent permanent noise-induced hearing loss, it is still essential to adhere to regulatory criteria, such as maintaining the 90 dB(A) limit for continuous 8 h exposure and gradually reducing working hours as noise levels rise. High-quality personal protection equipment, which serves as a last line of defense and enhances community relations by lowering outside noise, must be used in addition to engineering measures. Based on these methods, one study concentrated on vibration isolation devices as the main way to reduce structural noise from large machinery [106]. According to that research, sound transmission can be significantly disrupted by isolating the mechanical energy of devices like industrial fans, compressors, and grinding mills. The study documented the use of acoustic curtains in the particular case of grinding mills. Through well-designed and implemented sound barriers, localized noise levels can be reduced substantially, with an SPL drop from 104–112 dB(A) to 94–96 dB(A). The cooling fans and compressors will also receive noise attenuation through similar interventions. These acoustic measures have a profound impact on workers: as it is a requirement to work within the defined safe noise levels set out by legislation, lowering background noise will consequently increase the amount of time the workers can spend in these areas. The permissible exposure time can be raised for the workers, as every 10 dB(A) reduction in sound is equivalent to a tenfold reduction in noise intensity. Therefore, the workers may spend considerably longer periods in the areas working at these levels without exceeding their daily noise dose and in turn reduce the risk of noise-induced hearing loss (NIHL) to a far lesser degree.

In a recent case study [16] an integrated noise control strategy in a dry-process cement mill was demonstrated. The results support that the most efficient approach to control noise is at the source: the case study showed a reduction of 25 dB at the noise source using a modified silencer to Roots-type blowers, which had suffered failed silencers. Following structural changes to attenuate secondary noise transmitted through structures, the average sound absorption coefficient of the facility changed from 0.03 to 0.32. These modifications

included installation of sound absorptive doors, noise-resistant windows, and use of sound-absorptive materials in walls and ceilings. Following all the modifications, average daily noise exposure levels decreased from dangerous 102.9 to 88.3 dB(A), close to the regulatory limits on occupational exposure (85 dB(A)) and substantially reducing risks of NIHL. It must be noted that this specific quantitative reduction is derived from a single case study of a dry-process cement mill [16]. While it demonstrates the profound efficacy of source-control and structural acoustic modifications, the exact dB(A) reduction achievable in other facilities will vary depending on the initial age and condition of the equipment, the specific acoustic materials applied, and the physical constraints of the plant layout. Alongside these engineering control measures, another study focused on administrative controls and personal protective equipment [107]. The authors found impact noise produced from material impacts in the mills and aerodynamic noise originating from rotating parts were the main sources of noise at this plant and recommended the use of acoustic enclosures, pneumatic silencers, and personal hearing protection for all workers to reduce their exposure, continuous noise monitoring, and rebalancing of rotating parts and accurate alignment of all mechanical parts.

While technical noise control measures like vibration isolation techniques, sound barriers, and engineered silencers are quite effective at reducing industrial noise, their deployment involves substantial capital expenditure. The CAPEX of special engineering and high-performance materials presents a barrier for many users [108,109]. Instead of the cost of the equipment directly, plant layout reconfiguration can be used to reduce the exposure of noise by locating the high-noise-producing equipment away from the adjoining workspace or occupied space based on the principle of inverse square law. In many instances, site limitation does not allow such reconfiguration, especially at facilities located on congested areas or old plants which have physical limitations. Therefore, an integration with other noise control measures and regulations, such as occupational safety and economic feasibility, has become one of the important challenges and a direction to go for any new technology development in the cement plant industry to produce the appropriate modular, economical, and adaptable noise control solution.

4.2. Layout Optimization, Noise Mapping, and Administrative Controls

Apart from physical barriers, effective administrative control and careful operational planning are also of great importance in noise abatement at an industrial site. Occupational rotation is considered a significant factor in controlling total accumulated exposure to noise. By rotating staff from areas of low sound level to high sound level, an establishment may be able to significantly reduce occupational NIHL. The exposure of personnel to peak noise levels could be minimized if high-intensity noise-producing operations, such as primary crushing and clinker grinding, are scheduled during low-staff-level shifts. Noise control measures also benefit from modeling and visualization techniques, where optimal allocation of facilities was obtained through modeling and spatial allocation analysis. For example, optimization of plant layout is considered a passive and cost-effective method for reducing the level of noise. The ideal allocation scheme of temporary and permanent facilities for which staff exposure was minimized was calculated using a multi-objective optimization model integrated with GA and ACO (Figure 4) [110]. Optimal allocation can also significantly improve working efficiency, though with higher working difficulty. As administrative and engineering controls only represent a portion of noise abatement system, a hearing conservation program is an indispensable factor of any program on controlling occupation noise, and the constant provision of hearing protector (earmuffs and earplugs) and comprehensive training must be implemented. Fit testing and comprehensive knowledge about chronic effects of noise exposure are crucial to its success [111,112].

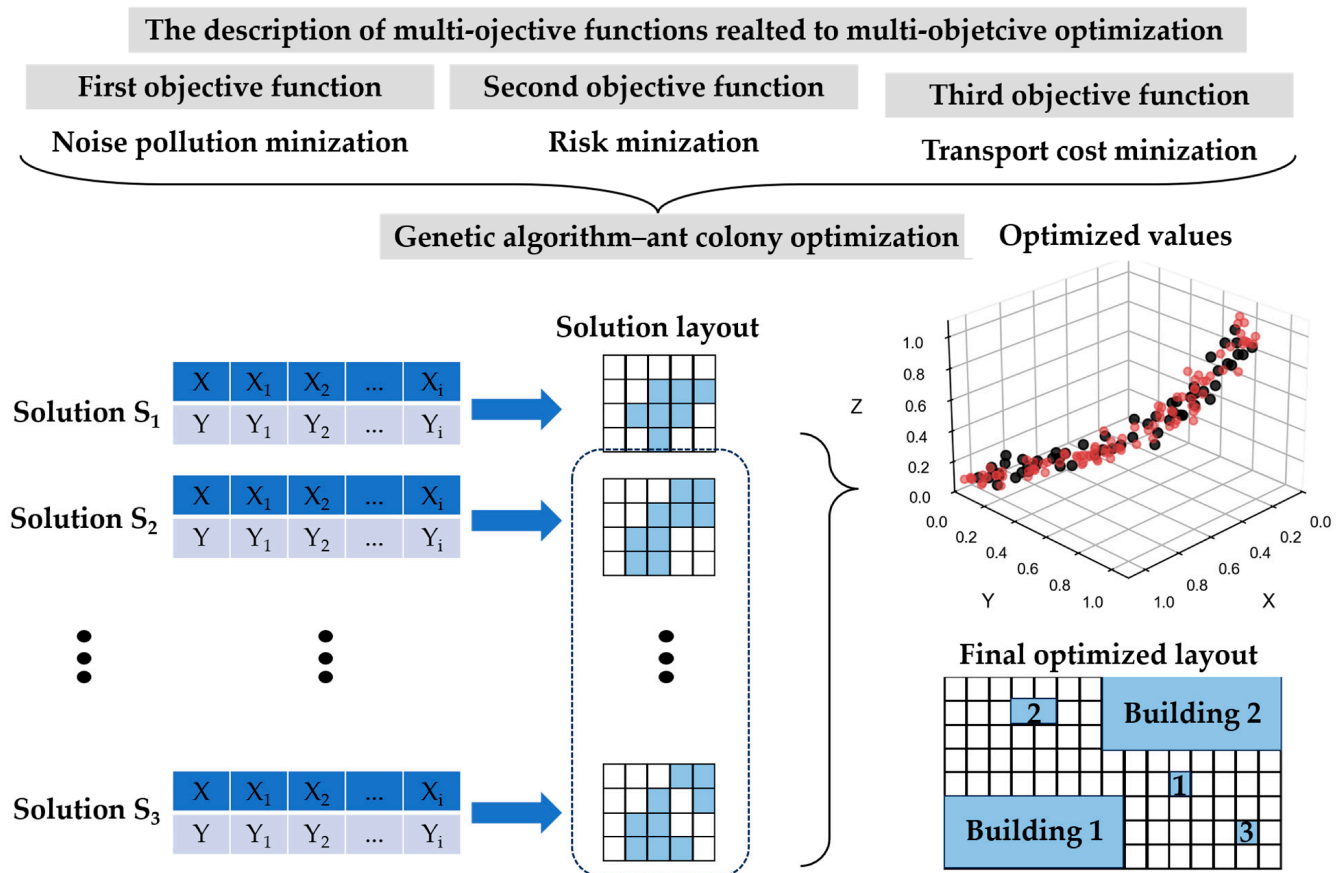


Figure 4. Multi-objective optimization model integrating genetic algorithm (GA) and ant colony optimization (ACO) for optimal facility layout allocation to minimize noise exposure in cement plants.

Administrative and design modifications nevertheless confront major practical challenges in spite of these steps. Rigid output quotas and the continuous nature of cement manufacturing, which necessitates continual kiln operation, frequently limit strategic planning for high-noise operations. Similar to this, engineering controls and layout changes can result in long-lasting noise reductions, but their application is dependent on available funding and site-specific spatial limitations. Therefore, the objective of source reduction must be balanced with the practical and financial constraints of contemporary cement plants in order for a noise mitigation approach to be effective. In order to reduce both traffic noise and fugitive dust emissions, efforts to regulate noise frequently coincide with more general environmental measures, such as building fences or enclosures, installing sound-absorbing materials, and regulating vehicle access. Controlling dust at the source is essential for both air quality and preventing the spread of pollutants to the surrounding environment, since the dust and particles produced during these activities frequently include hazardous trace metals and other contaminants. Soil pollution is the next environmental issue that logically follows from this connection. Soil management is an essential part of integrated pollution control because the deposition, accumulation, and persistence of dust and heavy metals from cement manufacturing can contaminate the terrestrial environment next to production sites.

5. Techniques for Lowering Soil Contamination During the Production of Cement

PM and heavy metal emissions can be seen as significant causes of soil contamination, and this poses a critical danger to the environmental sustainability of the cement industry. These emissions, consisting of trace metals like lead, cadmium, and chromium, disturb the pedosphere biogeochemical system, thereby preventing plants from growing, reducing the production of crops, and ultimately compromising crop yield [113,114]. Because PM is nonbiodegradable and recalcitrant, it remains in soil and groundwater and establishes contamination that is a long-term risk to humans and local plants for decades. Concentrations of PM close to cement industries have been shown to be above acceptable limits empirically. These heavy metals that settle via the atmosphere can accumulate in crops and make their way into the food chain, posing long-term health risks to the populations that live there [115]. As such, once these pollutants have been released into the soil, the need to mitigate this with an integrated approach is a necessity that takes care of source reduction as well as long-term stabilization of contaminated soil in situ.

5.1. Soil Remediation: Engineering, Biological, and Co-Processing Strategies

Several remediation techniques have been developed to eliminate, neutralize, or immobilize heavy metals in the soil in order to lessen the ecological impact of pollutants associated with cement [116]. These methods can be broadly divided into three categories: biological methods, engineering-based approaches like soil washing and microbial remediation, and co-processing in cement kilns. Using heavy metal-contaminated soil as a partial replacement for raw materials in cement kilns, researchers investigated a circular economy strategy [116]. The study assessed the possibility of chemical immobilization in the clinker matrix by substituting contaminated soil at levels of 3%, 7.6%, and 10% for conventional raw materials. Cr-containing soil was discovered to function as a retarder, lengthening the setting time and lowering the final cement product's total compressive strength. The high concentration of some heavy metals can jeopardize the structural integrity of the final concrete, even if co-processing can successfully trap metals in a crystalline structure.

It is important to take into account more than simply the cement's immediate performance when evaluating the environmental danger of co-processing heavy metal-contaminated soils in cement kilns. For atmospheric emissions from cement kilns, such as particles linked to heavy metal co-processing through flue emissions and particulate emissions, as well as their CKD and other residues, we need to create an emission pathway-based study. Because some heavy metals are semi-volatile, they will partially volatilize at kiln operating temperatures and then recondense in CKD and/or other particles. Therefore, to reduce possible atmospheric emissions during soil replacement periods, proper air pollution management measures, such as thorough atmospheric emission monitoring systems, must be implemented. In order to ascertain whether metal immobilization will remain stable in the environment and whether there will be any late effects on soil or groundwater, it is crucial to perform leaching tests on all clinker, cement, and concrete to be used in construction (including CKD or other waste) in addition to monitoring atmospheric emissions. Particularly in developing nations where baseline contamination and the ability to enforce regulations are frequently different, integrating human health risk assessment methodologies and utilizing the concentrations of heavy metals present and potential community exposure pathways can help develop a safe replacement rate for co-processed soils and a monitoring plan for the use of these materials.

Phytoremediation is an alternate technique for co-processing polluted soil in cement kilns [117,118], which extracts, stores, or stabilizes heavy metals in the soil by utilizing plant physiology [119]. Although its efficacy is still very site-specific, phytoremediation

provides less energy-intensive methods. Phytoextraction plants such as *Helianthus annuus* (sunflower) and *Brassica juncea* (mustard) have been shown to significantly reduce heavy metal levels in the vicinity of cement plants [120]. Researchers assessed the capacity for mercury (Hg) extraction from *B. juncea* in various combinations of fly ash (FA) and garden soil (GS) (Figure 5) [121]. With a bioconcentration factor ranging from 0.17 to 0.63, the study found that the majority of the mercury was stored in the plant roots. A 50% FA combination had the highest remediation rate (2.62 mg Hg per kg of biomass), indicating that high pollution levels may eventually reduce the biological efficiency of the plant. Phytoremediation is a “green” and economically feasible method, but its application is constrained by plant saturation limitations and biomass growth rates. Complementary chemical soil cleansing may be necessary for biological approaches in highly contaminated sites in order to lower toxicity levels to a range where plants can thrive.

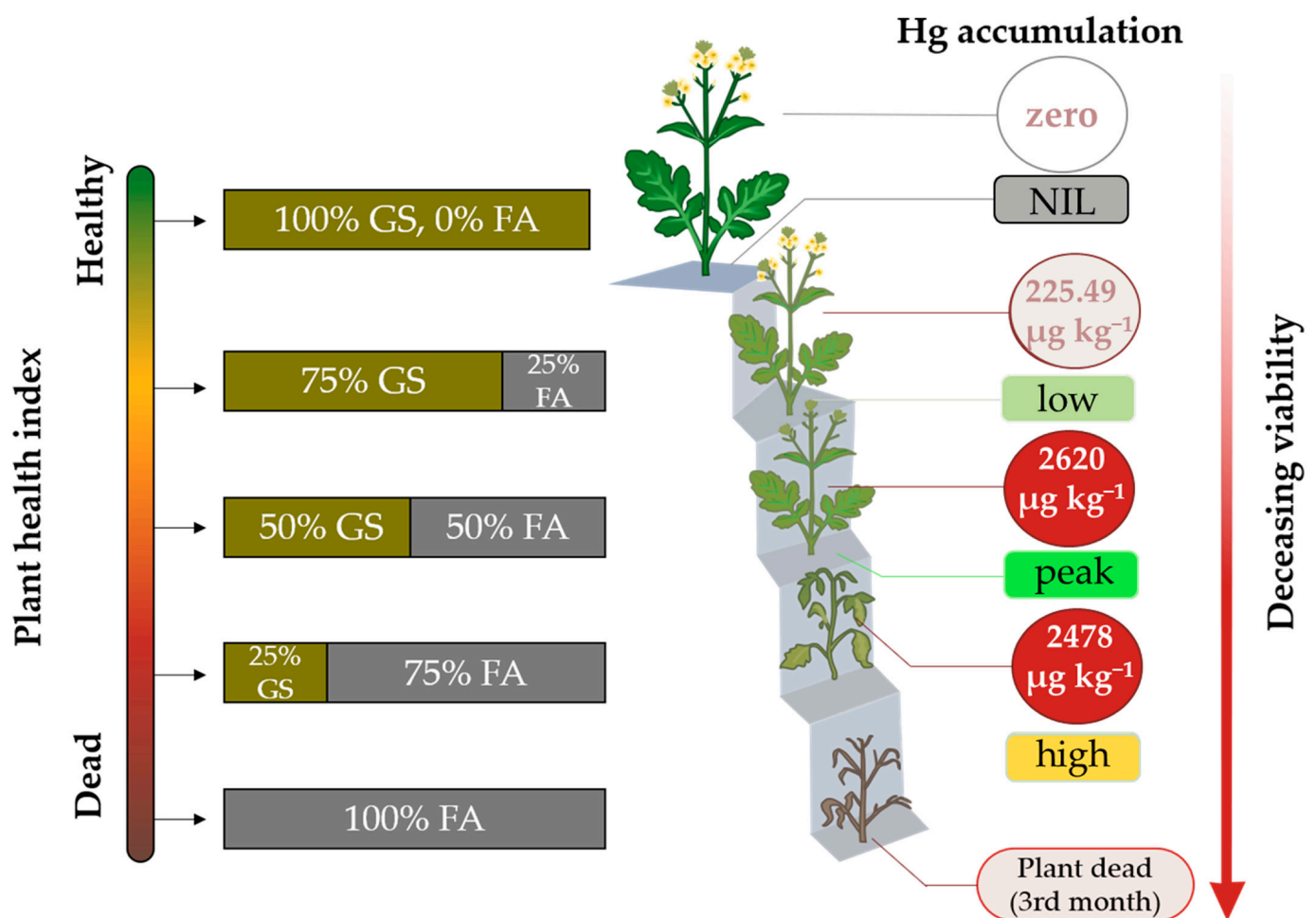


Figure 5. Mercury remediation potential of *Brassica juncea* (L.) Czern. in fly ash-contaminated sites, showing bioconcentration in roots and biomass accumulation.

Soils co-contaminated with heavy metals and polycyclic aromatic hydrocarbons (PAHs) can be treated with bioremediation. Certain resistant strains can endure and flourish in situations where heavy metals like copper (Cu), cadmium (Cd), and lead (Pb) normally limit microbial activity and enzyme function [122,123]. Certain bacteria and fungi like *Bacillus* and *Mycobacterium* have been found to be promising organisms in co-contaminated soil remediation. The latest studies have shown that use of microbial consortia, especially plant-associated microorganisms, can improve remediation efficiencies through reduced metal toxicity by their combined metabolic actions [123]. Acting as mediators and protecting the

key degraders from toxic levels of heavy metals, these bacteria facilitate enhanced biodegradation of organic contaminants. Although it is eco-friendly, bioremediation possesses many inherent limitations. This technology can be successfully applied for the degradation of biodegradable pollutants, while it has not proved to be useful against persistent synthetic pollutants. Biological processes have kinetic limitations, and site remediation takes long periods to be complete. Biological processes are extremely sensitive to changes in operating conditions, such as temperature, pH, nutrient concentration, and concentration of dissolved oxygen. Biotransformation may also result in intermediate products that are toxic. Thus, applicability of the process is usually limited to highly contaminated or large sites where in situ monitoring and control is very difficult.

Beyond the remediation of co-contaminated soils, MICP has emerged as a revolutionary biocementation technique with significant implications for both soil stabilization and the enhancement of cementitious materials. Recent advancements have focused on the static and cyclic hydromechanical performance of cement stone reinforced with fiber carrier-encapsulated MICP [124]. This innovative approach not only offers a sustainable, low-carbon alternative for structural reinforcement and microcrack healing but also demonstrates remarkable durability under complex cyclic hydromechanical loading conditions. By encapsulating MICP-inducing bacteria within fiber carriers, the long-term viability of the biological agents is preserved, ensuring continuous calcite precipitation that mitigates microcracking and enhances the overall hydromechanical resilience of the cement matrix. Integrating such biocementation technologies into the cement industry's mitigation portfolio presents a promising pathway to simultaneously improve structural durability and reduce the embodied carbon of cement-based composites.

Introduction of allochthonous or GMOs to the environment may cause negative impacts on the native microbial population. In soil-washing processes, water or aqueous solutions with medium-phosphate chelating agents are used to remove the heavy metals from soil particles [125]. It has been shown that for an efficient treatment strategy of Zn, Pb, Cd and Hg, a two-step process is required: separating particles from the contaminated soil, with physical properties such as gravity concentration, magnetic separation, and froth flotation, based on physical properties of the contaminants; and removing dissolved metal species or adsorbed metal ions with the use of acids and chelating agents [126]. The authors of the literature stress that integrating these strategies is crucial to maximizing cleanup efficiency, especially in locations damaged by extensive industrial operations or recycling plants [125,126].

5.2. CKD: Distinguishing Pollution Assessment from Beneficial Reuse

To properly address soil contamination, it is imperative to strictly distinguish between pollution assessment (evaluating the ecological risks of cementitious waste) and beneficial reuse (repurposing waste for geotechnical applications). From a pollution assessment perspective, inappropriate disposal of CKD and related waste results in significant chemical contamination of nearby terrestrial ecosystems. Because CKD constitutes 15–20% of total cement production, its traditional landfill disposal poses a severe environmental problem due to high concentrations of sulfates, alkalis, and chlorides that drastically alter soil chemistry and hydrogeology. Conversely, from a beneficial reuse perspective, CKD exhibits potential as a secondary material in civil engineering. Previous studies report that CKD can be effectively used for soil stabilization, improving compaction and permeability. For instance, an investigation into the modification of loess soil using CKD demonstrated that adding 5% to 20% CKD by dry weight yielded a maximum unconfined compressive strength (CS) about 9.9 times that of untreated native soil after 28 days of curing [127]. While these mechanical gains are remarkable, CKD cannot be universally framed as a

sustainable mitigation pathway without rigorous environmental safeguards. Before CKD is widely adopted for soil stabilization, its long-term environmental compatibility must be critically evaluated. The high alkalinity (free lime) and soluble alkalis in CKD can severely modify pore water composition and increase matrix dissolution under fluctuating water tables or high rainfall. Furthermore, leachate tests indicate that trace heavy metals (such as Ba and Cr) can leach from cement–CKD mixtures depending on pH and environmental conditions, proving that heavy metals are not permanently immobilized in ordinary matrices [128]. Therefore, while CKD offers undeniable geotechnical benefits and can prevent the environmental degradation associated with landfill disposal, its application must be strictly conditioned upon comprehensive, long-term leaching and ecotoxicological assessments to ensure that the pursuit of mechanical strength does not inadvertently trigger secondary soil and groundwater contamination.

Regarding its use in cementitious binders, the long-term chemical impact of CKD on hydration kinetics and durability is an essential factor for safe disposal. Studies show that at lower replacement levels (5–10%), CKD can slightly increase the mechanical strength of paste and mortar; however, beyond the threshold value of approximately 15%, compressive and tensile strengths rapidly decrease due to the high alkali content, which disturbs hydration and affects the matrix's structural properties [128]. Long-term durability is also highly sensitive to environmental conditions: in high-rainfall zones or areas with fluctuating water tables, free lime and soluble alkalis in CKD increase matrix dissolution and modify pore water composition over repeated wet–dry cycles. Although recent investigations indicate that incorporating CKD into geopolymer or alkali-activated systems provides greater binding capacity to contain metallic elements and reduces leaching compared to ordinary Portland cement, minimizing waste at the source remains the primary priority. Manufacturers have reduced CKD production by implementing closed-loop processes and controlling operational variables [129], and the use of alternative fuels like RDF and biomass can also reduce net CKD output [130]. However, achieving complete circular waste utilization remains challenging, as CKD utilization heavily depends on market demand and the economic advantages of recycling. Otherwise, landfilling remains the most common disposal method, posing significant hazards to the environment and human health, which underscores the urgent need for proper, long-term, and sustainable waste management schemes for the cement industry worldwide [128].

6. Water Pollution Mitigation in the Cement Industry

The impacts of soil contamination and water quality degradation are interdependent, especially at and around cement plants. Stormwater runoff, leachate, and precipitation events can move unconfined PM or improperly stored waste, such as CKD and other alkaline wastes, and release it into the surrounding environment. Once dissolved in water, heavy metals and elevated pH conditions can form and impact surface and groundwater sources. It is important, therefore, to manage terrestrial and aquatic systems together to prevent cement production pollution [131,132]. The following sections address several management and mitigation strategies that aim to reduce water resources impacted by the cement industry: specifically runoff management, water recycling, and advanced treatment of wastewater. As discussed above, several key aspects make cement production an important and detrimental factor in surface water quality: the discharge of process effluents containing heavy metals, suspended PM, and chemical additives [133–135]. Various aspects of the production cycle result in this discharge: the mechanical treatment of raw materials, the operation of the cement kiln at high temperatures, and runoff from the facility grounds itself. Washing raw materials (sand, limestone, and clay) produces the highest-turbidity effluents, and high concentrations of finely dispersed mineral par-

ticles and associated pollutants are prevalent in these effluents [82,136–138]. Moreover, contamination of surface waters by CKD will also increase the pH of the water, making it highly alkaline and detrimental to aquatic life. The addition of nitrogen, sulfur, and carbonates will further contaminate the surface water and can also contribute to future acidification and eutrophication by reducing the concentration of dissolved oxygen [139]. These pollutants can negatively affect local drinking water sources if a nearby reservoir exists.

6.1. Mechanical Approaches

The minimization of the hydrological impact of cement production involves an integrated technology approach targeting robust treatment, minimizing discharge, and avoiding pollution of water sources [140,141]. Besides end-of-pipe treatment of effluents, management through upstream process improvements should aim at limiting water consumption and effluent generation. Thus, the use of solid recovered fuel (SRF) derived from mechanical–biological treatment of municipal solid waste in cement kilns instead of traditional fossil fuel results in substantial positive impacts [142]. Experimental evidence, including studies in Croatia, shows that SRF can satisfy rigid cement industry requirements with adequate concentration limits for heavy metals and low moisture and ash content. Besides emission control, this alternative fuel can indirectly reduce net water consumption. Besides filtration, a common treatment method for high-particulate wastewater streams [143], it is becoming increasingly clear that long-term operational viability can only be achieved with the implementation of advanced water recycling and purification technologies. Advanced techniques for water recovery include the usage of ultrafiltration (UF) membranes and electrocoagulation. It is reported that UF membranes exhibit very high performance for removal of heavy metals, particulates, and organic substances, reducing pollutants up to 70% in treated water and significantly reducing pollutants in final effluents [144]. Electrocoagulation uses electrical current to cause destabilization and subsequent coagulation of the suspended and dissolved pollutants, and has proven to significantly reduce the COD (chemical oxygen demand) and TSSs (total suspended solids) of industrial effluents, and the produced water could be readily reused in industries.

6.2. Biological Treatment

Although physicochemical treatments such as filtration, membrane separation, and electrocoagulation effectively remove the particle burden and inorganic pollution, these processes are not usually capable of completely removing dissolved organic matter and the remaining nutrient concentrations [145]. Because of this limitation, biological purification techniques now are an important additional strategy for improving effluent quality and achieving sustainable performance. Biological treatment provides an additional level of purification that can increase effluent robustness and water recyclability for cement manufacturing operations by breaking down organic constituents and removing stabilized residue via microbial metabolism. Biological treatments work extremely well at degrading organic matter found at cement plants, although they do not remove metals as efficiently as mechanical filters [146,147].

The use of hybrid bio-support systems and activated sludge processes as potential biological methods for lowering pollution in the cement manufacturing process has been the subject of numerous studies; however, there is currently a lack of significant empirical data to demonstrate the potential benefits of either approach for different cement manufacturing facilities. These biological treatments can be made more successful with specially engineered systems like integrated fixed-film activated sludge procedures. In a pilot-scale system made up of stages of early sedimentation (primary sedimentation),

biological oxidation (aeration), and final sedimentation (sedimentation), researchers evaluated the effectiveness of natural *Luffa* sponges and synthetic polyurethane sponges as bio-support media (Figure 6) [148]. Their results demonstrated that when both media were used in a hybrid manner, removal efficiency was higher than when each method was used separately. For TSS, COD, and BOD (biochemical oxygen demand), the hybrid configuration's elimination efficiency was 94.5%, 87.8%, and 90.8%, respectively. Chemical pretreatment improved the vegetable sponge's effectiveness by increasing its surface area and allowing more microorganisms to adhere to it. This led to better rates of organic matter removal when compared to synthetic sponges.

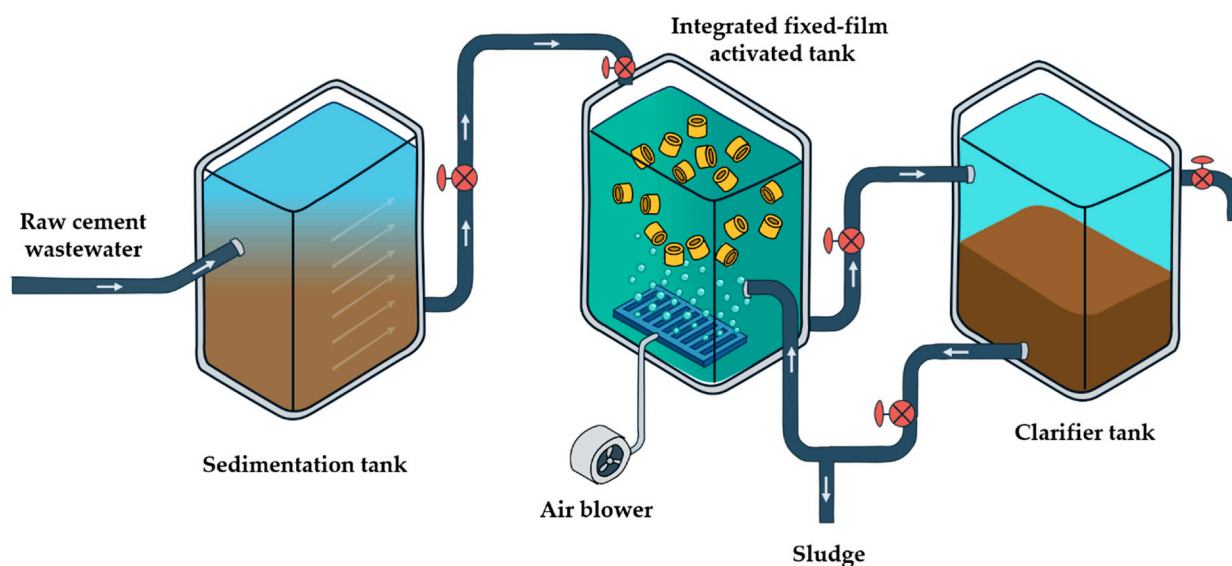


Figure 6. An integrated fixed-film activated sludge (IFAS) pilot-scale process scheme.

It is crucial to delineate the scope of the available empirical data. While the aforementioned IFAS pilot-scale study [148] specifically targeted and validated the treatment of cement industry wastewater, broader applications of biological treatments, advanced membranes, and ZLD systems [149–152] are currently derived from general industrial and municipal contexts. Although these general industrial frameworks offer highly scalable blueprints for advanced water recycling, their specific efficacy matrices for the unique high-pH, metal-rich, and alkaline profile of cement effluents require further dedicated empirical validation before being universally adopted as cement-specific baselines.

Regarding sustained water recycling throughout the entire production cycle, researchers emphasized the essential role of activated sludge systems in the process of degrading organic pollutants [153]. In these studies, biological treatment methods were found effective in the removal of most suspended particles and the mineralization of organic matter in an aqueous phase. However, a general lack of comprehensive demonstration studies on the industrial application scale of activated sludge and hybrid biological systems currently impedes the widespread application of these technologies. In the cement industry, the zero liquid discharge (ZLD) system is considered the most demanding indicator of wastewater management. By means of an advanced combination of processes such as reverse osmosis (RO), evaporation, and crystallization, ZLD completely eliminates any discharge of liquid effluent. ZLD addresses the issue of aqueous contamination by treating and recycling all industrial wastewater within a closed system which is vital for arid and semi-arid regions, where freshwater scarcity is severe [149–152]. In spite of the fact that ZLD is a highly achievable technology for abolishing any liquid discharge of industry, high CAPEX and high energy requirements are a main barrier for its overall adoption. Thus,

sustainable hydrological patterns in cement production can only be attained by technical developments in combination with the development of legal and economic frameworks that ensure industrial participation [152].

7. Regulations and Policies to Lessen Pollution from the Production of Cement

In addition to the development and use of technologies to control the impacts of pollution in the cement manufacturing industry, strong policy and regulation are crucial for controlling these impacts. Without a coherent policy and regulation structure in place to enforce strict environmental standards, direct the practices of the industry, and assign responsibility for actions throughout the life cycle of cement production, control will be difficult. This section reviews policy regulations targeting the reduction of environmental impacts from cement production and more specifically policies targeting GHG and carbon emissions and noise pollution, and prevention of soil and water contamination. These policies are critical components of reducing the cement manufacturing sector's environmental footprint and supporting sustainable manufacturing by specifying limits on emissions, standards for protection of water and soil, and mechanisms for compliance.

7.1. The Carbon Economy and Regulatory Frameworks

Stringent governmental regulations and early policy support are necessary to enable the transition of the cement industry towards a low-carbon industry, as rigorous emission controls have been identified as one of the key drivers of industrial decarbonization [154,155]. A recent study assessed the potential of changing production parameters, such as switching to other fuels and employing clinker substitutions, to significantly reduce overall CO₂ emissions in the cement sector by 2034 [156]. It revealed that despite being an economically viable technology, WHR contributes little to total CO₂ reductions relative to process-based structural changes, such as clinker substitution. The authors argue that supportive policy measures by the government, such as subsidized-interest loans, government research support, and carbon pricing mechanisms, are necessary to facilitate the implementation of sustainable alternatives. The need for bespoke financial mechanisms to compensate for the great initial CAPEX in installing CCUS technologies in the cement sector was subsequently highlighted [157–159].

Strict regulatory standards such as the US EPA Clean Air Act and the EU Industrial Emissions Directive enforce tight emission controls for NO_x, CO₂, PM, and SO_x emissions for developed regions [160]. Currently, a significant regulatory gap exists for emerging economies, as their rapid industrialization struggles to keep pace with enforcement requirements in compliance with global environmental standards. A globally harmonized regulatory framework is needed desperately. Since the last decade, the cost-effective application of economic incentives like the carbon tax and emission trading mechanisms for internalizing the cost of carbon to encourage low-emission technologies has been witnessed for mitigation and decarbonization efforts in developed nations [161]. Nevertheless, it is evident that the deployment of advanced mitigation measures such as CCUS is impeded by high upfront investment costs and inadequate infrastructure, particularly in developing countries. This will be overcome by designing a coherent financial package that includes direct subsidies, soft concessional loans, and favorable funding mechanisms to overcome the financial risks for cement producers. To address technological gaps and lack of technical expertise in emerging economies, strong international technology transfer and capacity-building mechanisms are required. Overall, the combined implementation of stringent regulation standards, tailored economic instruments, and global financial and technical

support is critical to enable broad deployment of CCUS technologies for meeting global emission reduction targets in the cement industry.

In recent studies, the importance of the economic incentive is highlighted in the China context with regard to its effectiveness on promoting low-carbon technology (LCT) uptake [162]. Among various LCTs applied to the cement industry, WHR is currently the most widely adopted, but EMSs (energy management systems) show the best potential in generating systematic energy and carbon saving over the entire cement industry. Based on the analyses, it was proved that a carbon price of CNY 60/t-CO₂ can promote EMS uptake. If the carbon price can reach CNY 100/t-CO₂, then the EMS would be taken up by all survey firms in 2025. Thus, carbon price could be recognized as the key driver of low-carbon investment. However, barriers related to financial issue and technology have constrained LCT deployment widely in developing countries. According to Liu et al. [162], policy instruments such as direct subsidies for CCUS investment and facilitation in access to international carbon trading can facilitate LCT adoption in resource-constrained contexts. The cement industry is a globalized sector; thus, domestic policy also should be complemented by international cooperation to mitigate the potential risks from carbon leakage where production may be shifted to regions with less restrictive regulation and lower levels of effort to meet the target of regional climate goals [163,164]. Without coordinated objectives and harmonized policy frameworks such as carbon pricing to create a fair playing field, sustained low-carbon investment without compromising the competitive position of regulated firms is unlikely, since the costs of developing clean technologies may increase their disadvantage in the global market, and thus effective globally coordinated policy measures should be taken to avoid “low-carbon dumping” [163,164].

7.2. Policies and Regulatory Frameworks for Reducing Noise

Governments and international institutions have to design, implement, and enforce specific acoustic legislation to prevent noise pollution in the cement production industry. Through the introduction of financial mechanisms such as tax allowances, subsidies, and carbon credits, companies will be encouraged to implement sophisticated abatement equipment and best available techniques (BATs), thus making compliance financially beneficial and environmentally appropriate. In fact, cement producers will have the opportunity to decrease GHG emissions as well as improve noise management within the plant by harmonizing site-specific noise control policies with environmental goals in terms of climate change abatement. Legislative frameworks specifically regarding noise control are obliged to clearly define auditable and measurable acoustic emission thresholds for proximate residential and commercial areas [165]. By prohibiting further residential expansion in noise-intensive industrial areas, these dedicated acoustically protected areas will largely reduce public health risk factors. International bodies such as the World Health Organization (WHO) and their *Guidelines for Community Noise* set levels of exposure that are considered appropriate for preventing noise annoyance and sleep disturbance based on a scientific framework. In the European Union, the industrial emission directive (IED) establishes strict emission standards for the entire production process, including the control of noise emission from cement plants, and requires producers to make use of BATs to limit noise at the source [6]. Finally, accurate control and systematic auditing of actual acoustically enforced situations is necessary in order for these regulations and innovative technology not to remain unimplemented.

Strong regulatory mechanisms must be used to make sure that policy moves into actual practice. According to the literature, a proactive approach to regulation that is above exposure limits must be embraced [26]. A combination of policies that include carbon pricing, emission trading, and specific subsidies are used to induce plants to take

appropriate action to reduce both noise and carbon emissions at the same time. Similarly, due to the lack of capital for investments in innovative noise abatement technology in some of the less affluent countries, the use of interest-free loans and other financial support will likely enable investment in acoustical barriers, improvements to equipment, and maintenance to combat the ongoing operation of machinery and associated mechanical degradation, which tends to increase the operational noise. Continued vigilance is necessary to ensure compliance, and empirical work clearly indicates the need for long-term, well-resourced compliance programs [166]. The internal installation of sound level-monitoring devices at several locations inside the facility, as well as outside along the perimeter, allows operators to obtain live telemetry to support zoning. This type of organized acoustic survey will be critical in helping engineers detect isolated sources of offensive sound that could be missed in a routine visit to the plant.

Additionally, socioeconomic and financial incentives strengthen compliance enforcement. Researchers pointed out that punishments such as fines and penalties can give high economic incentives not to comply and therefore force industry to take action for noise abatement. Participatory feedback mechanisms in the framework of collaborative governance can build local trust and social acceptance, and hence prevent industrial facilities from potential litigation and local opposition, as well as make noise mitigation strategies adapted to local needs. Effectiveness of these noise abatement measures is linked directly to frequency of measurement and enforcement strictness. Coordinated international efforts, such as alignment of noise regulations and carbon trading mechanisms, are crucial to create a level playing field in the global market and prevent the problem of “regulatory arbitrage,” which leads the industry to move to locations with laxer environmental regulation. Such an aligned global framework would help cement makers in developing economies by securing a steady market for them, improve global competitiveness, and promote international and regional environmental goals. In reality, however, the situation of a multitude of emerging economies with inconsistent regulation often leads to either weak enforcement or poorly formulated regulations in terms of environmental standards [167]. With application of remote sensing technology, automatic continuous measurements, and standardization of auditing procedures globally, abstract regulatory principles can be implemented efficiently across the industry, ensuring all cement facilities comply with social and environmental responsibilities.

7.3. Policies and Regulations to Lessen Soil Pollution

Strict government regulation of the management and disposal of hazardous waste is essential to reducing soil contamination in the cement sector. The use of soil remediation technologies could be encouraged by a number of financial incentives in addition to current government restrictions. These incentives could assist in covering some of the initial investment expenses (such as those associated with bioremediation and phytoremediation) and the use of carbon trading systems. Governments could provide financial breaks to businesses that utilize alternative fuels or reduce their impact on soil contamination by using low-impact disposal techniques in addition to regulatory control. Regulatory agencies must enforce thorough waste management procedures that handle these wastes as restricted substances in order to stop CKD and heavy metals from seeping into the pedosphere [167]. A strong example for this control is provided by international references like the US EPA regulations and the EU Industrial Emissions Directive (IED), which mandate that establishments adhere to strict limitations for pollutants discharged into the air, soil, and water [168,169].

A study that examined the relationship between FDI and the EU Emissions Trading System (EU ETS) further demonstrates the efficacy of these multilayered rules [170]. Ac-

According to their case study at a cement plant, adhering to these two frameworks produced a notable “joint benefit” effect that reduced SO₂ emissions by 65%, NO_x emissions by 30%, and PM emissions by 80%. These decreases in air emissions are directly linked to a lower risk of soil contamination, since atmospheric particles are the main vector for heavy metal deposition. Effective governance, however, necessitates a proactive infrastructure for regular environmental audits and goes beyond merely establishing boundaries. In order to find “hotspots” of contamination before they develop into systemic ecological problems, the literature highlights the necessity of routine soil and water sampling [171]. Government organizations should give financing for automated tracking technology top priority in order to protect the integrity of these monitoring systems. They should also promote collaborative governance by encouraging community involvement in reporting infractions. Governments can also assist by financing local environmental monitoring programs and encouraging the adoption of new, eco-friendly techniques for clearing up contaminated soils. Governments that collaborate with local communities provide people the chance to report contaminated soil and offer financial rewards to those who use inexpensive techniques to clean up their local soils.

In many high-growth regions, a global “regulatory gap” nevertheless exists despite the provision of these frameworks. Inadequate enforcement mechanisms allow facilities to operate without the necessary oversight to preserve local natural resources and public health. In order to address the need for regulation in rapidly expanding areas where established standards are lacking, international collaboration in the establishment of regulatory frameworks connected to soil pollution control and carbon pricing is crucial. Developing nations can learn how to use best practices in soil remediation through technology exchange programs and financial support from more developed nations. This will guarantee that cement plants in these developing nations adhere to the same international criteria for controlling soil contamination as all other facilities.

7.4. Policies and Regulations to Lessen Water Contamination

The deployment of uniform effluent treatment techniques and the efficacy of government control are critical to mitigating water deterioration in the cement sector. In addition to establishing strict guidelines for wastewater disposal, regulatory organizations are essential in promoting the use of circular water management techniques in industrial processes. Cement manufacturers can install advanced wastewater treatment and recycling technologies like reverse osmosis (RO), zero liquid discharge (ZLD), and electrocoagulation with the help of economic tools like tax exemptions, subsidies, and regulatory incentives. These incentives enable broader industry adoption and more sustainable water management practices by lowering the upfront costs of these technologies. Researchers looked at Croatia’s recovered solid fuel (RSF) regulations and found that co-incinerating waste in cement kilns can lower environmental externalities [142]. Adherence to European Union CSR quality standards guarantees ecologically responsible energy recovery procedures, demonstrating the connection between water pollution reduction and solid-waste management. In a similar vein, another study highlights the significance of strict effluent rules concerning COD, BOD, and TSS, emphasizing life cycle assessment (LCA) as an essential instrument for environmental policy and auditing [153]. However, development is still hampered by uneven regulatory enforcement and inadequate financial incentives.

One of the greatest ways to assess the health of aquatic ecosystems is to use biomonitoring to track the effects of pollutants. The need for biomonitoring of water pollution is growing as our civilization produces ever-increasing volumes of pollutants as a result of expanding industrial, agricultural, and home activities. Microbial toxicity testing has been particularly successful in evaluating and quantifying chemical toxins present in aquatic

environments through a variety of biomonitoring techniques employing ISO- and OECD-standardized methodology. These techniques enable scientists to guarantee the security and purity of water supplies utilized for human consumption, as well as to precisely evaluate the health of ecosystems.

Experts examined the ISO/OECD tests that are now available for determining how contaminants affect the microbial population and the surrounding aquatic environment [172]. They specifically describe the sensitivity and limitations of existing assays, such as inhibition of respiration, inhibition of nitrification, and luminous microorganisms. Additionally, they coined the phrase “physiological potential of the inoculum” as a foundation for assessing a microorganism’s suitability as an inoculum. They support the creation of an integrated toolkit targeted at minimizing animal testing and advise using these tools as pretests for biodegradation investigations. To demonstrate the viability of continuous ecotoxicological tracking, scientists assessed the Microtox testing system in the industrial effluents collected in the city of Camaçari (Bahia, Brazil) [173]. For around 25 years, the wastewater treatment plant (WWTP) (Figure 7) has been collecting and treating wastewater from the IDC, which is made up of 52 industrial facilities engaged in several production sectors, including chemical, petrochemical, metallurgical, pulp and paper, and brewing. It is important to contextualize that this WWTP represents a combined municipal–industrial treatment system rather than a cement plant-specific effluent. Nevertheless, the study demonstrated that following effluent treatment, toxicity was reduced by 92.71% and COD by 83.04% using the *Vibrio fischeri* luminescence method. While this exact quantitative reduction is specific to the IDC’s mixed profile, the case study is highly relevant to the cement sector as it proves the regulatory and operational viability of integrating standardized Microtox biomonitoring with industrial wastewater management. For cement plants operating within or discharging into similar combined systems, adopting such ecotoxicological tracking ensures compliance with stringent aquatic health metrics.

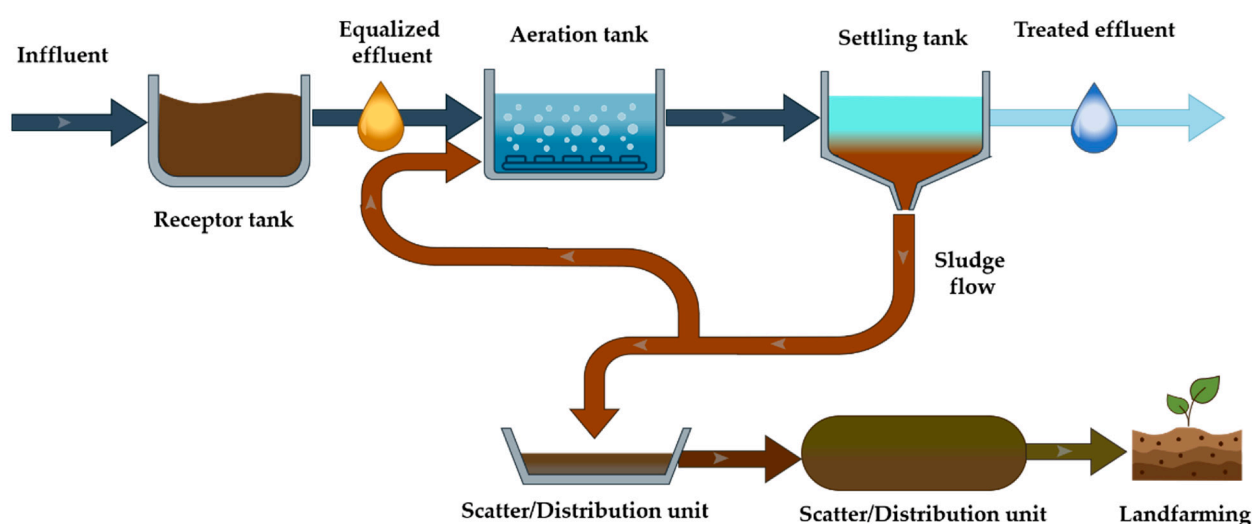


Figure 7. Schematic representation of an industrial wastewater treatment plant (WWTP).

Microbial toxicity tests are quick, sensitive, and successful in identifying a variety of harmful effects on microorganisms, such as contaminants from contaminated water, wastewater treatment facilities, and industrial waste. Among them are tests that use luminous bacteria, like *Vibrio fischeri*, also referred to as Microtox, to detect light production in order to evaluate the toxicity of contaminants and their effects on microorganisms engaged in nutrient cycle and biological decomposition [174,175]. The toxigenic potential of *Aspergillus fumigatus* isolates from patients with invasive aspergillosis, aspergillomas, colonized persons, and environmental samples was assessed by experts using the Microtox

bioassay [176]. Luminescent *V. fischeri* analysis of toxic culture filtrates showed notable variations in agglutination rates, with isolates from invasive aspergillosis patients showing more toxigenicity. The study showed that the Microtox bioassay is a useful method for monitoring environmental pollutants, such as mycotoxins, in treated water and sewerage systems, even if the primary focus is on fungal toxigenicity. Researchers examined how different substances, including pyrazole, phenol, N-methylaniline, and DMPP, inhibited nitrification [177]. The degree of inhibition was directly correlated with the compounds' biodegradability: short-term reversible inhibition was caused by biodegradable substances like phenol and N-methylaniline, whereas long-lasting inhibition, even at low concentrations, was caused by poorly biodegradable substances like pyrazole and DMPP. The researchers also emphasized that nitrification inhibition is greatly influenced by the length of time and the technique of chemical administration, whether it is added directly to the effluent or present in a solvent. Toxic compounds that are not biodegradable can have long-lasting impacts, which puts wastewater treatment procedures at serious danger.

Activated sludge or pure bacterial cultures like *Pseudomonas putida* are frequently used in biomonitoring to evaluate how contaminants affect microbial development. Growth inhibition assays reveal details about the microbial population's health and the possible long-term effects of chemical exposure on species essential to water treatment [178]. Microbial toxicity tests are sometimes paired with ecotoxicological assays that include organisms from higher trophic levels, such as fish, algae, and *Daphnia*. This integrated method reveals both immediate toxicity and possible long-term consequences on biodiversity and ecosystem services, enabling a thorough evaluation of the effects of pollutants on several organisms and ecosystem functions [179]. Data on the toxicity of cement products have been gathered into summary tables that provide an overview of study types, biological testing systems, target organisms, exposure pathways, ecotoxicological impacts, and human health indicators in order to support monitoring and management activities. These data are summarized in Tables 3–5, which show the range of microbiological and ecotoxicological tests, species examined, and exposure routes utilized to evaluate the effects on the environment and human health.

Table 3. Microbial toxicity testing conducted on contaminants associated with cement production.

Testing Organism	Pollutants Assessed	Toxicity Endpoint	Conclusion	Reference
Recombinant luminescent bacteria	Zn, Cd, Hg in contaminated soils	Metal bioavailability response	High susceptibility to bioavailable heavy metals in soils affected by cement	[180]
Activated sludge microorganisms	CKD, high-alkalinity wastewater	Respiration inhibition	Microbial respiration is significantly reduced at high pH and metal concentrations, which impacts the effectiveness of biological treatment.	[28]
Mixed bacterial consortia	Cement wastewater	Growth inhibition	Inhibited the growth of microorganisms in alkaline and metal-rich environments	[181]
<i>Vibrio fischeri</i> (Microtox® bioluminescence test)	Alkaline effluents, heavy metals, and cement leachates	Luminescence inhibition (%)	Acute microbial toxicity is indicated by a quick and sensitive reaction to metal-rich and high-pH cement leachates.	[182]

Table 4. Ecotoxicological effects of cement industry pollution on aquatic and terrestrial species.

Organism	Toxicity Endpoint/Exposure Medium	Ecotoxicological Effects Seen	Reference
Fish larvae	River water that is contaminated Behavior and survival	Increased mortality and changed swimming habits	[28]
Invertebrates in the soil	Soil affected by industrial dust: survival and reproduction	Decreased markers of soil fertility and population density	[183]
Crops grown for agriculture	Soil contaminated by cement and metal uptake (bioaccumulation)	High levels of Pb, Cd, and Cr in the tissues of food plants	[184]
<i>Daphnia magna</i>	Mobility inhibition and cement effluent/LC50	High quantities of heavy metals linked to acute toxicity	[185]
Algae (<i>Chlorella</i> spp.)	Surface water and growth suppression close to cement plants	Decreased biomass growth and photosynthetic activity	[29]

Table 5. Human health risks and toxicity endpoints related to cement industry pollution.

Principal Contaminants	Pathway of Exposure	Endpoint for Health	Health Hazards That Have Been Reported	Reference
Ni, Cr, Pb	Dust in homes	Risk factors for cancer and non-cancer	Children that live close to cement plants have higher health risk indices.	[186]
Cd, Pb, Cr	Soil–food chain transmission	Toxicity and food safety	Risks of dietary exposure as a result of metal bioaccumulation in crops	[187]
Heavy metals, high pH	Contamination of drinking water	Impact on the kidneys and digestive system	Prolonged exposure to metals may pose long-term health hazards.	[29]
NO _x , PM, SO ₂	Ambient air	Effects on the heart and lungs	Higher risk of long-term respiratory conditions in neighboring communities	[188]
Noise, PM, heavy metals	Inhalation at work	Loss of hearing and respiratory stress	Increased frequency of respiratory problems and hearing loss brought on by noise among employees	[20]

Cementitious material waste and effluents are specially evaluated for hazardous elements that can damage microbial populations, such as heavy metals and strongly alkaline compounds. Assays for microbial toxicity, such as growth inhibition and luminous bacterium tests (like Microtox), make it possible to systematically evaluate these pollutants and compare them across various ecological compartments and human exposure pathways. The cement industry can prevent pollution and track the efficacy of mitigation techniques in real time by combining biomonitoring with sophisticated treatment and recycling practices. Ecotoxicological information on aquatic and terrestrial organisms, such as *Chlorella* algae and *Daphnia magna* (water flea), can be found in Table 4. The information in this table illustrates the different ways that concrete affects the health of ecosystems (e.g., inhibition of aquatic plant development, behavioral changes/responses in fish). The possible threats to human health posed by pollution from cement production processes are highlighted in Table 5. It highlights the need for improved environmental and health monitoring at cement plant facilities by providing information on the various forms (or “pathways”)

of human exposure to emissions from the cement industry, how these emissions can harm human health (e.g., through inhalation of particles and/or exposure to “ambient air pollution” or “dust” generated in/within residential areas/products derived from cement plant operations), and the associated health risks (e.g., respiratory stress, cardiovascular disease, and long-term effects like cancer).

Because of their speed, simplicity, and great sensitivity, microbiological toxicology tests are crucial in determining how water pollution affects the environment. Microbiological toxicology tests enable a thorough evaluation of water pollution and support efficient mitigation techniques when paired with ecotoxicity assays and biodegradation studies. Additionally, they provide an ethical and effective method of environmental risk assessment by eliminating the necessity for animal experimentation. In conclusion, updated regulatory frameworks, thorough compliance monitoring, and focused funding are necessary for the shift to sustainable water management. Governments should fund research and development of affordable water treatment and biomonitoring solutions as well as offer subsidies to support cutting-edge wastewater treatment technologies. Effective water recycling and reuse should be required by law, and biomonitoring programs should be encouraged in order to regularly evaluate the health of ecosystems and water quality. By making sustainable water management technology available, especially in water-scarce areas, the cement industry will be able to limit its water impact, use less freshwater, and protect the environment and public health.

8. Strategic Thematic Extensions: Digitalization, Circular Economy, and Harmonized LCA

The sustainable transformation of the cement industry is not only reliant upon the isolated implementation of mitigation technologies or design of policy instruments, but also upon the synergy between among transversal axes: (i) digitalization and artificial intelligence for operational control and prognosis of the environmental impact; (ii) industrial symbiosis and circular economy mechanisms where environmental burdens become regional resource streams; and (iii) harmonized, yet adaptable life cycle assessment frameworks to guide and critically measure the efficacy of decarbonization road maps. This section builds upon the three cross-cutting axes mentioned in the main text (Table 1, Sections 3.2, 5.2, 6 and 10) and provides a strategic road map for accelerating large-scale industrial implementation. Cyber-physical systems are being integrated into the cement production process, pushing forward the frontiers of environmental control and energy efficiency. Although the main text recognizes optimization of processes and digitization as a CO reduction lever (Table 1), the most recent literature emphasizes a paradigm shift in how AI, IoT, and digital twins are now enabling new process efficiencies.

Digital twins are the dynamic virtual counterparts of rotary kilns, preheaters, mills, and clinker coolers coupled with machine learning algorithms. These make it possible to simulate the thermal profile, calcination kinetics, and mineralogy, for example (alite, belite, aluminate), the predictive estimation of the emission peaks (NO_x, SO₂, PM, and CO₂) within a 2–6 h lead time, thus allowing anticipation feed and combustion, and finally multivariable optimization through APC reducing by 5–12% the specific thermal energy consumption and by the quality steadiness of clinker. High-resolution sensors within the process produce a data flow to be processed in edge or cloud: as far as air is concerned, high-resolution CEMS with indicators of volatile metals (Hg, Cd and Pb), ultrafine particles (PM_{0.1}), and VOCs; for water, real-time pH, conductivity, turbidity, COD, and metal sensors placed along the outlets and the reuse circuits; and finally, for soil and noise, networks of miniature weather stations, telemetered piezometers, and georeferenced noise dosimeters for impact zones. Operational, maintenance, and raw material quality information can be used to train

machine learning models that allow predicting refractory wear and mill misalignment or fan failure, the remaining life span of the SCR catalyst and the ultrafiltration membranes, and the best blend of SCMs and alternative fuels based on their availability and the set carbon emission limits (Table 6).

Table 6. Implementation of AI, IoT, and digital twins in the cement sector, including operational challenges and mitigation strategies.

Challenge	Strategic Mitigation
Data silos and protocol incompatibility	Adoption of open standards (OPC UA, MQTT) and the federated data architecture.
Cybersecurity of critical systems (OT/IT)	The steps that will be taken to secure the network include: segmentation of the network, encrypting the end-to-end traffic, and performing regular audits on the system.
Lack of qualified staff	Training and professional development programs in collaboration with universities and technological centers.
Unknown return from legacy plants.	Implementation by module (scaling-up pilot) and financing through green loan to the efficiency KPI.

By nature, the cement sector is already circular: it turns waste into resources, sequesters contaminants, and is reusable after the end of his lifetime. However, circularity at a sectoral level is still segmented. Industrial symbiosis is one of the ways in which material and energy stream from one sector to another sector and to regions/value chains, and is enabled by an organization principle. There is a series of principles in the cement sector, such as the closing of the material loops: using regional supplementary cementing materials (SCMs) instead of clinker (slag, ashes, calcined clay, processed C&D waste); utilizing CKD as an additive for geotechnics, soil amendment, and secondary raw material (5–15% substitution); cascade recycling of process water integrating ZLD and non-potable water reuse; energy and heat exchange through WHR to district heating networks and adjacent industrial processes (drying, pasteurization, distillation); integration with biomass or biogas plants for meeting the residual thermal energy demand; and co-processing (environmental service). Safe landfilling of hazardous wastes, sludge from wastewater treatment plants, soils (contaminated) and tires with their thermal and mineral integration into the clinker matrix generate revenue for waste management services. Moreover, an alternative way of accounting for circularity and the metabolism of industrial sectors lies in a number of indices, e.g., the MCI (material circularity index), defined as the ratio between secondary/recycled inputs to the total input requirement, mass flow analysis with huge accounting of inputs and outputs of key elements (Ca, Si, Al, Fe, and trace elements) on a regional scale, and embodied carbon footprint, which includes CO₂ avoided from the substitution of clinker, reverse logistics, and during carbonation over the entire lifetime. These indicators will reinforce the circularity and industrial metabolism index of the cement industry. A few structural challenges can be outlined as far as regulations, legislation, and infrastructure are concerned, i.e., regulation and framework (classification of the waste as “by-product” or “waste” depends on region, leading to uncertain long-term investment planning), logistic constraints (using low-emission transportation for exchanges of secondary materials and thermal mass on a regional level), market constraints (variability in availability of SCMs and alternative fuels leading to the need for long-term agreements and strategic stockpiles).

Reliable, transparent, and comparable LCAs are needed to support the scientific validation of decarbonization routes. This manuscript mentions harmonization needs (Section 10), and literature reviews are identifying further areas where deficiencies will make it difficult to avoid greenwashing and support public policies. ISO 14040/44 [189,190],

EN 15804+A2 [191], and PCRs for cement and concrete are appropriate standards. The system boundary “cradle-to-gate” seems too narrow. Evaluating the whole-life-cycle “cradle-to-grave” or “cradle-to-cradle” is suggested. This system shall include extraction and pretreatment of raw materials, clinker/cement manufacturing (including CCUS, WHR, SCMs), use and hardening of concrete; and end-of-life secondary carbonation, demolition, crushing, and recycling. When attributing impacts, the most important aspect to highlight is that the chosen allocation methodology (mass, economy, or energy) has to be used consistently throughout the study and sensitivities to any changes of methodology must be included. Static LCAs fail to accurately represent impacts because they do not consider the impact of time: (1) concrete gains carbon-fixed from the atmosphere during service life and end of life that represent 10–25% of the CO₂ footprint of production; (2) environmental benefit of WHR, partial electrification, and CCUS increases as CO₂ impact on the grid gets reduced over time; (3) and cost and energy benefits from CCUS, geopolymers, and LC³ are expected in 10–20 years once they are commercially viable. Environmental benefits of alternative cements only hold if structural performance, maintenance, delivery of liquid activators, and end of life are also included in LCAs. LCAs that compare only the production phase favor some materials (Table 7).

Table 7. Comparison of the environmental performance, durability, and maturity of alternative cements versus traditional Portland cement.

Parameter	Portland Cement (OPC)	LC ³ /Belitic Cements	Geopolymers/Alkaline-Activated
CO ₂ reduction (production)	Baseline	30–50%	50–80%
Embodied energy	High	Moderate	Low–moderate
Durability/carbonation	Well characterized	In accelerated validation	Dependent on healing and matrix
Availability of raw materials	Global	Regional (clays and slags)	Linked to industrial waste
Standard maturity (EN/ASTM)	Consolidated	Expanding	Limited/project-specific

LCA may be used as a governance tool, e.g., to be used as a basis for EPDs, becoming a standard in public procurement and certifications, LEED, BREEAM, AQUA, or to support CBAM and carbon pricing, allowing the auditable accounting of embedded emissions in exports and regulation compliance, allowing integration with ESG and ISSB/TCFD reports through LC metrics bridging physical and climate disclosure. At the end, an ecosystem for decision-making through the conjunction of digitalization, industrial symbiosis, and dynamic LCA emerges in support of cement transition (Table 8). Recommendations by stakeholders depend on the authors, e.g., the industry shall focus on the digitalization of kiln control and adoption of regional SCMs prior to the investment of CCUS at industrial scale and use the cradle-to-grave LCA for new products. Governments and regulators should provide a legal framework recognizing the value of industrial co-products and facilitate symbiosis licenses and harmonized EPDs in public tendering. Academic centers and research facilities should focus on developing regionally customized LCI inventories, dynamic models for carbonation, and long-term validation protocols for new binders. Funding agencies should mandate that green credit lines depend on achieving appropriate values for MCI (>0.4), energy consumption (<3 GJ/ton clinker), and audited LCA data reporting.

Table 8. Gradual deployment framework: layers of action, enabling technologies, and maturity horizons.

Layer	Function	Technologies Enabling	Maturity Horizon
1. Monitoring and control	Continuous data collection, fault prediction, real-time optimization	IoT, APC, predictive AI, multimedia sensors	Commercial (TRL 8–9)
2. Circular integration	Closing material/energy cycles, co-processing, regional symbiosis	Expanded WHR, SCM networks, ZLD, logistics reverse	Pilot/commercial (TRL 6–8)
3. Validation and governance	Impact measurement, compliance, market transparency	Dynamic LCA, EPDs, traceability blockchain, MRV for CBAM	In consolidation (TRL 5–7)

9. Regulatory, Economic, and Governance Frameworks

The path of decarbonization and environmental mitigation in cement production requires a coordinated mix of effective public policies, appropriate market instruments, and clear governance frameworks and does not rely exclusively on technological progress. This part of the study extends the regulatory analysis done in Section 7 and takes into account international trade adjustment measures, ESG disclosure regulations and criteria, climate financing, and the necessary multilevel governance to allow this global transition by 2030. The European carbon border adjustment mechanism (CBAM), which started its final implementation process this year, changes the rules of the game for international competitiveness of carbon-intensive products and includes cement in its list of prioritized industrial sectors. Importers will need to declare integrated (direct and then indirect) emissions and buy CBAM certificates that reflect the CO₂ price within the EU ETS, thereby offsetting the competitive advantages originating from less strict climate regulation in their country of export. For developing countries and exporters from Latin America, Asia, and Africa, CBAM gives rise to three challenges, as follows. (1) MRV (measurement, reporting, and verification) capacity, given that most plants do not have a continuous CEMS (continuous emission monitoring system) or a standardized method of calculating process (calcination) and scope 2/3 emissions. (2) The absence of domestic carbon pricing in exporting countries implies that the European carbon price would translate fully into a trade surcharge, reducing export profit margins from 8% to 15% in cases of conventional cements. (3) Risk of trade fragmentation, as similar schemes are being considered in the UK, Canada, and regional trade blocs, and an internationally standardized approach is necessary to avoid overlap in regulations and technical trade barriers. The imposition of CBAM, on the other hand, provides the incentive to modernize the sector: in particular, plants that are likely to adopt WHR (waste heat recovery), a higher share of clinker replacement by SCMs (supplementary cementitious materials), and partial CO capture systems would be able to obtain better prices and sign long-term contracts with institutional buyers that meet low-carbon purchasing requirements. In order to prevent carbon leakage and to guarantee business justice, the harmonization of carbon calculation standards (e.g., EN 15978, ISO 14067 [192,193]) and the mutual recognition of carbon certificates are preconditions.

Frameworks of sustainability went from optional to a prerequisite of being able to access capital and the right to operate. Through a cascading adoption of IFRS S2 (ISSB, in compliance with TCFD), GRI 12 (cement and mining sector), and SASB (sustainability accounting standards), reporting entities not only need to disclose the emissions of GHGs, but also key indicators on social impact, health in the workplace, and the management of risks (physical and transition) and opportunities arising from climate change. With the cement sector, it is indispensable that an effective ESG framework also includes quantitative climate data such as the emissions of scopes: 1 (process, combustion), 2 (electricity), and

3 (supply chain management of SCMs, logistics, use of the products). The reports shall present emission reduction pathways consistent with scientific scenarios and stress tests in response to climate change. Data on health indicators (occupational exposure to noise, PM, heavy metals, and CKD, monitoring of effluents and adjacent soils, index of conflicts with local communities) and other socioenvironmental aspects are essential as well. These data, already systematized in Tables 3–5 of this manuscript, need to be reported annually, supported by independent assurance. Governance and anti-fraud disclosures should involve board-linked sustainability committees, due-diligence policies concerning supply chains of SCMs and alternative fuels, and third-party assurance procedures to mitigate the “greenwashing” risk in any “green cement” or “operational neutrality” claims. Regulatory convergence (EU CSRD, SEC climate disclosure, CVM 590/IN CVM 81, Brazil) sets a precedent where the deliberate misstatement or lack of information regarding environmental data could result in financial penalties, lack of access to financing, and removal of export licenses. Companies establishing continuous data collection through IoT, blockchain for input traceability, and integrated ESG reporting platforms will build a strong competitive advantage on a structural basis.

For CCUS, ZLD, alternative binders, and advanced digitalization, economics is the key driver for the mitigation technologies and depends significantly on the financial mechanisms designed to internalize the externalities and decrease the cost of capital. There are three types of vectors already at play in the current ecosystem (Table 9). The pricing of carbon, through taxes, permit trading, or sectoral systems, has emerged as the key catalyst for the uptake of the fastest, cheapest, and most easily deployable technologies. Studies suggest a carbon price of USD 60–80/tCO₂ drives substitution of clinker on a large scale and energy optimization, and above USD 100/tCO₂ for CCUS and alternative cements. Nevertheless, the lack of social protection and professional retraining tools may spark union and political opposition. Just-transition funds (fueled by carbon auction income or sectoral taxation) are needed in order to avoid industrial insecurity or local instability while implementing decarbonization.

Table 9. Financial instruments and markets to support the transition to a sustainable cement sector.

Instrument	Application in the Cement Industry	Conditions for Effectiveness
Green bonds and sustainability-linked loans	WHR financing, partial electrification, furnace upgrade, water recycling	Credible CO ₂ reduction targets per ton of clinker, fines for failure to meet these targets, and application of respective taxonomies at the regional level (EU, ASEAN, LatAm)
Carbon markets (compliance and voluntary)	Offsetting credits via clinker replacement, CO ₂ capture, soil remediation, and biomass sustainability	Well-demonstrated additionality, solid MRV, prevent double counting, alignment with Paris Article 6
Blended finance and just transition funds	CCUS, geopolymers, ZLD in arid zones, worker training on techniques	Public–private partnerships, sovereign guarantees, risk-sharing provisions, attention to TRL 6–8

Integrated pollution control (air, water, soil, and noise) requires governance arrangements beyond simple legal compliance and active involvement from diverse stakeholders. Some initiatives of this kind, for example, are the 2050 Net Zero Roadmap adopted by the GCCA, where sectors have set objectives, share good practices, and urge needed enabling policies. At the national and regional level, performance depends on various issues. PPPs (public–private partnerships) are especially important regarding CCUS hub development, CO transport infrastructure, or industrial symbiosis networks (heat exchange, waste to raw

material, shared effluent management); the importance of participatory and transparent monitoring through digital platforms that monitor emissions, water quality, or noise level in real time and that are validated by universities, NGOs, or local communities; the role of dynamically conditioned environmental permits that should substitute stationary standards and be renewable according to environmental performance, thereby pushing the adoption of BATs; and structured dialogue at sectoral level by tripartite commissions (government, industry, civil society) for investment priorities, historical liabilities, and resource allocation from climate finance. A license to operate is no longer a reputational benefit, but a condition of continued operation. Factories that combine transparency, audited ESG indicators, and structured community dialogue will severely limit legal action, environmental penalties, and market-loss risks. The interaction between policy, market, and governance determines the speed of the sustainable transition of the cement sector. Following the multi-criteria analysis and case studies already shown, some actions, grouped by spheres of influence, are recommended (Table 10).

Table 10. Strategic recommendations for key stakeholders regarding policy, finance, and decarbonization actions.

Actor	Priority Recommendations
Governments and regulators	Gradual introduction of carbon pricing, harmonize MRV with international requirements, establish just-transition funds for workers and communities, enforce TCFD/ISSB reporting for USD > 100 kt/year plants.
Industry and investors	Utilize green taxonomies for financing, make it a priority to invest in WHR + SCMs over CCUS, embed ESG data in process controls (APC/IoT), and verify scope 3.
Financial institutions	Tie credit lines to CO ₂ /t reduction targets, fund piloted alternatives to cement at TRL 6–8, environmental due-diligence clauses in long-term credit conditions.
Academia and research centers	Create harmonized dynamic LCI of alternative ligands, develop integrated health-risk models with ongoing monitoring, quantify distributional impacts of carbon policies in periphery regions.

10. Limitations and Future Prospects

There are still important gaps that keep the cement sector from completely switching to a circular sustainability model, despite the substantial advancements in mitigation technology and regulatory frameworks covered in this research. The geographic disparity of available data is a major limitation: the majority of case studies and technological validations concentrate on developed economies (such as the United States, China, and the European Union), leaving a significant knowledge gap regarding the applicability and economic viability of these solutions in developing regions, where the expansion of cement production is more rapid. Additionally, whereas technologies like CCUS and alternative binders (geopolymers, belitic cements) exhibit strong theoretical potential, they require long-term empirical validation on an industrial scale, particularly with regard to chemical stability and structural durability under varied climatic circumstances. By concentrating primarily on the levelized cost of production without fully incorporating the ancillary benefits in public health and ecological preservation, current economic analysis also has a tendency to underestimate social and environmental external costs.

The fragmentation of pollution control strategies has also been noted as a methodological issue. Biogeochemical interdependencies, such as the atmospheric deposition of heavy metals in the soil and their subsequent leaching into aquifers, have historically been overlooked in the development of strategies for air, soil, and water. The literature currently lacks integrated models that quantify these cross-pollutant flows in real time, despite this review's emphasis on the necessity of an analytical multimedia framework. Furthermore,

there are logistical challenges and a lack of unified regulatory standards that attest to the safety of these recycled materials in the construction supply chain when implementing net-zero discharge systems and fully valuing by-products like CKD. Future research should give priority to five critical directions in order to overcome these obstacles: first, the creation of second-generation carbon capture technologies that guarantee the profitability of CO₂ utilization CCU in conjunction with circular economy business models that have lower energy penalties and operating expenses; second, the digitization and incorporation of artificial intelligence for real-time process optimization, which allows for effective management of the water–energy–carbon nexus and predictive emission monitoring; third, international regulatory standardization is necessary to stop “carbon leakage” and guarantee that poor nations have access to technology transfer and climate finance channels for the use of BAT; fourth, in order to provide a comprehensive measure of sustainability, dynamic life cycle assessment (LCA) studies that include social and occupational health variables, particularly those connected to noise pollution and exposure to heavy metals, must be advanced; and fifth, studies should concentrate on the scalability of substitute binders, look into ways to overcome supply-chain obstacles, and verify structural performance in major infrastructure projects. In order to align the cement industry with the sustainable development goals and turn it from a major emitter into a key player in global decarbonization and environmental regeneration, technological innovation, strong governance, and international cooperation must come together.

11. Conclusions

This detailed account paints a clear picture of the environmental cost of producing cement: beyond the 5% to 7% of total global CO₂ emissions attributed to it, serious soil, water, air, and noise pollution result from its production. To transition toward a sustainable paradigm, the industry needs to embrace a multimedia approach in environmental impact assessments: the biogeochemistry of these different compartments of our planet is intertwined, with dust from the atmosphere depositing onto soil, whose leachate may end up degrading the waters beneath it. Although most innovative treatment solutions can already be applied technically, a systemic approach that allows technologies to be combined leads to substantial measured improvements. For instance, under optimal integrated conditions, replacement of clinker and the use of alternative fuels allow reductions of total energy and direct emissions by up to 44% and 50%, respectively, though this is limited by regional material availability. A state-of-the-art CO₂ capturing process (TRL 7–9) could potentially achieve as high as 90% reductions in emitted gases, provided that high energy penalties and economic barriers are overcome. In specific mill case studies, target-focused engineering solutions could reduce daily occupational exposure from 102.9 dB(A) to 88.3. Furthermore, in nonstructural geotechnical applications, the utilization of clinker kiln dust would enable up to a 9.9-fold increase in the compressive strength of specific native soil, a value that is highly dependent on local soil mineralogy and CKD composition, but these alternative binders or zero-liquid-discharge concepts need to be proven as feasible economically and at the scale of the overall industrial chain. Technology must go hand in hand with strong policy formation: in particular, USD 60–100 dollar per ton of CO₂ would create sufficient incentive for the needed material and technological shift toward cutting-edge capture systems and would lead the way to avoid carbon leakage through policy tools such as the carbon border adjustment mechanism or compulsory corporate reports. Integrating pollution management with assessment of ecological risk and corporate transparency is no longer optional, but a legal mandate required for any company wanting to gain social acceptance and maintain its license to operate as part of the international cement industry sector.

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Abbreviations

The following abbreviations are used in this manuscript.

ACO	ant colony optimization
BAT	best available technique
BOD	biochemical oxygen demand
CAPEX	capital expenditure
CBAM	carbon border adjustment mechanism
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCUS	carbon capture, utilization, and storage
CKD	cement kiln dust
CO ₂	carbon dioxide
COD	chemical oxygen demand
EMS	energy management system
FA	fly ash
GA	genetic algorithm
GHG	greenhouse gas
GS	garden soil
I-CCU	integrated carbon capture and utilization
IED	industrial emissions directive
LCA	life cycle assessment
LCTs	low-carbon technologies
NIHL	noise-induced hearing loss
NPV	net present value
PM	particulate matter
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RDFs	refuse-derived fuels
RO	reverse osmosis
SCMs	supplementary cementitious materials
SDGs	sustainable development goals
SO ₂	sulfur dioxide
SPLs	sound pressure levels
SRF	solid recovered fuel
SS	sewage sludge
TSSs	total suspended solids
UF	ultrafiltration
WHO	World Health Organization
WHR	waste heat recovery
WoS	Web of Science
ZLD	zero liquid discharge

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