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Innovative Environmental Protection Technologies to reduce Air Pollution from Cement Manufacturing Industry in Liberia

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Abstract. The cement industry is a significant source of air pollution that has traditionally caused a great deal of public concern. Residents of Billima, Cow Factory, and Doe towns along the Japanese Freeway formerly Somalia Drive in Monrovia Liberia have continuously complained about air pollution in their neighborhoods as a result of the Cemenco cement production factory, which is the country's largest cement manufacturing plant. Furthermore, there have been long-running disputes concerning air pollution from the Cemenco cement production complex and its potentially detrimental impacts on health and the environment. This paper presents an analysis of the cement manufacturing process, an outline of the pollutants generated from cement manufacturing plants, and the effects of these pollutants on human health and the environment. Finally, the research evaluates various non-technical pollution reduction strategies (emission control directives), innovative environmental protection technologies, and technological equipment to reduce pollution from the cement manufacturing industry.

Keywords. Cement Manufacturing, Air Pollution, Emission Control Directive, Environmental Protection Technology

1. INTRODUCTION

Following a 14-year civil war in Liberia that caused extensive damage to the nation's infrastructure, the construction sector experienced significant growth. This growth was fueled by the construction of various infrastructure projects such as roads, bridges, and multi-story residential buildings. Consequently, there was a substantial increase in the demand for cement. However, due to the unavailability of the essential raw materials required for cement production within Liberia, manufacturing companies resorted to importing these materials into the country in order to process them and create the final product.

Due to the pressing need for continuous reconstruction in the country, there is a significant demand for cement. However, it has become imperative to address the environmental risks associated with cement production. To achieve this, implementing environmental laws and regulations is crucial. These measures would encourage investments in the sector while safeguarding the environment and the well-being of citizens residing near production areas. As

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the process of industrial globalization alters the world, numerous innovative technologies have emerged to mitigate air pollution stemming from the cement manufacturing industry. Air pollution is recognized as the foremost global environmental threat to human health, causing over 7 million premature deaths each year. Given that most pollutants impact local weather patterns and contribute to greenhouse gas emissions, air pollution and climate change are closely interconnected.

Cemenco, the largest cement manufacturing company in Liberia, operates a manufacturing plant situated on the Japanese Freeway, previously known as Somalia Drive. The plant emits a significant amount of pollutants into the air, resulting in adverse effects on the nearby communities. Over the years, residents from Billima, Cow Factory, and Doe communities have continuously expressed their concerns about air pollution caused by Cemenco's cement manufacturing plant. During the production process, dust particles are generated and dispersed through the air, ultimately being deposited in a location far away from the actual production site. This process leads to the release of harmful substances such as nitrogen dioxide, carbon monoxide, and sulfur dioxide into the atmosphere. Consequently, the affected communities are at risk of experiencing respiratory diseases at elevated levels.

Figure 1. Cemenco Cement Manufacturing Plant on Japanese Freeway

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Figure 2. Location of Cemenco Cement Manufacturing Plant (Google Earth)

The absence of modern technology and effective pollution control mechanisms at the Cemenco cement manufacturing plant has resulted in a significant increase in air pollution. This has had several adverse effects on the environment and surrounding communities:

- Emission of Pollutants: The plant's reliance on outdated equipment and processes without advanced kiln design, dust collection systems, and pollution control equipment has led to high emissions of various pollutants during cement manufacturing. These emissions include particulate matter, sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other harmful substances. The lack of measures to mitigate these emissions has a direct impact on air quality in the plant's vicinity.
- Inefficient Fuel Combustion: The cement plant's power generation relies solely on fossil fuels, which results in inefficient combustion and higher emissions of greenhouse gases, particularly carbon dioxide (CO_2). This contributes to the plant's overall carbon footprint and exacerbates climate change concerns.
- Dust Generation: Cement manufacturing involves the handling and processing of raw materials, which can generate significant amounts of dust. Due to ineffective dust control mechanisms at Cemenco, the cement plant releases large quantities of particulate matter into the air, further deteriorating air quality.
- Lack of Monitoring and Compliance: The absence of a monitoring and compliance system at the plant, as well as inadequate oversight from the Environmental Protection Agency (EPA) of Liberia, poses challenges in accurately measuring and controlling emissions. Real-time monitoring and control systems are crucial for ensuring compliance with environmental regulations. Without such systems in place, it becomes difficult to address and mitigate air pollution effectively.

The cumulative effect of these factors is an ongoing increase in air pollution levels surrounding the Cemenco cement manufacturing plant. This pollution not only contributes to environmental

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degradation but also poses health risks to nearby communities. The lack of modern technology and proper pollution control measures highlights the urgent need for the implementation of cleaner and more sustainable practices in cement manufacturing. Additionally, establishing effective monitoring and compliance systems is essential for ensuring environmental protection and reducing the impact of cement production on air quality.

Particles are produced during various activities such as transportation, storage, and packaging. Likewise, the manufacturing plant releases mineral dust that contains a significant quantity of metals known to be harmful to humans, plants, and animals. Consequently, the rise in the number of cement manufacturing plants in Liberia, although it addresses the substantial cement demand, poses an environmental problem that necessitates a creative solution. Moreover, the cement production process requires a large amount of energy due to the raw materials utilized and manufacturing steps like clinker production, making the cement industry the primary source of worldwide air pollution and CO2 emissions.

2. CEMENT MANUFACTURING PROCESS

Cement production methods vary depending on the machinery arrangement, scale of operations, and power consumption. Numerous cement producers have upgraded from outdated, less effective wet and dry kilns to contemporary materials that can be efficiently processed using advanced technologies such as pre-heating and pre-calcining. The adoption of these new technologies has become a prominent trend in emerging markets due to their superior efficiency and the effectiveness of clinker-blending. (Rahman et al., 2015).

Cement is a substance that combines with other materials, and these materials are utilized in construction by undergoing the processes of setting, hardening, and adhering to other substances. Cement cannot be used alone; rather, it is combined with fine aggregate (sand) and coarse aggregate (gravel). When cement is mixed with sand, it forms mortar that is used for tasks such as block laying and plastering. Additionally, when cement is mixed with both sand and gravel, it forms concrete. The initial step in cement production involves mixing different raw materials to achieve the appropriate chemical composition. These materials are crushed into small particles, which become reactive and well-blended. Subsequently, they are introduced into a cement kiln where they are subjected to extremely high temperatures (Mohsen, 2015).

The ultimate structure and characteristics should conform to the exact guidelines specified in the production manual, and this applies equally to the initial materials. Cement necessitates the appropriate quantities of calcium, silicon, aluminum, and iron, although the chemical composition and physical arrangement of these fundamental components can be altered based on the desired strength. Within a kiln, the chemical elements of the raw materials are subjected to exceptionally high temperatures, burned away, and subsequently replenished with oxygen sourced from the surrounding air (Mohsen, 2015). Table 1. shows the raw materials used to produce the main cement elements and Fig 1. illustrates the step-by-step processing of cement manufacturing.

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Table 1. Raw materials are used to produce the main cement elements (Mohsen, 2015)

Raw Materials Element			
Ca	Si	Al	Fe
Limestone	Clay	Clay	Clay
Marl	Marl	Shale	Iron ore
Calcite	Sand	Fly ash	Mill scale
Aragonite	Shale	Aluminum	shale
shale	Fly ash		Blast furnace dust
Seashells	Rice hull ash		
Cement kiln dust	Slag		

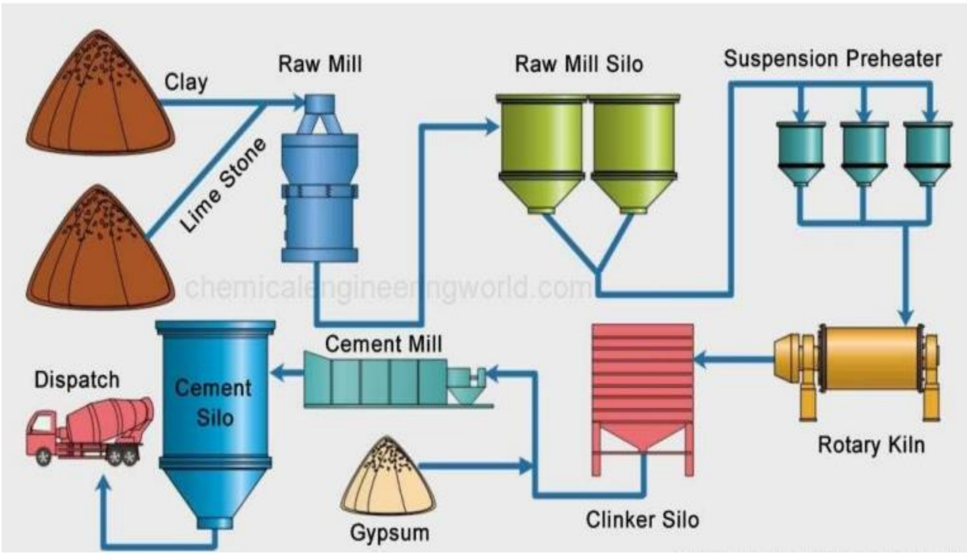

Figure 3. The step-by-step process of cement Manufacturing (Mohsen, 2015)

- **Quarry**

The process of obtaining raw materials for cement manufacturing involves mining and quarrying natural materials from the earth. This includes excavating soil, drilling, blasting, crushing, handling, loading, transporting, screening, stacking, and storing the products. Quarrying operations involve removing the earth and drilling for natural material deposits like limestone (sourced from marl or chalk), silica, iron oxide, and alumina (typically found in sand). Some industrial by-products, such as power plant ash and blast furnace slag, can be used as partial replacements for raw materials as long as they don't compromise the necessary cement qualities.(Irin & Sakib, 2020).

- **Raw material preparation**

To create the raw materials for the dry process of cement production, the materials recovered during the mining process undergo pre-homogenization, drying, and grinding in a mill. The raw materials are then homogenized and stored in silos to maintain the required chemical composition. (Rahman et al., 2015).

- **Clinker Burning**

Cement clinkers are produced through pyro-processing, which involves heating the raw material mixture obtained from milling in a rotating kiln. The kiln is a long, inclined steel cylinder with a diameter of 8 to 12 feet and a length of 200 to 400 feet. The raw materials can be supplied as slurry, powder, or moist pellets, depending on the processing method. The pyro-processing consists of three steps: preheating, calcining (which produces calcium oxide), and burning. The energy for this process primarily comes from fuel like natural gas, oil, or coal, but there is an increasing use of additional fuels like petroleum coke, waste rubber, and waste solvent to promote environmental sustainability. (Irin & Sakib, 2020).

- **Clinker cooling and final grinding**

After the burning process, the clinker, which is in hardened, spherical nodules with a diameter of 0.32 to 0.5 cm, is cooled in a clinker cooler. The temperature of the clinker is around 1400°C when it leaves the kiln's hot end. The cooled clinker is then processed in a ball mill with gypsum and necessary additives to produce cement. The different types of cement are stored separately in the cement grain store before being packaged and shipped. (Rahman et al., 2015).

- **Cement Packaging & Dispatch**

The cement is transported from the grinding mill to a vertical storage silo, often called the packing house or shipping department. The transportation method may involve the use of an elevator bucket and a conveyor belt to transfer the cement to storage silos before it is sent to the bagging or packaging unit. The final cement product is typically packaged in bags with a standard weight of 50 kg, or sometimes in larger quantities depending on the project requirements and desired strength.(Irin & Sakib, 2020).

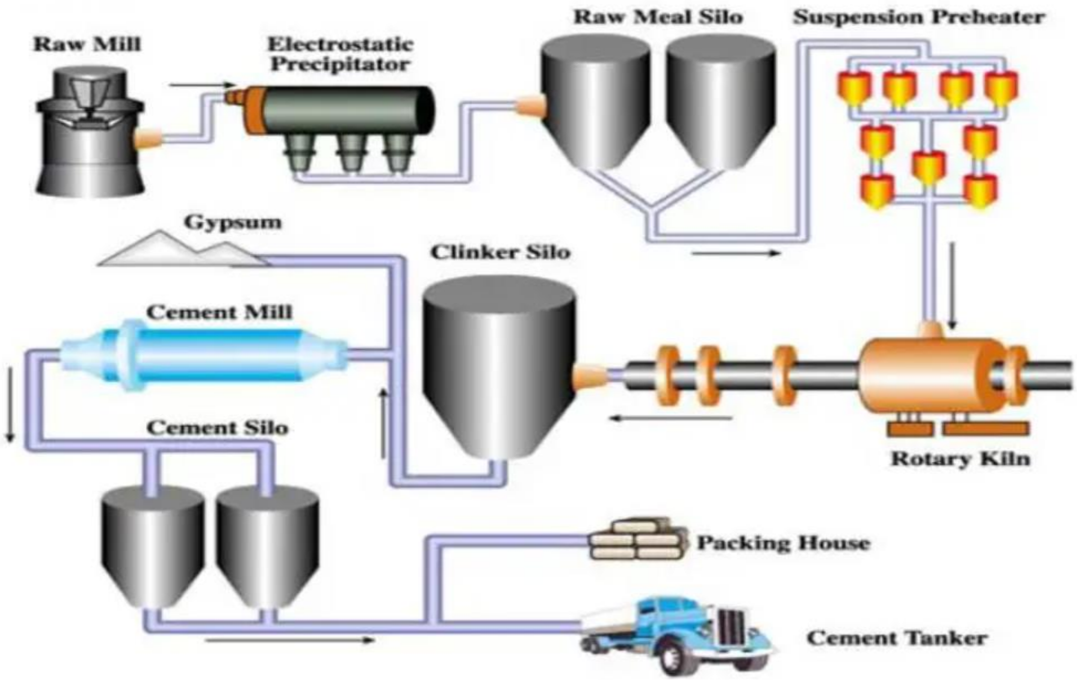

Figure 4. Wet Process of Cement Production (Theconstructor.org, 2019)

3. POLLUTANTS FROM CEMENT FACTORIES

Cement production has consistently played a major role in causing global warming and continues to be a leading contributor. The entire process of manufacturing cement involves

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releasing various harmful substances into the environment, impacting both the natural world and human health. This industry is responsible for generating 5 to 10 percent of global human-made carbon dioxide (CO2) emissions. (Ighalo & Adeniyi, 2020). The pollutants emanating from the cement manufacturing facility can be divided into two groups: particulate matter and combustion gases discharged by cement kilns. Additionally, other production procedures contribute to pollution, such as wastewater resulting from the cooling of process equipment, as well as sludges and remnants from the maintenance of wastewater plants. Furthermore, waste from research activities and laboratory experiments is also considered. (Irin & Sakib, 2020).

The cement manufacturing process emits three main air pollutants, namely sulfur dioxide (SO2), nitrogen oxides (NOX), and particulate matter (PM). These pollutants can be classified into two groups. (Sana, 2013):

- Particulates matter (PM)
- Gaseous pollutants

From a technical standpoint, the primary methods employed to address pollution caused by cement production globally have concentrated on reducing the following contaminants:
Dust and other particulate matter (PM)

- Sulphur dioxide (SO2)
- Hydrogen Fluoride (HF)
- Mercury and other heavy metals
- Nitrogen oxides (NOx)
- Carbon monoxide (CO)
- Ammonia (NH3)
- THC (or TOC)
- Dioxins/ furans

- **Particulates Matter (PM)**

Particulate air pollution is a mixture of diverse particles with varying chemical compositions and sources. Industrial processing plants release smoke and dust particles ranging from 2.5 millimeters to 100 microns in size, while the burning of fossil fuels produces tiny particles smaller than 2.5 microns. (Sana, 2013).

Particle matter emissions are a continuous occurrence in the entire process of cement manufacturing. They occur during quarrying, crushing, grinding (dry methods), blending, and transporting raw materials. Emissions also happen during kiln operation, clinker cooling, stockpiling, packaging, and the movement of vehicles for delivering finished cement or transferring raw materials. These activities can release gaseous pollutants and particle matter. (Irin & Sakib, 2020).

- **Volatile organic compounds**

Incomplete combustion in kilns during clinker formation is the main source of volatile organic compounds (VOCs) and carbon monoxide (CO) emissions. The release of volatile organic compounds primarily occurs during the initial stages of preheating the feed material in the preheater and pre-calciner. Due to the prolonged gas residence times and high temperatures in the kiln, the emission of volatile organic compounds can be minimal when the system reaches a stable state. (Avila et al., 2022).

- **Gaseous Pollutants**

Gaseous pollutants, such as SO2, NO2, CO2, CO, and O3, have significant impacts on human health and the environment. Interactions between SO2 and NO2 result in acid formation, causing acid rain on land and oceans. The increasing levels of these pollutants in the atmosphere contribute to climate change, emphasizing the need to monitor their emissions. Cement kilns contribute to NOx emissions, which harm human health, while the processing of sulfur-containing materials and the burning of sulfur compounds in cement production lead to SO2 emissions(Sana, 2013).

Gaseous pollutants, including nitrogen oxides (NOx), sulfur dioxide (SO2), carbon oxides (CO2 and CO), volatile organic compounds (VOCs), ammonia, chlorine, metallic compounds, and trace amounts of hydrochloric acid, are released during the cement manufacturing process. These pollutants primarily originate from clinker formation in rotary kilns, as well as the preheater and clinker cooler stages. (Irin & Sakib, 2020).

4. HEALTH EFFECTS OF AIR POLLUTION FROM THE CEMENT MANUFACTURING PLANT

Cement factories and limestone-induced air pollution have significant health risks for workers and nearby communities, as well as negative effects on buildings and agriculture. Concrete production, which heavily relies on coal and involves various stages from mining to transportation, emits harmful substances such as PM, NOx, CO2, SO2, VOCs, O3, H2S, PCDDS, PCBs, and other pollutants. (Etim et al., 2021).

Air pollution worsens respiratory and cardiovascular conditions, making breathing difficult and leading to increased emergency room visits, medication usage, and even sudden death. It primarily affects the respiratory and cardiovascular systems, with the specific pollutants, exposure level, individual health, and genetics playing a role in the response. The respiratory system, including the mucosal epithelium, bronchi, and airway, is the most affected organ system, along with alveolar macrophages in the lungs and alveoli responsible for converting carbon dioxide to oxygen (Muhammad et al., 2021).

Human perception involves the five senses of sight, hearing, smell, touch, and taste. Smell and taste are chemical senses that help distinguish scents and flavors based on specific compounds. While vision and hearing play vital roles in survival and have evolved significantly, the sense of smell is considered more fundamental. Inhaling air pollution can cause respiratory illnesses that further harm the respiratory system, especially in individuals with hypersensitivity (Muhammad et al., 2021).

4.1.Effect of air pollutants on different human organs and systems

- Respiratory system

Research indicates that both high concentrations and prolonged exposure to various forms of air pollution can negatively impact the airways. Asthma patients exposed to elevated levels of substances such as sulfur dioxide, nitrogen oxides, and certain metals like arsenic, nickel, or vanadium can experience bronchoconstriction, breathing difficulties, and irritation of the nose and throat. Lung inflammation can also occur due to the presence of ozone and airborne particles that reach the alveolar epithelium. Pollutant-induced inflammation exacerbates existing lung conditions and increases vulnerability to respiratory infections. Prolonged exposure to ozone and certain heavy metals impairs lung function and is linked to asthma, emphysema, and possibly lung cancer (Kampa & Castanas, 2008).

- Cardiovascular system

Carbon monoxide binding to hemoglobin reduces its oxygen-carrying capacity and affects organs like the brain and heart, leading to symptoms such as poor concentration, sluggish reflexes, and confusion due to decreased oxygen supply. Particulate matter triggers inflammation throughout the body, impacting blood coagulation and pulmonary inflammation. Air pollution can block blood vessels in the heart, resulting in angina and potential heart attacks, while also causing lung irritation and alterations in blood coagulation. Exposure to heavy metal pollution, including mercury, nickel, and arsenic, can lead to symptoms like tachycardia, elevated blood pressure, and anemia due to its negative impact on hematopoiesis. Studies have found a connection between dioxin exposure and higher mortality rates from ischemic heart disease, while heavy metals have been observed to increase triglyceride levels in mice. (Kampa & Castanas, 2008).

- Nervous system

Exposure to lead, mercury, and arsenic, among other heavy metals and dioxins, can have neurotoxic effects on the nervous system. This exposure has been linked to symptoms like cognitive disturbances, sleep issues, hostility, fatigue, hand tremors, vision problems, and speech difficulties. Lead, in particular, can harm memory-related functions, affecting the NMDA receptor complex, glutamate system, and dopamine system. Furthermore, mercury exposure has been identified as a contributor to neurological maldevelopment in children.(Kampa & Castanas, 2008).

- Urinary system

Heavy metals can initially cause tubular dysfunction in the kidneys, leading to a decrease in the glomerular filtration rate (GFR) due to increased excretion of low molecular weight proteins. Additionally, they elevate the risk of developing kidney stones or nephrocalcinosis.

- Exposure during pregnancy

Air pollution can have significant effects on a developing fetus. Pregnant women exposed to lead have a higher risk of spontaneous abortion and fetal development issues like preterm labor and low birth weight. Maternal exposure to lead is also associated with nervous system abnormalities in the fetus, leading to impaired motor and cognitive development in newborns. Additionally, dioxins can cross the placenta and disrupt the growth and development of the central nervous system in the fetus as endocrine disruptors. Air pollutants have a shared biological mechanism of causing harm by acting as prooxidants or generating free radicals. This leads to oxidative stress and inflammation in the body. Free radicals and reactive oxygen and nitrogen species then proceed to damage lipids, proteins, and DNA in cells, disrupting their normal functions. Dioxins, in particular, cause damage to gastrointestinal and liver cells, as evidenced by the elevated levels of specific enzymes in the bloodstream. (Kampa & Castanas, 2008).

5. INDUSTRIAL CO2 EMISSIONS CONTROL DIRECTIVE WITHIN THE EUROPEAN UNION

The EU has updated its legislation on industry's environmental impact to align with its zero-pollution vision, energy and climate goals, and circular economy policies. The Industrial Emission Directive is the main tool for regulating pollutant emissions from industries. Large agro-industrial establishments engaged in covered operations must obtain permits from the appropriate authorities. The directive applies to various manufacturing facilities, waste treatment, incinerators, and intensive poultry or pig farming. To reduce emissions from the industry, the European Parliament's Green Deal Plan proposes specific actions (EU Legislation in Progress Revision of the Industrial Emissions Directive, 2022):

- **Circular Economy Action Plan for a cleaner and more competitive Europe**

The current linear approach of "take-make-use-dispose" in product manufacturing fails to incentivize manufacturers to prioritize circularity and sustainability. The European Union (EU), with its significant influence in the global market, aims to establish international standards for product sustainability and shape global product design and value chain management. Existing EU initiatives and legislation have addressed sustainability to some extent, but comprehensive requirements for circularity are lacking. To address this, the EU proposes a legislative initiative to expand the application of the Eco-design Directive, ensuring circularity across a wide range of products. The initiative focuses on improving energy efficiency, reducing harmful compounds, enhancing durability, repairability, and reusability, increasing the use of recycled materials, supporting high-quality recycling and remanufacturing, reducing environmental and carbon footprints, limiting single-use, and imposing restrictions on disposal of durable items. It also emphasizes the importance of manufacturers taking responsibility for their products throughout their lifetimes and utilizing digital tools for product information. Incentives tied to sustainability performance would be introduced to encourage high-performance products (Szaniawski, 2015).

- **European Union Action Plan towards zero pollution for Air, Water, and Soil.**

The European Union's 2050 climate-neutrality goal and zero pollution ambition are interconnected objectives that align with the UN 2030 Agenda for Sustainable Development and complement other environmental targets. These goals are integral to the European Green Deal and will continue to be pursued through various initiatives. The action plan aims to guide EU policies in preventing pollution, promoting synergies, and addressing any gaps or trade-offs. It sets important 2030 objectives to accelerate pollution reduction and move closer to the vision of a healthy planet by 2050. The EU adopts a "zero pollution hierarchy" that prioritizes preventive measures, source remediation, and the polluter pays principle, along with climate neutrality efforts. The EU advocates for a shift in how products are created, distributed, used, and disposed of to tackle pollution at its source.(European Commission, 2021).

- **European Union Chemical Strategy for Sustainability Towards a Toxic-Free Environment**

The European Union's Chemical Strategy for sustainability aims to protect human health and the environment by addressing pollution from all sources and working towards a toxic-free society. Chemicals play a crucial role in various aspects of human life, including technology, resources, and materials. To support the green and digital transformation, the chemical sector needs to invest more in innovation and provide safe and sustainable chemicals. Hazardous substances pose risks to both the environment and human health, affecting various bodily systems and reducing resistance to illnesses. However, not all hazardous chemicals carry the same level of risk. (EU, 2020).

Chemical pollution is a significant global threat that exacerbates climate change, ecological degradation, and biodiversity loss. The EU's regulatory system, considered the most advanced globally, promotes safety and has become a benchmark for regulations in Europe. The EU has successfully established an internal chemical market, reduced hazards from specific chemicals, and created a stable business environment. To further progress, the EU Commission collaborates with stakeholders, conducts impact assessments, and establishes a high-level roundtable involving industry, science, and civil society. The goals include improving legislation effectiveness, promoting the development of secure and environmentally friendly chemicals, and ensuring a toxic-free environment aligned with the European Green Deal (EU, 2020).

The EU's toxic-free hierarchy chart outlines a long-term vision for chemical policy, focusing on maximizing the contribution of chemicals to society while avoiding harm to the environment and future generations. The chart aims to position the EU chemical sector as a global competitor in secure and environmentally friendly chemical manufacturing and usage. It provides a roadmap and timeline for industry transformation, encouraging investment in safe and sustainable products and production techniques. The hierarchy chart emphasizes the development of safe chemicals, enhanced environmental and human health protection, streamlined and legally protected chemicals, evidence-based policy-making, and responsible chemical management globally (EU, 2020).

6. INNOVATIVE ENVIRONMENTAL PROTECTION METHODS AND TECHNOLOGIES TO REDUCE POLLUTION

Due to technological advancement, cement manufacturers can now produce more than plants could in the past. However, the increase in production levels has also been identified as the main source of air pollution. This emanates from the increased activities of excavation, dumps, tips, conveyer belts, crushing, mills, and kiln emissions in the cement manufacturing industry. On-site waste and pollution can be significantly reduced by using suitable technologies in the manufacturing process. Hence, utilizing the right technological equipment will increase industrial competitiveness as it will lower total production costs and minimize the manufacturing process's negative effects on the environment and human life. Therefore, the following, although not only, should be considered for the advancement of Liberia's cement manufacturing sector.

6.1. Air pollution monitoring and control system

Air pollution monitoring and control play a critical role in cement manufacturing plants as they ensure adherence to regulations. Cement plants are obligated to comply with strict air pollution regulations set by the national government. By monitoring and controlling air pollution, these plants can meet regulatory requirements, preventing legal consequences, penalties, and potential closures. To establish an air pollution monitoring, reporting, and control system for a cement manufacturing plant, follow these essential steps (JMOE, 2009):

- Gain understanding of regulations: Ensure that the company familiarizes itself with national regulations concerning air pollution control for cement manufacturing plants. These regulations specify emissions limits, monitoring criteria, and reporting responsibilities that must be adhered to.
- Identify pollution sources: Determine the different potential sources of air pollution in the cement plant, such as kilns, raw material grinding, cement grinding, and clinker cooling processes. Prioritize the sources that significantly contribute to air pollution for monitoring and control purposes.
- Choose suitable monitoring equipment: Select the appropriate air pollution monitoring equipment that matches the pollutants you need to measure. Typical emissions from cement plants include particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO2), carbon monoxide (CO), and volatile organic compounds (VOCs). Consider utilizing continuous emissions monitoring systems (CEMS) or stack monitoring equipment to measure emissions from specific sources.

- Install monitoring equipment: Properly install the monitoring equipment at the designated emission sources. Ensure that the equipment is calibrated, maintained, and meets the necessary standards. Trained professionals should handle the installation to ensure precise data collection.
- Collecting and reporting data: Set up a system to collect real-time or periodic emissions data from the monitoring equipment. Create a reporting mechanism to compile the data in a format that meets regulatory requirements. This may involve utilizing specialized software systems designed for emissions monitoring and reporting.
- Analyze data and ensure compliance: Evaluate the collected data to assess your plant's adherence to air pollution regulations. Identify any instances where emissions surpass the specified limits and implement necessary corrective measures. Regularly review the data to spot trends, potential problems, and areas that can be improved.
- Implementing control measures: Introduce measures to mitigate air pollution from the identified sources. This may include upgrading equipment, optimizing processes, adopting cleaner technologies, or implementing pollution control best practices. Seek guidance from air pollution control experts to identify the most suitable solutions for your particular plant.
- Continuous monitoring and maintenance: Consistently monitor emissions to maintain compliance and evaluate the effectiveness of control measures. Perform regular equipment maintenance and calibration to ensure precise and dependable measurements.
- Employee training and awareness: Educate employees about the significance of air pollution control, the monitoring system, and the correct operation of pollution control equipment. Promote an environmental responsibility culture and motivate employees to report any possible issues or concerns related to air pollution.
- Regular audits and inspections: Perform routine internal audits and inspections to ensure compliance, identify areas for enhancement, and promptly address any non-compliance matters. Cooperate with regulatory authorities during external inspections, providing the required documentation and data as necessary.

The specific requirements and procedures can vary depending on the location of the plant and the regulatory framework in effect. It is crucial to seek advice from environmental experts, engineers, and relevant authorities to guarantee accurate compliance and the effective implementation of pollution control measures (JMOE, 2009).

6.2.Controlling particulate emissions

Controlling particulate emissions at a cement manufacturing plant is crucial to minimize air pollution and protect the environment. Therefore, here are some methods that can be employed in the cement manufacturing industry in Liberia:

- **Flexible Pulse Jet Filters**

Flexible pulse jet filters, also known as bag filters, are crucial in cement manufacturing plants for controlling air pollution and capturing particulate matter. They remove dust and pollutants generated during cement production, ensuring compliance with environmental regulations. These filters optimize processes, prevent equipment blockages, and improve overall plant performance. They also maintain a clean work environment, safeguarding workers' health. Furthermore, they enable the recycling and reuse of collected materials, promoting sustainability and resource conservation. Overall, flexible pulse jet filters play a vital role in maintaining air quality and supporting responsible cement manufacturing practices (Zimwara et al., 2012).

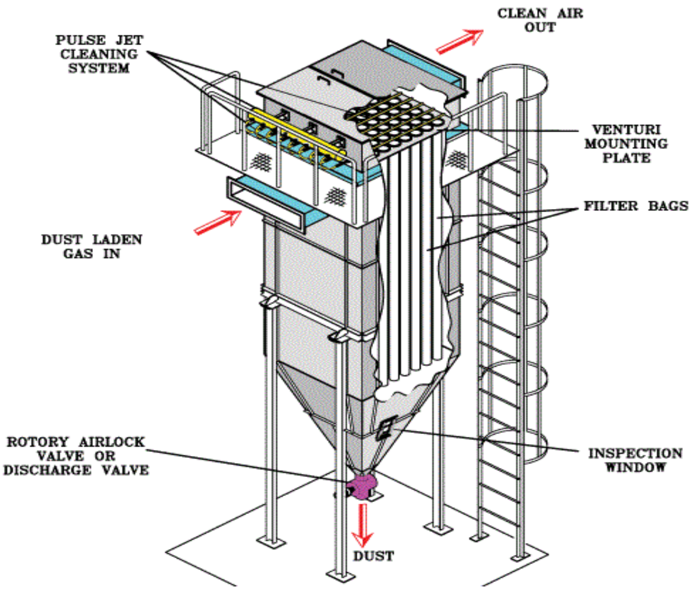

Figure 5. Flexible Pulse Filters workflow process diagram (Zimwara et al., 2012)

- **Electrostatic Precipitator**

Electrostatic precipitators (ESPs) are essential in cement manufacturing for controlling air pollution by removing particulate matter from flue gases. They ensure compliance with environmental regulations, conserve energy, maintain clean equipment, and can facilitate the recovery of valuable materials. ESPs use electrostatic forces to capture particles, contribute to air pollution control, and optimize the efficiency of cement manufacturing processes (Mulvaney, 2012).

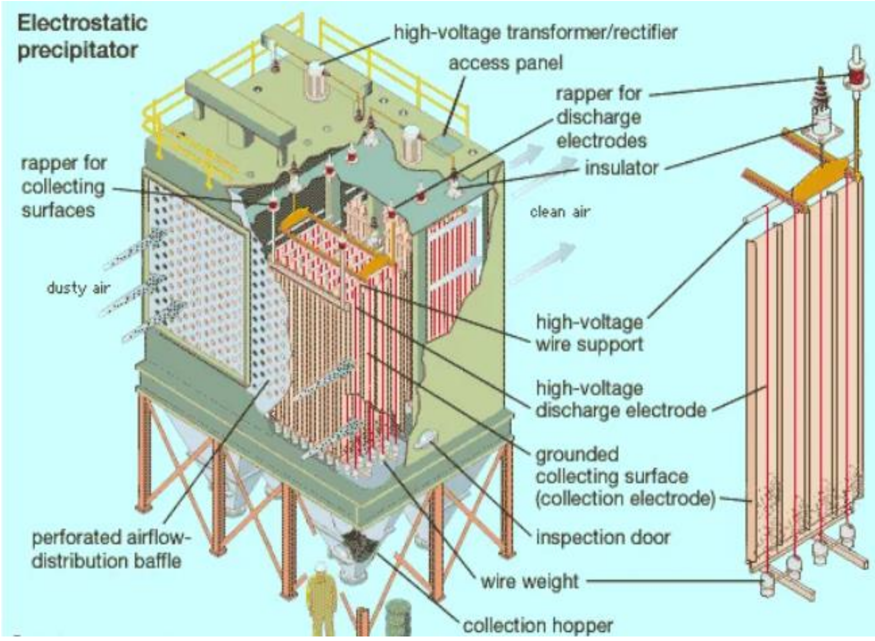

Figure 6. Electrostatic precipitator workflow process diagram (Zimwara et al., 2012)

- **Wet Scrubbers**

Wet scrubbers are important in cement manufacturing to control air pollution by removing particulate matter and gases. They capture dust and neutralize acidic gases, ensuring compliance with environmental regulations. Wet scrubbers also help control odors and can recover heat for energy efficiency. Overall, they contribute to reducing emissions, protecting air quality, and promoting sustainable cement manufacturing practices.(Zimwara et al., 2012).

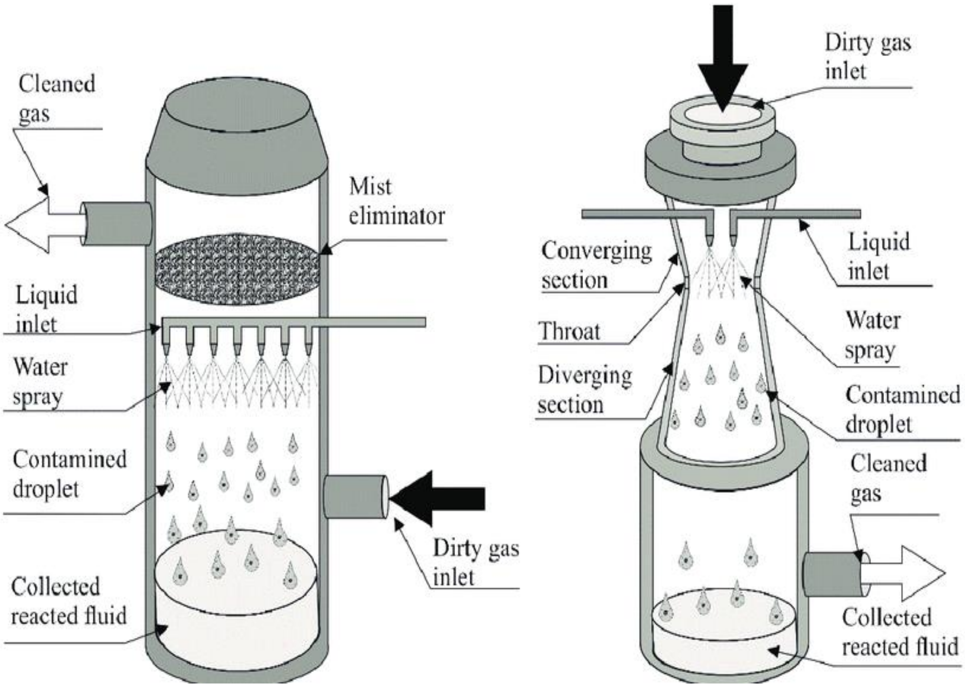

Figure 7. Wet Scrubbers workflow process diagram (Sobczyk et al., 2019)

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- **Ordinary Bag House Method**

The Ordinary Bag House method is commonly used in cement manufacturing to control air pollution by capturing particulate matter. It ensures compliance with environmental regulations by reducing emissions and maintaining air quality. The method involves using fabric bags as filters to trap dust particles while allowing clean air to pass through. Additionally, it contributes to a clean work environment, optimizes processes, and promotes energy conservation. By preventing the accumulation of dust and particulates, it enhances equipment efficiency and reduces the risk of blockages, improving overall plant performance. (Zimwara et al., 2012).

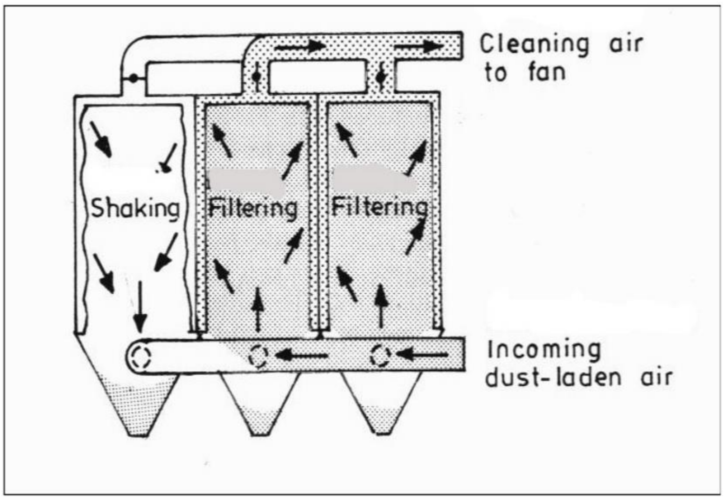

Figure 8. Bag-House Schematic (Zimwara et al., 2012)

6.3.Co-Processing in the Cement Industry

It is a fact that the cement sector is responsible for 5% of all human-generated CO2 emissions. Within this sector, 50% of these emissions come from the chemical conversion of limestone into clinker, 40% from fuel combustion, and the remaining 10% from power usage and transportation. However, by adopting the practice of co-processing, where waste materials are used alongside fossil and natural resources, the cement industry can transform the waste issue into an opportunity for creating value. (Gmbh, 2005).

Co-processing refers to the utilization of waste materials as substitutes for natural resources and fossil fuels, either as raw materials or sources of energy, in industrial processes. This practice allows for the replacement of traditional fuels like coal, petroleum, and gas in various industrial operations. In the cement industry, waste materials can not only serve as alternative fuels but also enable the recovery of valuable raw materials. For example, foundry sand, a waste product from the foundry sector, can be effectively utilized as a substitute for the silicates required in cement manufacturing. (Gmbh, 2005). The Co-processing presents a triple "win" situation as shown in Fig 10.

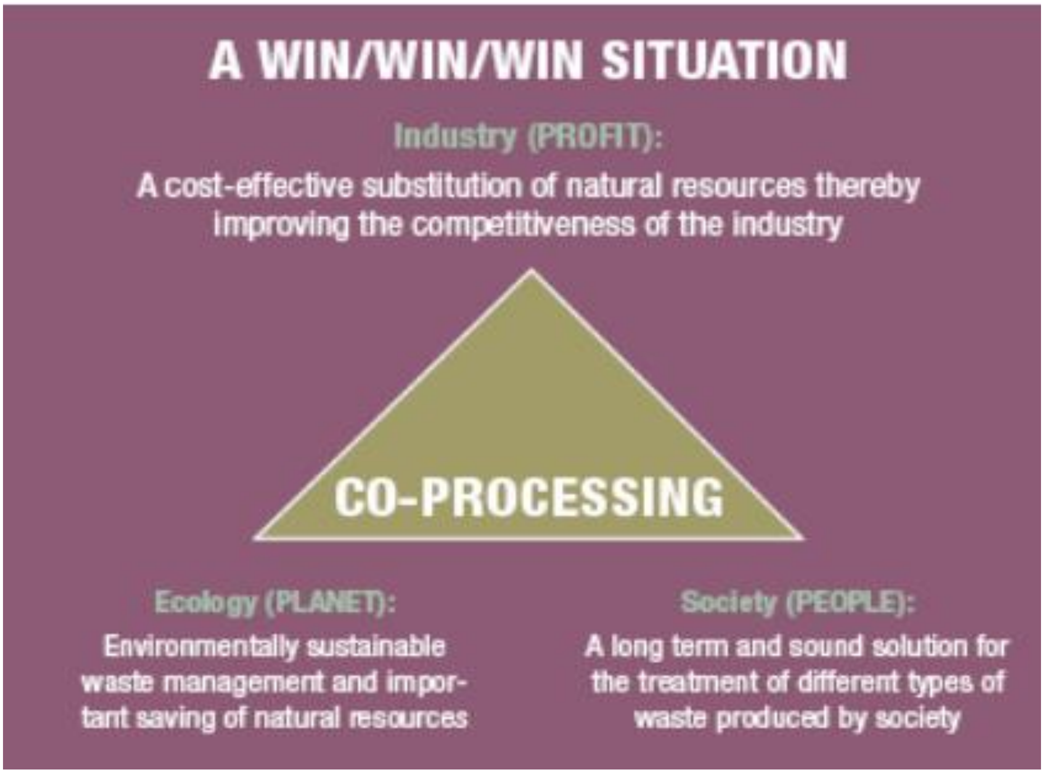

Figure 9. Co-processing is a triple "win" situation (Gmbh, 2005)

Co-processing in the cement industry offers several benefits, including:

- Enhanced Industrial Competitiveness: By transitioning to fossil fuels or alternative raw materials, the cement industry can reduce overall production costs, leading to increased competitiveness. Additionally, the industry can generate additional revenue by providing waste disposal services.
- Protection of Natural Resources and Reduction of Global Emissions: Co-processing helps preserve natural resources by substituting them with waste materials. This contributes to lowering global emissions by reducing the reliance on fossil fuels and minimizing the extraction of raw materials.
- Sustainable Resolution of Regional Waste Management Issues: Co-processing provides a sustainable solution to regional waste management challenges. By utilizing waste materials as inputs in cement manufacturing, the industry helps divert waste from landfills and contributes to a more environmentally friendly waste management approach.

Furthermore, co-processing offers a secure and ecologically responsible option for dealing with pollutants generated in the kiln. It aligns with the waste hierarchy, positioned after resource destruction, landfilling, controlled burning, and recycling, but before prevention, reduction, reuse, and coprocessing. The co-processing of waste is recognized as a recovery operation under EU legislation. (Gmbh, 2005).

7. CONCLUSION AND RECOMMENDATIONS

The increasing demand for cement in Liberia, driven by development needs, will likely result in a rise in proposed cement plant constructions. While the cement production industry brings advantages such as job creation and economic growth, it can have negative impacts on both people and the environment if not managed effectively. The mitigation of air pollution caused by the Cemenco cement manufacturing plant, which affects nearby communities, necessitates not only legislation and environmental laws but also the commitment and engagement of the company to improve its technological processes and environmental management strategies.

The air pollution reduction technologies and methods mentioned in this paper represent just a few of the many approaches developed to mitigate emissions from cement manufacturing. Enhancing the technological process of cement manufacturing in Liberia would not only decrease production costs but also minimize the adverse effects on the environment and human health throughout the manufacturing stages. This would enhance industrial competitiveness and ensure compliance with international best practices.

To align with the climate monitoring measures outlined in the Paris Agreement, it is crucial for all countries, including Liberia, to establish an emission monitoring, control, and reporting system. Currently, Liberia lacks a comprehensive climate monitoring program. Therefore, I strongly urge the Liberian government, in collaboration with the Environmental Protection Agency, to develop a climate monitoring program that encompasses all industrial sectors. This will enable accurate data gathering for yearly emission reports, which can inform policy formation, climate financing, and adaptation strategies while providing the means to forecast future emissions from each sector.

Dedication

This study is in honor of my father, Mr. Edward Emmanuel Gboe. He has given up lucrative overseas positions to serve his country because he is so passionate about changing Liberia. You have been a source of motivation, encouragement, and direction. You have taught me to be distinct, resolute, confident, and to always continue. I'm very grateful and proud to call you father.

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