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Reducing Cement Plant Emissions via Microlgae Cultivation and Anaerobic Digestion

Hailey Muchnok and Ann C. Wilkie

College of Agricultural and Life Sciences, University of Florida

Faculty Mentor: Ann C. Wilkie, Department of Soil, Water, and Ecosystem Sciences

Abstract

Concrete is an essential aspect of modern infrastructure, and is a much-preferred construction material as it is highly resistant and low maintenance. Concrete is produced through the creation of a paste comprised of cement and water that is mixed with aggregates such as sand and gravel. Cement, one of the primary constituents of concrete, emits 0.93 pounds of CO_2 for every pound produced. Thus, concrete production is a major source of CO_2 emissions and accounts for approximately 8% of global carbon emissions, rendering it one of the largest consumers of natural resources globally. As the demand for concrete continues to increase, efforts must be made to reduce emissions associated with its production. This research proposes that microalgae cultivation can be integrated into the process of cement production to reduce associated emissions. Microalgae uptake CO_2 through photosynthesis and have a CO_2 bio-fixation efficiency 10-50 times higher than terrestrial plants. Microalgae have the ability to capture 1.8 kg of CO_2 per kilogram of algal biomass. Therefore, we hypothesize that, through the integration of microalgae cultivation and cement production, CO_2 can be effectively recycled through a closed-loop system. Microalgal biomass can be cultivated using the CO_2 emitted from cement flue gas and harvested to produce methane gas (CH_4), via anaerobic digestion, to power cement plants; this process also produces CO_2 to be captured through further algal cultivation. This closed-loop system will significantly reduce CO_2 emissions associated with cement and concrete production, thus also addressing overarching climate problems.

Keywords: cement, microalgae, flue gas, anaerobic digestion, biogas, carbon capture

Introduction

Concrete and cement comprise the foundation upon which an urbanizing world is able to be built. They are the most commonly used construction materials because of their durability and versatility. Concrete is the second-highest consumed substance on the planet, second only to water (Hasanbeigi et al., 2012). However, their use, transport, production, and demolition are highly carbon dioxide (CO_2) intensive. In 2019, the CO_2 emissions associated with concrete and cement production, transport, usage, and demolition comprised 10% of global energy-related CO_2 emissions (Cao et al., 2021). As urbanization and population growth are projected to significantly increase in the coming decades, concrete and cement production demands will continue to increase. Therefore, the development of innovative solutions is imperative in addressing and reducing greenhouse gas (GHG) emissions, as they affect atmospheric conditions, local and global climate conditions, visibility and air quality (smog), and human health (Belaïd, 2022).

Cement is the primary ingredient in concrete, and its production is associated with higher CO_2 emissions than concrete. Cement emits 0.93 pounds of CO_2 for every pound produced. Portland cement is a fine powder composed of materials such as “limestone, shells, and chalk or marl combined with shale, clay, blast furnace slag, silica sand, and iron ore” that, when heated, form a substance called clinker that is ground into the fine powder that is cement. It is manufactured via a chemically controlled combination of silicon, aluminum, calcium, iron, and other ingredients (Portland Cement Association, 2023).

Cement is customarily manufactured via a dry method, with the first step being the quarrying of principal raw materials — particularly limestone. The quarried rocks are crushed in multiple stages. In the first stage, rock size is reduced to approximately 6 inches. In secondary crushers, rock size is further reduced to a maximum size of 3 inches. These crushed rocks are then mixed with other ingredients such as fly ash or iron ore (Portland Cement Association, 2023).

These ingredients are heated in cement kilns at a temperature of approximately 2700°F (1482°C). The slurry, or ground material, is fed into the higher end of the kiln while a blast of flame is emitted from the lower end. This flame is “produced by precisely controlled burning of powdered coal, oil, alternative fuels, or gas under forced draft.” This burning produces gases and a substance called clinker, which is discharged red hot from the kiln as gray balls approximately the size of marbles. After the clinker is ejected from the lower end of kiln, it is reduced to handling temperatures in coolers. The heated air of the coolers is then returned back to the kilns to increase burning efficiency and preserve fuel. The cooled clinker is ground and mixed with small amounts of limestone and gypsum (~5%); it is so fine that there are 150 billion grains in one pound of cement (Portland Cement Association, 2023).

Research on the growth of algae has revealed their potential for carbon capture to reduce GHG emissions and for conversion into a fuel source for bioenergy applications. Through photosynthesis, algae use solar energy to capture the CO_2 and store it in their cells. Algae can be used as a feedstock to produce biogas, a methane-rich form of bioenergy, through the process of anaerobic digestion where bacteria break down the organic components of algal biomass and release biogas as a by-product (Wilkie, 2008; Wilkie et al., 2011). Unlike macroalgae (seaweeds), microalgae are unicellular organisms that can grow in fresh, brackish or salt-water environments. Microalgae absorb nutrients and toxins from wastewater streams, helping to keep water sources free of contaminants (Edmundson and Wilkie, 2013; Lincoln et al., 1996; Wilkie and Mulbry, 2002). Moreover, microalgal cultivation is not restricted to arable land and potable water, and can therefore be cultivated in many environments such as wastewaters, marginal lands, saline aquifers, and oceans (Wilkie et al., 2011).

The purpose of this research is to analyze the results of existing literature to ascertain the possibility and efficacy of microalgae cultivation under different conditions to create biomass to be digested anaerobically to produce biogas. We hypothesize that, through the cultivation and anaerobic digestion of microalgae, a synergistic closed-loop system can be created in order to reduce the energy inputs and GHG emission outputs associated with cement production.

The significance of this research is rooted in the unsustainable nature of current cement production, the by-products associated with it, and the overarching implications of these factors on global climate change. There has previously been much research devoted to CO_2 capture and storage (CCS) strategies. However, the biological approach proposed in this paper entails not only carbon capture but also carbon utilization for renewable energy production, essentially recycling CO_2.

Materials and Methods

This paper reviews the literature on methods by which microalgae can be cultivated in order to reduce CO_2 emissions associated with cement production, as well as the harvesting and anaerobic digestion of microalgae to produce biogas that can be used to power cement plants. The data presented in this paper is from analysis of existing peer-reviewed literature and studies pertaining to microalgae cultivation and biogas production from algal biomass. Peer-reviewed studies were analyzed and their findings have been categorized on the basis of experiment type, results, and takeaways, to address the overarching questions presented.

Results and Discussion

Microalgae Cultivation with Cement Flue Gas

Microalgae growth rates and photosynthetic rates are higher than terrestrial plants — having the ability to sequester 10-50 times more CO_2 — with the capacity to grow in a diverse array of conditions. Microalgae have the ability to capture 1.83 kg of CO_2 per kg of algal biomass (Chisti, 2007). Given such efficient growth and photosynthetic rates, microalgae are ideal feedstocks for biomass cultivation and CO_2 mitigation. To reduce the GHG emissions associated with cement production, the approach proposed in this paper is the use of cement flue gas as a source of carbon for microalgae cultivation; once cultivated, microalgae can be digested anaerobically into biogas (methane) to be used in turn to power cement plants — thus creating a closed-loop system, as depicted in Figure 1.

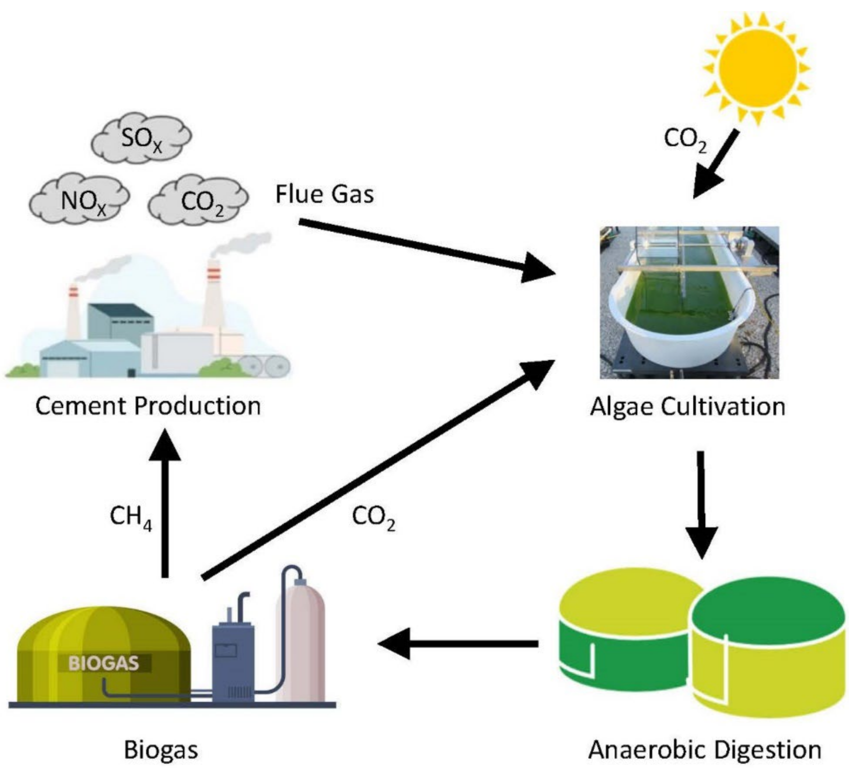

Figure 1. Integrated, Closed-loop Cement/Algae/Biogas Production Process. Microalgae are cultivated from the flue gases emitted from cement plant production processes. This algal biomass is then digested anaerobically to produce biogas (CH_4), which functions as a power source for the cement plant.

Cement flue gas contains CO_2, nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with trace amounts of potentially toxic heavy metals (Lara-Gil et al., 2016). The concentrations of these constituents in flue gases are dependent upon fuel type, combustion process, and raw material type. When natural gas is used as fuel, approximately 5-6% CO_2 is generated, whereas the use of coal produces 10-15% CO_2 during the combustion process (USDOE, 2010). Furthermore, it is possible that these gases can function as nutrients, as algal species such as *Scenedesmus dimorphus* and *Botryococcus braunii* have high tolerances for NO_x and SO_x (Jiang et al., 2013; Yang et al., 2004a, 2004b). The primary components of SO_x and NO_x, SO_2^- and NO, can be oxidized to sulfate and nitrite which can be assimilated by microalgae — reducing both fertilization requirements and associated costs (Lara-Gil et al., 2016).

When studying microalgae tolerance to carbon-saturated environments, researchers analyzed which species indicate high tolerance whilst simultaneously rendering high biomass production. Selection of appropriate species must take into account factors including species' tolerance of flue gas components such as NO_x and SO_x, pH optima, and photosynthetic requirements. Common freshwater species utilized in carbon capture include *Chlorella*, *Scenedesmus*, and *Spirulina platensis*; marine species that have been studied include *Dunaliella salina*, *Isochrysis galbana*, and *Nannochloropsis*. Microscopic images of these species can be seen in Figure 2.

CO_2 Fixation

Microalgal cultures do not require pure CO_2 for growth and photosynthetic processes and are consequently able to sequester the CO_2 present in flue gases produced by combustion processes. The efficiency of CO_2 capture by microalgae depends upon the type of strain selected, the concentration of CO_2, the cultivation system, and environmental and operating conditions such as culture medium, temperature and light intensity. The efficiency of capture and sequestration of CO_2 by microalgae ranges between 40% and 93.7% (Ighalo et al., 2022) . Furthermore, as CO_2 concentrations increase, microalgae can adapt to such altering conditions. As a result of this, higher fixation and growth rates can be fostered through a slow increase of CO_2 supply.

Cole et al. (2014) demonstrated this through the introduction of CO_2 into cultures of *Oedogonium* sp., a filamentous alga. The results were an increase in the dry weight of the cultures from 3.37 g m^{-2} d^{-1} to 8.33 g m^{-2} d^{-1}. O'Connell and Wilkie (2018) achieved a harvest productivity of 13.7 gVSS m^{-2} d^{-1} for *Oedogonium* with CO_2 supplementation. These results demonstrate the potential that algal cultures have for enhanced biomass yield from CO_2 addition.

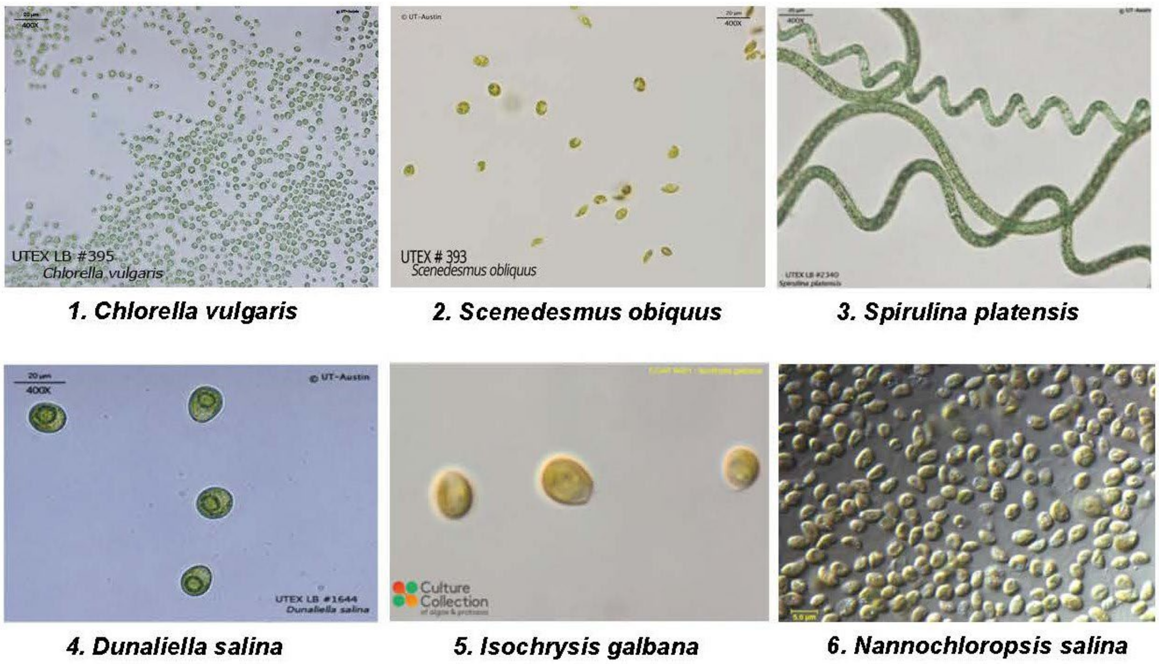

Figure 2. Microsopic Images of Microalgae Species.
Sources:
1-4: UTEX Culture Collection of Algae, The University of Texas at Austin. https://utex.org/
5: Culture Collection of Algae and Protozoa, Scotland. https://www.ccap.ac.uk/catalogue/strain-949-1
6: Center for Freshwater Biology, University of New Hampshire. http://cfb.unh.edu/phycokey/phycokey.htm

All components of flue gas must be considered in order to fully utilize it, generate environmental benefits, and establish cultivation techniques that result in high tolerance levels. In order to mitigate flue gas and repress gas toxicity, the effects of cement kiln dust (CKD) must also be accounted for. Lara-Gil et al. (2016) applied a cultivation strategy consisting of 24 h aeration cycles with CKD additions to increase tolerance of *Desmodesmus abundans* RSM, a CO_2-tolerant isolate, to cement flue gas. Gas components at concentrations close to maximum values (25% CO_2, 800 ppm NO, and 200 ppm SO_2) were investigated together with the effect of CKD to control culture pH. Their results demonstrated that CKD was an effective buffering agent of cement flue gas. Thus, the integration of CKD in algal mitigation systems could regulate culture pH levels and solve problems associated with its disposal.

Cultivation Methods and Conditions

Microalgae can be cultivated in open, closed, or hybrid systems. The most common method for cultivating microalgae, which is also used on industrial scale, is an open pond that allows direct CO_2 uptake from the atmosphere (Iglina et al., 2022). It is therefore essential that ponds be established in an area that provides sufficient light irradiation for cultures and promotes the growth of the specific species being cultivated. Ponds are typically 0.2-0.5m deep with mixing and recirculation to promote biomass growth. Benefits associated with open systems include that they are economical, make sufficient use of sunlight, and are easy to maintain (Razzak et al., 2017). However, cultures grown in open systems are exposed to variable weather conditions and contaminants or other organisms that may limit algal growth; they also require large areas. Closed cultivation systems, or photobioreactors, resolve many of these complications.

In closed systems, algal growth conditions can be precisely controlled. Photobioreactors allow for ideal mixing, to achieve optimum light for cell growth and to improve gas exchange (Razzak et al., 2017). They can be operated indoors to facilitate temperature control. In general, photobioreactors have higher biomass productivities and cell concentrations than open systems. They are also better able to sustain pure cultures of single species compared to open systems, as they shield cultures from contaminant microorganisms. However, photobioreactors have high initial and operating costs and difficulties in reactor scale-up.

In addition to inorganic carbon requirements, microalgal cultures also require large amounts of water. The use of potable water is unsustainable in large-scale algal cultivation, especially in arid regions. However, the use of waste nutrient and water resources may alleviate environmental impacts and economic constraints (Edmundson and Wilkie, 2013; Lincoln et al., 1996, Wilkie and Mulbry, 2002). Therefore, this paper proposes the use of non-potable wastewater produced by cement plants as the algal culture medium. The use of wastewater removes the barrier posed by high water requirements and provides cultures with nutrients for biomass production (Edmundson and Wilkie, 2013; Wilkie et al., 2011).

Cultivation Results of Different Species

Both marine and freshwater microalgal species can be cultivated using the emissions produced from cement production. Two marine species, *Nannochloropsis* and *Isochrysis galbana*, were able to grow under various concentrations of CO_2; furthermore, the study revealed that a 10% CO_2 concentration yielded the highest biomass productivity (Wang et al., 2018). It was also found that biomass cultivation of *Nannochloropsis* was slightly higher when it was supplied with soluble sodium carbonate/bicarbonate derived from flue gas as opposed to using only dissolved CO_2 as a source of carbon (Saifuddin et al., 2015). The maximum yield of dry biomass was 0.55 g with a 20% carbonate solution, while the maximum yield of dry biomass was 0.44 g when using 15% dissolved CO_2; therefore, it can be concluded that not only can flue gas be used, but biomass yields can be increased via alkali absorption and storage in the form of carbonates and bicarbonates (Saifuddin et al., 2015).

Freshwater *Chlorella* sp. is capable of growing in CO_2 concentrations up to 40% and, in a study, the highest biomass concentration, 2.05 g L^{-1}, was attained at a concentration of 10% (Rinanti, 2016). *Scenedesmus* sp. cultivation showed even more potential, as this species was able to not only survive in 100% CO_2 conditions but also produced a biomass concentration of 3.65 g L^{-1} in a 30-day period under such conditions, whilst it was only 1.19 g L^{-1} under atmospheric CO_2 concentrations of 0.036% (Seckbach and Libby, 1970).

Chlorella pyrenoidosa XQ-20044 was found to have high tolerance to nitrite (NO_2^-, 368 ppm) and sulfite (SO_3^{2-},1600 ppm) (Du et al., 2019). Negoro et al. (1991) assessed ten different species in their ability to remove NO_x and SO_x from industrial flue gases. The results indicated that although cell death and growth inhibition were observed when sulfur dioxide (SO_2) concentration was increased from 50 ppm to 400 ppm, such results could be attributed primarily to lower pH; therefore, pH moderation can increase the tolerance limit of species, and such limits can increase after initial acclimation processes (Negoro et al., 1991). They also found that, after a longer lag period, *Nannochloris* sp. grew in a high NO_x environment of 300 ppm. Liang et al. (2014) found that *Chlorella* sp. XQ-20044 was able to attain a high tolerance to sulfite (1600 ppm) through maintenance of the conditions that transform sulfite into sulfate; such conditions included a temperature of 35°C, sodium bicarbonate concentration of 6 g L^{-1}, pH of 9-10, and a cell concentration of 0.8 optical density. These results suggest that *Chlorella* sp. XQ-20044 can be cultivated with flue gas without removing SO_2, assuming adequate pH control.

Furthermore, it can be beneficial to cultivate multiple species in a single system to increase biomass production and mitigate high levels of CO_2 in flue gas because one species may have a high tolerance to the conditions to which the culture is exposed (Nagappan et al., 2020). A diverse culture also has higher resistance to foreign species invasion and cross-contamination (Wilkie et al., 2011).

Table 1 depicts the results of several studies of the amounts of CO_2 absorbed by different microalgae when subjected to different cultivation conditions.

Table 1. Microalgae Biomass Productivity and CO_2 Capture Under Different Conditions.

Microalgae	Biomass Productivity (mg L^{-1} d^{-1})	CO_2 Content (%)	Temperature (°C)	CO_2 Capture (mg L^{-1} d^{-1})	Source
Nannochloris sp.	350	15	25	658	Negoro et al. (1991)
Nannochloropsis sp.	300	15	25	564	Negoro et al. (1991)
Chlorella sp.	950	50	35	1790	Maeda et al. (1995)
Chlorella sp.	700	20	40	1316	Sakai et al. (1995)
Chlorella sp.	1000	15	25	1880	Lee et al. (2002)

Oedogonium, a freshwater filamentous alga, was also shown to be a promising species for biomass production and carbon sequestration (O'Connell and Wilkie, 2018). In a study performed by Lawton et al. (2013), equal proportions of the algal species *Oedogonium*, *Cladophora*, and *Spirogyra* were subjected to different conditions to determine which species showed potential for high biomass production. After three weeks, the concentration of *Oedogonium* reached concentrations exceeding 80% in all treatments, indicating its high productivity and dominance over other filamentous species (Lawton et al., 2013). Studies have also reported higher harvest levels of filamentous species compared to microalgal species, with CO_2 supplementation (O'Connell and Wilkie, 2018). Harvesting filamentous algae could lead to a reduction in the costs of algal production due to the relative ease of harvesting long thin filaments compared to the small (3-30 μm diameter) cells of microalgae (Bjorndal and Wilkie, 2020; O'Connell & Wilkie, 2018; Wilkie et al., 2011).

Anaerobic Digestion of Cultivated Biomass

After microalgae species have sequestered CO_2 and other flue gas components, the harvested biomass can be digested anaerobically to produce biogas to power cement plants, creating a closed-loop, sustainable system (Wilkie et al., 2011). Biogas is comprised primarily of methane and CO_2, often containing traces of ammonia and hydrogen sulfide. The methane content of biogas is typically 50-70% (v/v) and biogas can be used readily in all applications designed for natural gas (Wilkie, 2008). In particular, the biogas can be used to replace fossil fuels used by the cement plant.

Anaerobic digestion consists of a series of reactions, which are catalyzed by a mixed group of bacteria, through which organic matter is converted to methane and CO_2 (Graunke and Wilkie, 2014; Wilkie, 2005). In practice, anaerobic digestion is the engineered methanogenic decomposition of organic matter, carried out in reactor vessels called digesters. The viability of methane production from algal biomass is enhanced because microalgae lack lignin and can have high protein, starch, and lipid content — which can all be metabolized by anaerobic microbes. In addition, nutrients are conserved in the digester effluent (digestate) to be recycled for further algae cultivation. Table 2 summarizes the methane yield results from anaerobic digestion of different microalgal species.

Table 2. Methane Yield from Anaerobic Digestion of Microalgal Biomass.

Microalgae	Methane Yield	Loading Rate	Source
Chlorella sp., *Scenedesmus*	0.17-0.32 L g^{-1}VS	1.44-2.89 gVS L^{-1}	Golueke et al. (1957)
Chlorella vulgaris	0.24 L g^{-1} VS	1.00 g VS L^{-1}	Ras et al. (2011)
Dunaliella	0.44 L g^{-1} VS	0.91 g VS L^{-1}	Chen (1987)
Nannochloropsis salina (lipid extracted biomass)	0.13 L g^{-1} VS	2.00 g VS L^{-1}	Park and Li (2012)
Scenedesmus sp.	0.17 L g^{-1}COD	1.00 gCOD L^{-1}	González-Fernández et al. (2012)
Scenedesmus sp. and *Chlorella* sp.	0.143 L g^{-1} VS	4.00 g VS L^{-1}	Yen and Brune (2007)
Spirulina maxima	0.32 L g^{-1} VS	0.91 g VS L^{-1}	Chen (1987)

Solubilization is a critically important step in anaerobic digestion because the microbial consortia require organic matter in a soluble form for cellular assimilation. The rate at which particulate material is solubilized can determine the overall kinetics of anaerobic digestion and the overall vitality of the microbial consortia (Graunke and Wilkie, 2014). Some algae may require pretreatment to facilitate cellular biodegradability and promote higher methane yield. Pretreatments aim to solubilize recalcitrant cell walls and would be genus/species-specific. Mahdy et al. (2015) demonstrated that pretreatment can significantly enhance biogas production; specifically, after enzymatic pretreatment, methane yields from *Chlorella vulgaris* were enhanced by 2.6-fold when compared to the raw biomass.

Conclusion

Cement is instrumental in the construction of modern infrastructure, yet its production represents a significant source of GHG emissions. As each pound of cement produced emits 0.93 pounds of CO_2, reduction efforts must be made without compromising the integrity of the materials themselves. This paper proposes microalgae cultivation with cement flue gas combined with anaerobic digestion of the harvested biomass as a carbon capture and utilization strategy, since microalgae absorb significant amounts of CO_2 during photosynthesis. Preferred species should have high CO_2-tolerance and biomass productivity. Microalgal biomass can function as a feedstock in the production of biogas, which is a renewable fuel source. The biogas can be used to replace fossil fuels used by the cement plant, creating a sustainable closed-loop system that maximizes GHG emissions reduction.

Species selection must also consider tolerance of flue gas components such as NO_x and SO_x, as well as pH and photosynthetic requirements. Microalgal cultures can attain a tolerance to the components of flue gases through timely acclimation and can utilize NO_x and SO_x as nutrient sources. Furthermore, the literature supports using non-potable cement plant wastewater as a source of nutrients. The potential of filamentous algae has also been identified, being more easily harvested compared to microalgae. The evidence suggests that, through future research and application, this sustainable carbon capture and bioenergy approach can be applied to cement plants to reduce GHG emissions associated with the industry.

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