Sustainable Carbon Dioxide Capture and Utilization System (SCDCUS)

Abstract

Climate change is an imminent threat to most global ecosystems, hence we have urgent calling for sustainable technologies in carbon capture and utilization. SCDCUS is a sustainable concept which biomimetically replicate ecosystem services like climate control through a specifically developed system that captures atmospheric carbon. This theoretical system integrates advanced nanostructures for light harvesting, synthetic chloroplast-like entities for CO_2 fixation, innovative biomimetic membranes for selective gas separation, artificial stomata and synthetic photosynthesis. It provides a very effective method towards using atmospheric CO_2 for the production of value added products such as plastics, fuels, and building materials, within a circular carbon economy framework by working in tandem with nature's processes for carbon sequestration and mineralization and therefore may be considered as a answer for global warming. The following work describes the design and operation of the SCDCUS.

Introduction

Ecosystem services are defined as critical functions performed by natural systems, such as the regulation of climate, filtration of water, and plant pollination. However, human activities disturb this balance through increasing the concentration of greenhouse gases and breaking down climate stability. According to the Millennium Ecosystem Assessment, 2005, biomimicry is promising engineering response to this challenge which is the development of devices modeled after nature's best solutions. SCDCUS is a theoretical concept which uses biomimicry from nature to solve climate change which is a global problem. SCDCUS aligns with the net zero carbon emission goal of United Nations which is crucial to save our planet.

SCDCUS is theoretical concept which is a sustainable system of capturing a potent green house gas (CO2) and utilizing this CO2 by forming valuable compounds which can be used in building materials, synthetic fuel such as ethanol , methanol and it can be used as a raw material for formation of biodegradable plastics. Thus by doing this it saves environment, it is economical as it gives valuable products and it doesn't affect social system so it aligns with triple bottom layer of sustainability.

SCDCUS draws inspiration from Crassulacean Acid Metabolism (CAM) plants like Cactus, Agave, Clusia Pratensis, whose biologically function is intake of CO_2 at night time, CAM plants store water effectively by fixing CO_2 at night. By using this function of carbon capture we can make a system that captures CO2 through artificial stomata. After Carbon capture, It performs CO2 fixation which is inspired from chloroplast and then calcification processes which is inspired from marine organisms like corals and mollusks. Marine organisms use dissolved CO_2 from seawater to form calcium carbonate through a process called calcification. SCDCUS system is envisioned to capture atmospheric CO_2 and convert it into value-added chemicals, therefore encouraging a circular carbon economy in which carbon emitted would be recycled. It is also combined with artificial photosynthesis process to convert CO2 into chemicals like poly carbonate.

The primary mission is to actively contribute toward positive mitigation of climate change by capturing atmospheric CO_2 into sustainable materials, thus opening up new pathways toward a carbon emission reduction roadmap.

Methodology

SCDCUS follows four steps which are

- Capturing of CO_2
- CO_2 fixation or conversion
- Utilization of CO_2
- Product formation

Capture of CO_2:

CO_2 is captured from artificial stomata which is made from nanoengineered membranes with tunable pores, which functionally emulate the stomata-like natural activity of leaves. Zhu et al. (2024) explores artificial stomata systems that mimic the gas exchange functions of plant leaves, providing a model for tunable pore technologies. From this we can make artificial stomata which can mimic the function of stomata.

It enables higher intake of CO_2 during the night while releasing oxygen. The system contains sensors devised from natural processes of plants, aiding it to regulate the opening of pores for optimal capture of CO_2.

According to Robeson (2008), recent advancements in membrane technology have significantly enhanced the efficiency of CO_2 separation processes, particularly through the use of polymide membranes that selectively allow CO_2 to pass while blocking other gases like nitrogen. This artificial stomata can be made from material such as polymide which has self-assembly copolymer membranes which are used for gas separation. These type of membranes are best as In this case, these membranes allow CO_2 to pass effectively while blocking N_2 or other gases.

The primary reaction for CO_2 capture involves the interaction of CO_2 with water to form carbonic acid, which can subsequently participate in various reactions.

$CO2(g)+H2O(l)\rightleftharpoons H2CO3(aq)$

CO2 Fixation-Conversion

Calvin cycle (natural)

According to Nocera (2012), the principles of artificial photosynthesis and the design of synthetic systems is mimicking natural processes which are crucial for developing effective energy conversion technologies. SCDCUS uses synthetic chloroplast like entities which are designed to mimic the natural process of how plants absorb and utilize CO_2 for energy. This theoretical system is, in fact, similar in a broad sense to the whole process of uptake and utilization of CO2 by plants for its energy generation. The system adopts genetically modified enzymes like RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) which enhance carbon fixation and therefore give a much higher effective conversion of CO2 into useful compounds like sugar, biofuels and chemical feedstocks.

This reaction is the fixation of carbon dioxide into sugar or biofuels. The key enzyme involved is RuBisCO, which catalyzes the first step in the Calvin cycle:

1. Carboxylation: RuBP(aq)+CO2(g)→Using catalyst RuBisCO→23-PGA(aq)Where RuBP = Ribulose-1,5-bisphosphate, and 3-PGA = 3-phosphoglycerate.

2. Reduction: 3-PGA(aq)+ATP+NADPH→G3P(aq)+ADP+NADP^+Where G3P = glyceraldehyde 3-phosphate.

3. Regeneration**:** G3P(aq)→RuBP(aq)

• Synthetic Photosynthesis

Apart from marine organisms which convert CO2 into solid compounds we can integrate artificial photosynthesis which can give sugars, polycarbonates. This process mimics how plants use sunlight to transform CO_2 into sugars. This synthetic photosynthesis employs light-harvesting nanostructures and catalysts to produce CO2 in the forms of some valuable products like polycarbonates or other chemicals. SCDCUS uses advanced catalytic systems like manganese catalyst cores which are combined with polypyridyl ligands for enhanced catalytic performance for CO_2 Reduction and Water Oxidation.

Utilization of CO2

The development of synthetic systems that mimic natural processes is essential for advancing artificial photosynthesis (Nocera, 2012). SCDCUS performs carbon mineralization which chemically transforms CO2 into stable minerals. It is inspired from biomimicking from marine organisms which convert CO2 into their solid shell forms, like corals. This form of storage is in a solid phase. In carbon mineralization, CO_2 reacts with minerals, typically involving metal ions (such as calcium) to form stable compounds like calcium carbonate ($CaCO_3$). This process effectively locks away carbon in a solid phase, preventing it from re-entering the atmosphere. We can accelerate carbonate formation method by following two-step mechanism: one, the emulsification of carbon dioxide gas into the form of a bicarbonate; and two, the precipitation of calcium carbonate with the assistance of designer proteins into stable mineral deposits. By offering supplementary paths to CO_2 removal, SCDCUS decreases the load from natural carbon sinks, such as forests or oceans. Notably, it reduces the general concentration of CO_2 and allows for a reduced rate of ocean acidification, which contributes to richer biodiversity in the marine fauna.

Formation of Calcium Carbonate:

- The mineralization of CO_2 through reaction with calcium ions can be represented as follows:

  Bicarbonate Formation: $CO_2(g)+H_2O(l) \rightarrow H_2CO_3(aq)$

  $H_2CO_3(aq) \rightleftharpoons HCO_3^-(aq)+H^+(aq)$

  Precipitation of Calcium Carbonate: $Ca^{2+}(aq)+CO_3^{2-}(aq) \rightarrow CaCO_3(s)$

Product formation

Subsequently, captured CO_2 is valorized in the form of plastics, fuels, and even building materials by tapping into pathways for a circular carbon economy. This, in essence, means reuse of carbon is involved; this would reduce the levels of emission that contribute to climate change.

Product Formation

Conversion of CO_2 into Fuels and Plastics:

1. Production of Methanol (from CO_2): $CO_2(g)+3H_2(g) \rightarrow CH_3OH(g)$
2. Production of Polycarbonate (from CO_2):

- Polycarbonates can be synthesized through the reaction of bisphenol A with phosgene, with CO_2 serving as a carbon source in some synthetic routes.

$$nCO_2+nR\text{-}OH+nR\text{-}NCO \rightarrow [R\text{-}O\text{-}CO\text{-}NR]_n$$

Conclusion

SCDCUS offers an sustainable biomimetic approach to address the global warning by capturing and converting atmospheric CO_2 into products like fuels, plastics, and building materials by biomimicking from natural processes which are found in CAM plants, marine calcifiers, and photosynthesis. SCDCUS provides a sustainable solution for saving the planet by reducing GHG gases which are the main causes for climate change. The system's integration of advanced nanomaterials, synthetic chloroplasts, and artificial stomata demonstrates the potential for carbon capture technologies to not only mitigate CO_2 emissions but also create economic value. Ultimately, SCDCUS holds promise as a key contributor to achieving the global net-zero emissions goal of United Nations and combating climate change.

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Flow chart is on next page

please zoom in to see flow chart clearly

Start
Problem Statement: Climate Change
Excess CO_2 emissions from human activities contribute to global warming and ecosystem disruption.
Objective: Capture Atmospheric CO_2
Convert Captured CO2 into valuable products
Develop a biomimetic system to capture and convert atmospheric CO_2 into valuable products.
Biomimetic Inspiration
CAM Plants: CO_2 capture mechanism inspired by Crassulacean Acid Metabolism (e.g., cactus).
Marine Organisms: Carbon mineralization process modeled after coral calcification.
CO_2 Capture Process
Artificial Stomata: Use nanoengineered membranes to mimic stomata, enabling efficient CO_2 intake.
CO_2 Fixation
Synthetic Chloroplasts: Replicate natural photosynthesis using RuBisCO enzyme for carbon fixation.
Artificial photosyntheis using nanostructures and catalyst like mangnese core
CO_2 Utilization
Carbon Mineralization: CO_2 reacts with calcium ions to form calcium carbonate ($CaCO_3$), inspired by marine organisms.
Accelerated Carbonate Formation: Use emulsification and precipitation methods to convert CO_2 into solid carbonates.
Product Formation
Methanol Production: Convert CO_2 and hydrogen into methanol (synthetic fuel).
Polycarbonate and Plastics: CO_2 serves as a carbon source in the production of polycarbonates and other biodegradable plastics.
Final Outcome
Mitigation of Climate Change: Reduces atmospheric CO_2 levels while supporting sustainability and economic growth.
Circular Carbon Economy: Reuse captured CO_2 to create value-added products like fuels, plastics, and building materials, contributing to net-zero carbon goals.
End