Carbon Sequestration: A Review of Biological Methods

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Abstract:

Carbon dioxide is a gas present in Earth's atmosphere and is vital for fundamental life systems through the carbon cycle, such as photosynthesis. The concentration of CO2 in the atmosphere has risen in the past 150 years, from 250 parts per million to 418 ppm, due to the excessive burning of fossil fuels for domestic and industrial purposes. Currently, global warming caused by this dramatic increase in anthropogenic emissions is one of the main environmental issues. In addition, high CO2 levels also result in changes in the amount of rain, eutrophication or acidification of water bodies, extinction of vulnerable species, and overall changes in ecosystems, which negatively impacts the human population. These problems can be countered through the extraction and storage of CO2 through both technological and biological means. As previously mentioned, the gas is needed for photosynthesis. This process is the most efficient known form of biosequestration as it involves photosynthetic organisms such as plants and some microorganisms storing carbon dioxide as biomass. This also occurs also in marine environments with phytoplankton and algae (R. Gayathri et al, 2021). In terrestrial ecosystems, trees and forests, as well as soil, are the main method of conservation. Carbon capture in soil is heavily affected by the microbes within the environment and the root microbiome of plants, trees and crops. This paper reviews the most common forms of biosequestration, agroforestry and afforestation, microbes, changes to anthropogenic agricultural practices, and marine forms of biosequestration through algal photosynthesis and ocean fertilization (N. Nayak et al, 2022).

Introduction:

Biosequestration is the process of storing carbon dioxide in various forms through biological means. The main biological process is photosynthesis, which is carried out by autotrophic organisms as they convert sunlight, water, and carbon dioxide into glucose, the energy of which is then broken down and consumed through cellular respiration.

Forestry, including agroforestry and afforestation, have been proven efficient, due to their storage of large amounts of carbon through photosynthesis. However, they are difficult to implement as permanent solutions because of scarce access to ample amounts of land. Afforestation, or adding forestry in places where there previously were none (such as urban landscapes), increases carbon biosequestration by capturing and storing more CO2 than otherwise would have been stored in such locations. (N. Nayak et al, 2022).

Even so, some agricultural carbon capture methods aim to store as much carbon as possible in cultivated land. This is done by working to increase carbon levels in the soil through practices such as no-till, nitrogen-fixing, perennial crops, and biochar.

Also, algal methods have been found to be the most efficient due to a number of economic and biological factors. For example, algae have extremely flexible thresholds for CO2 levels, ion levels, and temperature, and have been discovered to sequester carbon dioxide through a variety of pathways and organisms (R. Gayathri et al, 2021).

In addition, both plant waste and algae can be converted to biofuels and used as an environmentally-safer alternative to traditional fossil fuels, through domestic growth of algae in an assortment of water bodies (Nogia et al, 2016).

Finally, microbial biosequestration also plays a large role in the storage of carbon in ecosystems. Both aerobic and anaerobic bacteria take part in this process, along with archaea, fungi, and cyanobacteria (R. Gayathri et al, 2021).

To summarize, many methods of carbon biosequestration are being widely used and developed today, mostly through utilizing photosynthesis. Carbon is stored as biomass, either in forestry carbon sinks, underground through microbial processes, in stable forms such as biochar, or in phytoplankton and algae as potential biofuel

Terrestrial Ecosystems

To begin, terrestrial ecosystems hold large amounts of carbon and are classified as carbon sinks (N. Nayak et al, 2022). Phytosequestration takes place through the process of photosynthesis, in organisms from microbes to trees. Trees are mainly responsible for the biosequestration of carbon on Earth today. They store carbon as one of the most effective carbon sinks in the ecosystem, by converting inorganic carbon to an organic form. Forestry has several disadvantages, however, such as the need for large swaths of land and heavy use of resources. Deforestation and clear-cutting impact the environment tremendously by increasing CO_2 in the atmosphere and removing the organisms that are able to store it (Nogia et al, 2016).

Forestry

Biomass in the form of trees is responsible for a large percentage of terrestrial carbon sinks, but due to clearing of land for agricultural, urban, and other uses, the amount of tree cover has significantly decreased. Conversion to farmlands is especially impactful as it decreases the SOC (soil organic carbon). However, lost carbon stock can be recovered through the addition of trees in different environments, whether or not forestry existed in that location previously.

Agroforestry refers specifically to agricultural landscapes. It is the incorporation of trees into farming environments. Effectiveness depends on the species of tree as well as the conditions and climate of land, but agroforestry can increase the SOC stock by up to 19% and recover up to 35% of biomass lost to agriculture through its aboveground structures. However, the implementation of agroforestry as a solution requires consistency over a long term, as halting these practices can easily reverse the effects. It has been projected that by increasing agroforestry by 5% every five years, the country of India has the potential to sequester half of all carbon dioxide emissions by 2050. Additionally, croplands in West Africa have the possibility of attaining net-negative emissions over two decades with this process (N. Nayak et al, 2022).

Afforestation is defined as growing trees in locations where they did not exist previously. Though they have the potential to fix a large amount of carbon dioxide, doubts concerning the effectiveness of afforestation have risen due to a wide range of estimated results. Other factors that have been considered to affect large-scale implementation are tree species, soil type, land and its usage history, and climate, as the exact effects on soil are unknown. Afforestation has greater potential in land that has a lower SOC stock. Some soil carbon stock will be lost in places that have an initially-high SOC as the soil equilibrium will be affected, causing decomposition. When new input changes the rate of SOC decomposition, that is referred to as 'soil priming', and the PE (priming effect) is the effect on the rate of conversion into substances that are more easily available to plants; this is the process of mineralization (N. Nayak et al, 2022).

Microbial

Both photosynthetic and non-photosynthetic pathways are used to sequester carbon in microorganisms (R. Gayathri et al, 2021). In the bacterial category, eubacteria, archaebacteria, and cyanobacteria carry this out as autotrophs. Bacteria that are resistant to many antibiotics (gram-negative) are responsible for the bio-fixation of carbon by using energy from hydrogen molecules. Certain species convert CO2 to the enzyme Acetyl-CoA, but the bacteria that are able to perform this are anaerobic and therefore are unable to survive in the presence of oxygen. This is one of the main disadvantages of this form of biosequestration, and one that could potentially be changed via genetic engineering. Additionally, another type of bacteria, Proteobacteria, use different pathways to sequester carbon through cycles such as the Calvin Cycle and Krebs Cycle and to produce single-bonded hydrocarbon compounds (alkanes) (R. Gayathri et al, 2021).

Archaea

Archaea, unicellular prokaryotic extremophiles, are classified into three groups: halophiles, thermoacidophiles, and methanogens. Methanogens use CO2 to produce methane from wastewater, and the methane can be used as biofuels. Some species use several specific pathways to sequester carbon, while others use the enzyme Acetyl-CoA and another bicarbonate molecule to create the chemical succinyl-CoA, which is passed through another mechanism to produce more molecules of Acetyl-CoA. Other enzymes are then used to fix the CO2 into biomolecules (R. Gayathri et al, 2021).

Fungi

Fungi are the main decomposers and therefore one of the main sources of carbon capture in terrestrial ecosystems, serving as carbon sinks. They are heterotrophic eukaryotes, with cell walls made of chitin. Two groups exist: saprophytic and mycorrhizal fungi. The latter thrive by forming a mutually beneficial relationship with other plants. The former use a variety of enzymes for the process of decomposition, converting the organic chemicals into forms that are more available to plants and rotating carbon through the carbon cycle. The mycelium of the fungus also contributes greatly to the biosequestration of carbon. The CO2 is stored within the fungus and produces a higher quantity of biomass when the efficiency of the decomposition is raised by the incorporation of the mycelia (R. Gayathri et al, 2021).

To conclude, there are many benefits to microbe-based biological carbon sequestration, though some key characteristics of the organisms themselves and their preferred environments may hinder the path to implementing this solution on a large scale (R. Gayathri et al, 2021).

Soil and Agriculture

Moving on to carbon capture abilities of human habits, soil and agriculture have great potential for the biological sequestration of carbon dioxide. Through not only the soil microbiome but also through alteration of anthropogenic activities, such as agriculture, humans could greatly increase the capacity and amount of carbon in the ground. Many such practices exist (N. Nayak et al, 2022). Several methods for capture are described below.

Biochar

Biochar is the result of pyrolysis, or heating biomass at extremely high temperatures without the presence of oxygen (N. Nayak et al, 2022). It is also known as ‘black carbon’ and is less susceptible to decomposition due to its acting as an inferior substrate for microorganisms. Its half-life depends on its starting materials, but generally has been measured to be anywhere from hundreds to thousands of years. This makes it a long-term option for the storage of carbon, for it is added to soil as a fertilizer, similar to charcoal (Nogia et al, 2016). It is estimated to potentially offset 12% of emissions. However, biochar also has several disadvantages. Except for the case of infertile and sandy soils, it was found to have a negative soil priming effect. This occurs when there is an influx of organic soil carbon into the ground, which causes decomposition of previous SOC stock due to an affected soil equilibrium (N. Nayak et al, 2022).

Crops

The selection of crops that are planted also have a substantial effect on the amount of carbon that is sequestered. By adding perennial crops, more can be stored in the expansive root microbiome. Also, growing nitrogen-fixing plants increases carbon levels by lessening the decomposition of organic matter. Additionally, bio-energy crops (crops such as biofuels that can be used to produce energy) can play a large role in CO2 biosequestration. They have the potential to replace traditional fossil fuels as an option that is healthier and safer for the environment (Nogia et al, 2016). Additionally, through actions including but not limited to minimum soil disturbance (no-tillage soil practices in order to let greenhouse gases remain in the ground) and crop diversity (planting a variety of crops to preserve the heterogeneity of microbes in the soil), it is possible to improve the biosequestration capacities of agriculture (N. Nayak et al, 2022).

These changes have high potential but also assorted disadvantages, such as the environment in which biochar is most efficient. To conclude, altering habits in the agriculture industry could prove to be a valuable method of carbon capture and storage due to plants (photosynthesis) and variety in the soil microbiome (N. Nayak et al, 2022).

Marine Biosequestration

Beyond traditional terrestrial carbon capture, marine carbon sequestration, known as 'blue carbon' is the capture of marine CO2 and accounts for 55% of total biosequestered carbon (N. Nayak et al, 2022). This makes it extremely important to conserve ocean and coastal ecosystems, as without the process of photosynthesis carried out by them, our environment will be a hostile one in which all aerobic organisms, including humans, will struggle to survive (N. Nayak et al, 2022).

Algae

Algae is known today as one of the most efficient and productive methods of blue biological carbon fixation. It uses enzymes to capture carbon via RuBisCO in the Calvin-Benson cycle. Both micro and macroalgae exist, and due to the high lipid content in microalgae, it has proven to be a valuable resource as a biofuel. Algal growth can be employed as biorefineries, for approximately 1 kilogram of microalgae sequesters 1.84 kilograms of atmospheric CO2. Algal production near the source of carbon dioxide emissions is an efficient method of capture but factors such as species of algae should be taken into account. Some species such as *Chlorella sp* have a very high capacity for CO2 exposure, but extreme overexposure is considered toxic. Microalgae have a CCM (carbon concentration mechanism). This pathway is mainly based on a chemical reaction in which RuBisCO is used concerning carbon dioxide and bicarbonates; this mechanism is found in all algae and cyanobacteria, the latter of which involves transporting CO2 or bicarbonates into the cell membrane or chloroplast. Through a series of four reactions, bicarbonates and CO2 are transported and utilized, and the separation and concentration of RuBisCO increases (R. Gayathri et al, 2021).

Cyanobacteria

Furthermore, cyanobacteria live in water but fix atmospheric carbon dioxide, as microscopic or macroscopic bacteria or algae. They are autotrophs and harness light from the sun to generate energy (R. Gayathri et al, 2021). They sequester carbon in the cytoplasm of the cell, through structures within the cell that contain enzymes. Those enzymes are carbonic anhydrase and

RuBisCO (Nogia et al, 2016). There are two types of carboxysomes: alpha and beta. These differ in the cyanobacteria depending on which type of RuBisCo (IA or IB) is found in the cells. Additionally, CCMs, or Carbon Concentrating Mechanisms, alter the Calvin Cycle of photosynthesis to more efficiently sequester carbon (R. Gayathri et al, 2021).

Ocean Fertilization (Phytoplankton)

Ocean fertilization is yet another form of carbon biosequestration, done by the photosynthetic processes of plankton. Phytoplankton are marine autotrophs. Ocean fertilization comes from the discovery that certain nutrients, when their marine concentration is increased, are beneficial to the growth of plankton. One such substance is iron. Research has found that the addition of iron improves productivity as it stimulates more plankton growth. Other nutrients found to have similar effects include ammonium and nitrate. However, potential disadvantages stem from the fact that changing the amounts of nutrients in the ocean, like so, could have harmful side impacts on marine ecology. It is possible that stored organic matter could decompose and release greenhouse gasses such as methane and nitrogen monoxide. In order to be effective, ocean fertilization would need to be implemented on a very large scale (Nogia et al, 2016).

Conclusion

Each method of biological carbon sequestration holds both advantages and disadvantages. Forestry is efficient and already implemented on a large scale, but requires an abundance of land and resources. Certain anthropogenic alterations to agricultural practices will need to be largely implanted but are productive. Additionally, microbial and marine organisms, though have proven their efficiency, do not hold clear results on their environmental impact. In this paper, each of these potential solutions are individually reviewed and their advantages and disadvantages are listed along with an overview of the chemical processes and other information regarding their impact, future, and currently known mechanisms (N. Nayak et al, 2022).

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