Understanding Carbon Sequestration: Mechanisms and Strategies for Enhancing Soil Health and Crop Productivity

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Carbon is an essential element found in various forms on Earth. It is the building block of life and play a critical role in the carbon cycle. The carbon cycle is a natural process that involves the continuous exchange of carbon dioxide (CO2) between the atmosphere, plants, animals, and soil (Fig.1). Through photosynthesis, plants absorb CO2, converting it into organic carbon compounds. When plants and animals respire or decompose, carbon is released back into the atmosphere as CO2.

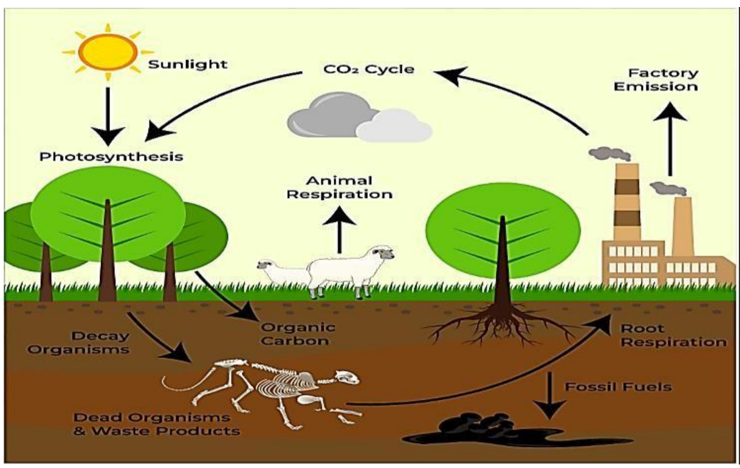

Fig 1. Carbon cycle

CO2 is one of the main greenhouse gases that is causing global warming and forcing climate change. The continued increase in CO2 concentration in the atmosphere is believed to be accelerated by human activities such as burning of fossil fuels and deforestation. One of the approaches to reduce CO2 concentration in the atmosphere is carbon sequestration. Carbon Sequestration is the placement of CO2 into a depository in such way that it remains safely and not released back to the atmosphere. Sequestration means something that is locked away for safe keeping. The trapping of a chemical in the atmosphere or environment and its isolation in a natural or artificial storage area. Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing global climate change (Ussiri, D A and Lal R, 2017).

Mechanism of carbon sequestration

Organic matter decomposition plays a major role in the cycling of carbon (C) and nutrients in terrestrial ecosystems across the globe. Climate change accelerates the decomposition rate to potentially increase the release of greenhouse gases and further enhance global warming in the future.

However, fractions of organic matter vary in turnover times and parts are stabilized in soils for longer time periods (C sequestration). Overall, a better understanding of the mechanisms underlying C sequestration is needed for the development of effective mitigation policies to reduce land-basedproduction of greenhouse gases. Known mechanisms of C sequestration include the recalcitrance of C input, interactions with soil minerals, aggregate formation, as well as its regulation via abiotic factors.

Mechanism of Carbon sequestration in soil

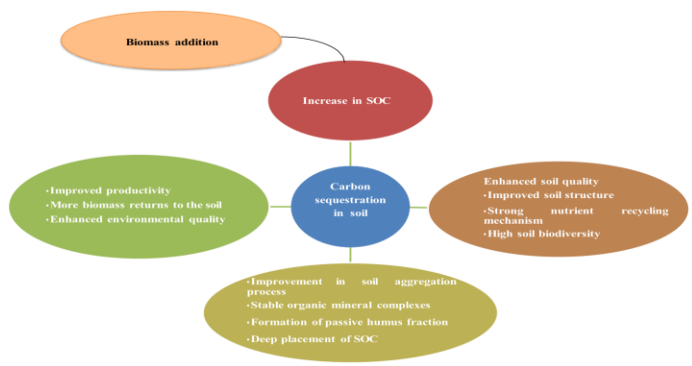

Fig 2. Mechanism of Carbon sequestration in soil

In Figure 2. explains how biomass addition leads to carbon sequestration in soil, increasing soil organic carbon (SOC) and improving soil health.

1. **Biomass Addition → Increase in SOC**
   - Biomass (crop residues, plant roots, organic matter) is returned to the soil.
   - This organic material decomposes, increasing Soil Organic Carbon (SOC).

2. Carbon Sequestration in Soil → Benefits

Improved Productivity and Environmental Quality

- Improved Productivity: Higher SOC enhances soil fertility, leading to better crop yields.
- More Biomass Return to Soil: Healthy crops generate more biomass, further contributing to SOC.
- Enhanced Environmental Quality: Sequestering carbon reduces atmospheric CO_2, mitigating climate change.

Enhanced Soil Quality & Nutrient Recycling

Improved Soil Quality: Higher SOC enhances soil fertility, water-holding capacity, and microbial activity.

- Improved Soil Structure: SOC helps bind soil particles, reducing erosion and increasing aeration.
- Strong Nutrient Recycling Mechanism: Organic matter decomposition releases nutrients essential for plant growth.
- High Soil Biodiversity: A diverse microbial community in high SOC soils supports better nutrient cycling and disease resistance.

Soil Aggregation & Stability

- Improvement in Soil Aggregation Process: SOC binds soil particles into stable aggregates, improving aeration and root penetration.
- Stable Organic Mineral Complexes: SOC interacts with minerals, forming stable compounds that prevent nutrient leaching.
- Formation of Passive Humus Fraction: Humus, a stable organic material, stores carbon long-term and improves soil fertility.
- Deep Placement of SOC: Carbon is stored deeper in the soil profile, making sequestration more effective and long-lasting.
- Stable Micro-Aggregates: Tiny soil particles stick together, enhancing soil structure and reducing erosion.

Classification of carbon sequestration

a. Geological carbon sequestration

Geological sequestration refers to the storage of CO2 underground in depleted oil and gas reservoirs, saline formations, or deep, un-minable coal beds. Once CO2 is captured from a point source, such as a cement factory, it would be compressed to ≈100 bar so that it would be a supercritical fluid. In this form, the CO2 would be easy to transport via pipeline to the place of storage. The CO2 would then be injected deep underground, typically around 1 km, where it would be stable for hundreds to millions of years. At these storage conditions, the density of supercritical CO2 is 600 to 800 kg / m^3.

b. Oceanic geological sequestration

If CO2 were to be injected to the ocean bottom, the pressures would be great enough for CO2 to be in its liquid phase. The idea behind ocean injection would be to have stable, stationary pools of CO2 at the ocean floor. The ocean could potentially hold over a thousand billion tons of CO2. However, this avenue of sequestration isn't being as actively pursued because of concerns about the impact on ocean life, and concerns about its stability. A biological solution can be growing seaweed that can naturally be exported to the deep ocean, sequestering significant amounts of biomass in marine sediments. River mouths bring large quantities of nutrients and dead material from upriver into the ocean as part of the process that eventually produces fossil fuels. Transporting material such as crop waste out to sea and allowing it to sink exploits this idea to increase carbon storage. International regulations on marine dumping may restrict or prevent use of this technique.

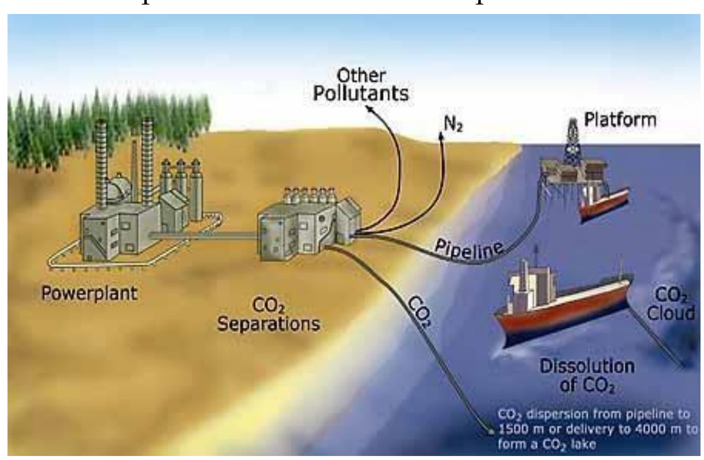

Fig 3. Oceanic carbon sequestration

c. Terrestrial carbon sequestration.

Terrestrial sequestration is a process that captures and stores carbon dioxide (CO2) in vegetation and soil within a few feet of the Earth's surface, providing them with the components they need to live and grow and reducing CO2 in the atmosphere. During photosynthesis, carbon from atmospheric carbon dioxide is transformed into components necessary for plants to live and grow. As part of this process, the carbon present in the atmosphere as carbon dioxide becomes part of the plant in a leaf, stem, or roots, and the carbon is sequestered for a long period of time. Once the plant dies, or as limbs, leaves, seeds, or blossoms drop from the plant, the plant material decomposes and the carbon is released. Trees are valuable as greater amounts of carbon are tied up for longer time periods.

Strategies to improve carbon sequestration

a. **Reclamation of degraded soils:** Degraded soils usually have poor soil structure, so when we reclaim the soil then soil structure improves soil structure, leads to the formation of macro and micro aggregates, which in turn help in carbon sequestration.

b. **New cultivars and new species:** Herbicide resistant crops can reduce the use of herbicide and weeding, it promotes no-till, which in turn reduces CO2 emissions. GM crops can increase C sequestration by increasing the productivity and the amount of residue carbon that can be sequestered.

c. Crop residues and biomass management: Crop residues are materials left in an agricultural field after the crop has been harvested. Crop residues can be incorporated back into the soil, so it will increase carbon content and return back nutrients to the soil.

d. Conservation tillage: Tillage loosens the soil increasing the exposure of soil organic matter and hence speeding oxidization. This results in a reduced soil organic matter content and consequent release of CO2 into the atmosphere. On the other hand, conservation tillage can reduce carbon dioxide emission from the soil and effectively retain carbon in the soil.

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