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CARBON SEQUESTRATION THROUGH VEGETABLE CROPS – TOOL FOR RESILIENT FARMING

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ABSTRACT

The present study is based on the carbon sequestration approaches to mitigate climate change that aims to capturing and storing the atmospheric carbon-dioxide in order to lower the greenhouse concentration. This can be done by cutting offsets emissions from industries, power plants, farms and factories using renewable energy, electrifying homes and changing transportation, protecting coastal wetlands and promoting sustainable agroforestry and decentralizing energy distribution. Some of the approaches related to carbon sequestration includes biological, terrestrial, soil and geological. The carbon is stabilized in solid and dissolved form so that there are no any effects on atmosphere. Decarbonization aims to afforestation, carbon capture storage, electrification and by replacing fossil fuels with clean energy sources. Carbon pool is the system of store carbon that is carbon stocks which is measured in mass. Examples related to carbon pool include earth's crust, ocean reservoirs, terrestrial ecosystem and atmosphere. Greenhouse gas emissions and climate change problems reduced by carbon-dioxide bioconversion and by grapheme production and engineered molecules. Through physical, residual, solubility and mineral trapping carbon-dioxide can be stored in geological formations. Human can help in controlling carbon sequestration by planting more and more trees, sustainable forest management, managing crops and soil by reducing soil erosion, removing pollutants from bodies of water and by reducing the use of chemical fertilizers. Government can help in controlling carbon sequestration by funding, carbon credit schemes, carbon capture and storage policy, public procurement, tax credits and by research and development. The important component of human nutrition are vegetables that encompasses great species diversity and are very sensitive to unpredictable climate changes. The increase in frequency of drought, flooding, high-temperature, low-temperature, salinity and changes of atmospheric carbon dioxide or ozone level affect morphological, physiological and biochemical changes in the plant. To avoid risk in vegetable farming and to ensure sustainable livelihoods of the agricultural community, genetic improvement of vegetable crops is an appropriate adaptation strategy to cope with climate change adversities.
***Keywords*:** Afforestation, Agroforestry, Carbon sequestration, Carbon pool, Decarbonization, Greenhouse, Renewable Energy.

Introduction

Carbon sequestration aims to capturing and storing the atmospheric carbon-dioxide in order to lower the greenhouse concentration. This can be done by cutting offsets emissions from industries, power plants, farms and factories using renewable energy, electrifying homes and changing transportation, protecting coastal wetlands and promoting sustainable agroforestry. Developing technologies to reduce the rate of increase of atmospheric concentrations of carbon-dioxide from annual emissions. Natural carbon sinks such as forests, wetlands and agricultural lands plays a vital role in absorbing carbon-dioxide through photosynthesis and storing it in vegetation and soils, technological solutions like CSS involve capturing carbon-dioxide emissions from industries and storing them underground in geological formations (Prajapati *et.* al. 2023). Carbon sequestration can occur naturally in ecosystems or through human- engineered techniques. Carbon is a key element to sustain soil biological activity, ecosystem productivity, soil biodiversity and the quality of the environment. Atmosphere carbon enters terrestrial ecosystems through the natural metabolic process of photosynthesis and is returned to the atmosphere through a variety of processes referred toa as respiration (Gaikwad, 2021). The small imbalance between atmospheric carbon sequestration and the emissions of carbon into the atmosphere may lead to remarkable decadal variations in climate change. Increased global temperature would require demand for more high temperature adaptable varieties. The climate change will affect suitability and adaptability of current cultivars by altering the growing period (Dhillon and Gill, 2015). Under changing climatic situations crop failures, shortage of yields, reduction in quality and increase in pest and disease problems are common and they render the vegetable cultivation unprofitable (Lal *et al*. 2014). Vegetable crops are very sensitive to climatic vagaries like sudden rise in temperature as well as irregular precipitation at any phase of crop growth (Afroza *et al*., 2010). The estimated potential yield losses are 17% due to drought, 20% due to salinity, 40% due to high temperature and 15% due to low temperature. (Ashraf *et al*. 2008). Widely cultivated for the high value of their products, horticultural crops include fruits and vegetables which provide essential food, minerals and vitamins that are critical to human nutrition. Ensuring the food and nutritional security under a changing climate is one of major challenges of our era. (Fakir Mohan Sahu. 2016). Innovation of climate resilient technologies in vegetable development of new robot Dino in vegetable farming highly effective robot to weeding in vegetables in field, both in raised beds and in rows ex. Lettuce, carrots, onions etc. (Bhavna *et.* al 2021). Climate smart horticulture play important role in the efficient water optimization for horticultural crops using IOT, atomization of greenhouse using ARDUINO & GSM module, automated grafting robot in cucurbitaceae and Solanaceae family crops by using robot AFGR-800CS, use of senor technology in detection of various biotic and abiotic stresses, use of drone, remote sensing sustainably increases the production, productivity, adaptation & mitigation of climate changes (Kumar *et al*., 2020). The development of automated grafting robot AFGR-800CS for Cucurbitaceae and Solanaceae family grafting success rate is 87.3%, binding success rate is 68.9% and productivity is 700-800 plants/hr. developed by the center of excellence for digital farming solutions for enhancing solutions by robots, drones and AVGs. VNMKV, Parbhani. (Khemsk. 2021). Vegetables are extremely sensitive to changes in their environment and have limited ecological potential because of their succulent nature, with water content frequently exceeding 90% (Bhardwaj *et al.* 2025). In particular, during important phases of development like flowering and fruiting, abiotic stresses like flooding, high temperatures, erratic precipitation, and soil salinity- all of which are made more frequent and intense by climate change-disturb plant morpho-physiology and metabolic processes, negatively impacting vegetable growth, yield and quality (Laxman *et al*. 2024).

Evolution of Carbon Sequestration

In 1920, the technology behind carbon sequestration began with the development of carbon-dioxide scrubbers, initially used to remove impurities from methane before it was sold. In 1938, scientists first proposed a carbon capture plant. In 1970, oil and gas companies started using processes similar to carbon capture and storage (CCS) processes, initially for enhanced oil recovery, where carbon-dioxide was injected into depleted oil and gas reservoirs to increase oil production. In 1972, the first commercial project to inject carbon into soil started. In 1996, the first integrated carbon capture and sequestration plant, the sleipner project in Norway, marked a significant step in the development of CCS technology. People have long observed the natural cycling of carbon through the atmosphere, Oceans, land and living organisms.

Classification of Carbon Sequestration

Emission rates from fossil fuel combustion increased by 40 % between 1980 & 2000 (Wofsy, 2001). Yet, the amount of carbon-dioxide accumulating in the atmosphere remained the same over this period because the excess carbon-dioxide released is being removed by oceans, forests, soils and other ecosystems (Battle *et al*., 2000). Soil carbon sequestration is a promising approach, with degraded and agricultural soils having significant potential to reduce carbon-dioxide levels. Carbon is one of the most abundant elements in all forms of life. The mechanism of photosynthesis in plants converts carbon-dioxide into carbon compounds to maintain metabolic functions and build their basic vegetative and reproductive structures (Dietze *et al*., 2014).

Biotic sequestration : Biotic sequestration is based on managed intervention of higher plants and microorganisms in removing carbon-dioxide from the atmosphete. It differs from management options which reduce emissions.

Abiotic sequestration: Abiotic sequestration is based on physical and chemical reactions and engineering techniques without intervention of living organisms (e.g. plants, microbes).

Terrestrial sequestration : It is also known as biological carbon sequestration. Carbon-dioxide from the atmosphere is absorbed naturally through photosynthesis and stored as carbon in biomass and soils. It includes sequestration by soils, vegetation, forests and wetlands.

Oceanic sequestration: It store atmospheric carbon into deep oceans and serve as carbon sink. One-third of human generated emission are estimated to be entering the ocean. Carbon is naturally stored in the ocean via two pumps, solubility and biological and there are analogous man made methods, direct injections and oceanic fertilization.

Direct injection in oceanic sequestration : Capturing carbon-dioxide from industrial sources, transporting it to the deep ocean and then directly injected into the deep ocean at a designated site. At great depths, the high pressure causes carbon-dioxide to become denser than seawater, allowing it to settle on the ocean floor as a liquid or hydrate deposit.

Ocean fertilization: Ocean fertilization or ocean nourishment is a type of technology for carbon-dioxide removal from the ocean based on the purposeful introduction of plant nutrients to the upper ocean to increase marine food production and to remove carbon-dioxide from atmosphere. Ocean nutrient fertilization, for example iron fertilization, could stimulate photosynthesis in phytoplankton that converts the oceans dissolved carbon-dioxide into carbohydrate. Adding iron to the ocean increases photosynthesis in phytoplankton by up to 30 times.

Geological sequestration : Carbon-dioxide is captured from industrial or energy related sources. The carbon-dioxide pressurizes until it becomes a liquid. The liquid carbon-dioxide is injected into porous rock formations deep underground.

Procedure of Carbon Cycle

Carbon-dioxide enters the atmosphere through respiration and industrial processes like burning fossil fuels. Plants absorb carbon-dioxide through photosynthesis. Animal consume plants incorporating carbon into their systems. When plants and animals die, their bodies decompose and carbon is released back into the atmosphere.

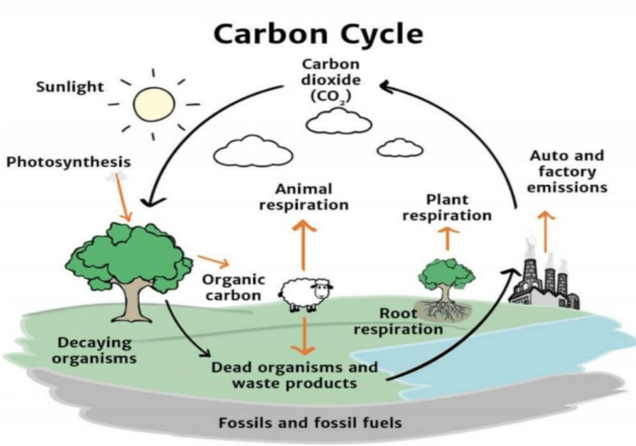

Fig. 1 : Carbon cycle

Arrhenius (1896) recognized the significance of atmospheric carbon-dioxide concentrations concerning global temperature towards the end of the 19th century. However, the perturbation of the global carbon cycle caused by human activities during the 20th century has been an unprecedented event in history. It is crucial to comprehend the global carbo cycle and its disruption by anthropogenic actions to develop effective strategies for mitigating climate change.

Biomass Carbon Accumulation in Vegetable Crops

It is also known as carbon pool. Amount of carbon stored in a system, such as soil, wood products or living biomass. The largest pool of carbon in forest containing soil organic matter. Ocean is the biggest carbon stock on earth, containing around 40,000 billion tonnes of carbon.

Biomass carbon accumulation in vegetable crops involves plants capturing atmospheric CO2 via photosynthesis and storing it as organic matter (carbon) in leaves, stems, roots and soil, crucial for climate mitigation and soil health. This sequestration varies by crop type (e.g., onion accumulate more than bitter gourd), density and farming practices like no-till, cover cropping and compost use, which enhances soil organic carbon. High-biomass, deep-rooted vegetables and improved management techniques significantly boost carbon storage in agricultural systems, turning farms into valuable carbon sinks.

Policy to mobilize carbon stock in vegetable crops

Policies to increase carbon stock in vegetable crops focus primarily on providing incentives and framework that encourages farmers to adopt sustainable agricultural practices (SAPs). Often by supporting initiatives like reforestation, sustainable land management practices and carbon capture and storage technologies, essentially incentivizing landowners and industries to actively sequester carbon from the atmosphere and store it in natural carbon sinks like forests or underground geological formations.

Governments and private entities are developing carbon markets that allow farmers to earn "carbon credits" for quantifiable greenhouse gas (GHG) reductions and carbon sequestration.

Policies incentivize specific agricultural practices that enhance carbon storage in vegetable systems like conservation/no-tillage, cover cropping and crop rotation, organic amendments and biochar, agroforestry and policies encourage in-situ management of crop residues (e.g., direct incorporation into the soil) and discourage burning with penalties for non-compliance.

Government schemes and financial support policies often involve direct financial support and subsidies to help farmers transition to climate-friendly practices. Subsidies for equipment providing discounts on machinery for conservation tillage, such as happy seeders or shredders, encourages less soil disturbance and improved residue management.

Capacity building and awareness is a crucial policy component is educating farmers and providing technical assistance on sustainable practices and carbon accounting. This involves collaborative efforts between governments bodies, NGOs and research institutes to bridge the knowledge gap.

Practical Implications of Carbon Sequestration in Vegetable Crops

Adopting carbon farming practices improves long-term soil fertility and resilience to climate variability (e.g., drought), which helps ensure food security and sustainable production.

Incorporating cover crops, utilizing crop rotations, especially with legumes.

Vegetable crops naturally absorb atmospheric CO_2 through photosynthesis. Practices that enhance this process help reduce greenhouse gas (GHG) concentrations in the atmosphere, contributing to global climate change mitigation efforts.

Organic matter in soil significantly increases water infiltration rates and water-holding capacity, which helps crops withstand drought conditions and reduces the need for irrigation.

Healthier soils with balanced nutrients and better water retention lead for increased and more stable crop yields over the long term, even under climate variability. Specific practices, like planting deep-rooted crops, help build a more resilient rooting environment.

Carbon sequestration can enhance agricultural productivity. Carbon sequestration can help protect forests, wetlands and other ecosystems. It can be used to recover oil from depleted oil and gas fields, also can help neutralized emissions from human activities like manufacturing and construction. Carbon sequestration helps forest maintain a good carbon balance, which protects them from becoming deserts. This process helps moderate runoff and reduce erosion, store carbon in soil through practices such as no-till agriculture and iron fertilization.

Strengths of Carbon Sequestration in Vegetable Crops

It increases soil organic matter, leading to better aggregation, aeration and reduced compaction. Higher organic carbon boosts water infiltration and retention, reducing drought stress. Healthier soils, better water and nutrients translate to more vigorous plant growth and higher productivity. Cover crops like legumes, grasses and high-biomass crops enhance soil organic matter and microbial life. Carbon sequestration in soil can improve water retention, nutrient availability and reduce erosion. It Reduces the negative health effects of exposures to high levels of carbon- dioxide. Carbon capture and storage technologies can create jobs in construction, engineering and maintenance. It improved air quality. Carbon rich soils support biodiversity and contribute to ecosystem health. It Support rural development and foster community innovation. It enhances food security, create jobs and boost economic growth.

Constraints of Carbon Sequestration in Vegetable Crops

Many vegetables crops have short life cycles, limiting total biomass and carbon input compared to perennial crops. Soils or those lacking clay minerals struggle to hold carbon, while heavy soils can become waterlogged. Limiting nutrients (like sulphur or manganese) can hinder plant growth and microbial activity needed for carbon stabilization, even if carbon inputs are high. Poor structure, compaction, and low organic matter limit microbial processing of carbon. Droughts reduce photosynthesis, while waterlogging creates anaerobic conditions, potentially increasing methane emissions. Carbon sequestration can be expensive to develop and operate. The cost of building and maintaining the infrastructure, including pipelines and storage facilities, can be high. The energy used to capture and compress carbon-dioxide adds to the cost. There is a risk of leakage from underground reservoirs. Carbon sequestration strategies like agroforestry and cover cropping can reduce overall land availability and output. If carbon-dioxide is not contained properly, it could escape into the atmosphere. The stored carbon-dioxide could have unforeseen and potentially harmful effects on the environment.

Climate Change Mitigation Plan in Vegetable Crops

Heat tolerant hybrids in Chinese cabbage and breeding lines in tomato (CL5915) were developed at the Asian Vegetable Research and Development Centre, Taiwan (Pena and Hughes 2007).

In tomato, gene Pat-2 governs parthenocarpic fruit development at high temperatures. This trait will be helpful in increasing fruit set in tomato at high temperatures where normal fruit set is impaired. (George *et al*., 1984).

In India, Wild genes have already been successfully introgressed into the cultivated types in vegetable crops like tomato and okra for disease resistance and quality (Plucknett *et al*., 1987).

A wild relative of tomato '*S. pennellii*' is tolerant to drought due to the thick cuticle, waxy leaves which allow conserving leaf water in dry soils. (O' Connell *et al*., 2007).

Low temperature tolerance is transferred successfully to *Phaseolus Vulgaris* (French bean) from P. retensis by hybridization followed by embryo rescue (Jakhar & Sastry, 2005).

Chilling resistance of tomato + potato somatic hybrids was intermediate between the chilling resistances of tomato and potato. These somatic hybrids might be useful for transferring genes for chilling resistances into the domestic tomato (Smillie *et al*., 1979).

A salt-resistant somaclonal variation (SCV) line in eggplant was obtained from cell culture in a medium containing 1% sodium chloride (Jain *et al*., 1988).

Frost tolerance gene *AFP 1* (Anti-freezing protein) was introduced into a tomato cultivar from winter flounder fish (Hightower *et al*., 1991).

A heat stock protein gene (HSP17.7), which confers high-temperature tolerance, was isolated from carrot. This gene can be transferred to other vegetable crops for improvement against high temperature (Malik, 1989).

Twenty-three quantitative trait loci (QTL) were identified for recovery after drought stress in potato (Anithakumari *et al*., 2011).

AFLP markers were used for mapping of ten QTL associated with drought tolerance at seedling stage and maturity in cowpea (Muchero *et al*. 2009).

Thirteen QTL were detected for taproot length and the ability to extract water from deep in the soil profile in lettuce (Lactuca sativa) and the wild L. *serriola* by using AFLP markers. (Johnson *et al*. 2000).

Marker-assisted selection (MAS) is extensively used in crop improvement in bacterial disease resistance followed by nutrition and quality (Pro vitamin A in sweet potato & cassava). (Vogel 2009).

Disease resistance and nutritional quality are important as diseases are aggravated and the quality of vegetables is affected badly by climate change. (Koundinya *et al*. 2014).

Genetic markers, namely 3000 restriction fragment length polymorphism (RFLP), 800 simple sequence repeat (SSR), 120 random amplified polymorphic DNA (RAPD) and nine isozyme markers were identified for drought tolerance in cassava (Okogbenin *et al*. 2013).

Watermelon plants were made drought tolerant by grafting onto ash gourd plants (Sakata *et al*. 2007).

Grafting onto *Solanum melongena* rootstock helped in bacterial wilt and flooding tolerant in tomato (Palada & Wu 2007).

Rootstocks from *cucurbita* species were more tolerant to salt than rootstocks from *Lagenaria siceraria* (Matsubara 1989).

Interspecific rootstocks like *Solanum lycopersicum* × S. *habrochaites* provided low soil temperature (10 to 13^0 C) tolerance to their grafted tomato scions and S. *intengrifolium* × S. *melongena* rootstocks provided low soil temperature (18 to 21^0 C) tolerance to eggplant scions, respectively (Okimura *et al*. 1986).

At the Central Tuber Crops Research Institute, Thiruvananthapuram, an experiment was conducted on organic farming in elephant foot yam for five years. They found a 20% yield increase and net profit was estimated as 28% higher compared to chemical farming. (Suja *et al*. 2012).

Rice straw mulching in a tomato crop exhibited maximum B:C ratio due to higher fruit yield and lower initial input requirement during summer (Pandey and Mishra 2012).

Future Opportunities and Challenges of Carbon Sequestration in Vegetable Crops

Carbon sequestration has a promising future in mitigating climate change innovations in capture technologies can make carbon sequestration more feasible and less expensive. Carbon sequestration in vegetable crops offers huge potential for climate mitigation via improved soil health (using cover crops, no-till, compost, rotations) but faces challenges like high costs, water scarcity, integrating practices with intensive veg. farming, measuring/ verifying carbon and farmer adoption, requiring policy and economic support to unlock opportunities in carbon markets. Carbon-dioxide can be stored in oil and gas reservoirs, coal beds, deep saline formations, shale basins and coal beds. Soil organic carbon (SOC) can be built up through litter and other organic matter entering the soil. Carbon sequestration can help meet global climate goals, such as reducing emissions and achieving climate neutrality. Other climate change mitigation efforts transitioning to renewable energy sources, enhancing energy efficiency, adopting regenerative agricultural practices and reducing emissions through carbon offsets.

Conclusions

Carbon sequestration is a promising method to reduce greenhouse gas emissions and slow climate change. It can be achieved through biological or geological processes.

Purposeful manipulation of biological processes can accelerate the carbon-dioxide sequestration process with adoption of regulatory measure and identification of policy incentives.

However, for these management systems to be effective, there is a strong need for an integrated system approach. While the global C cycle is affected by human activities.

The sequestration potential varies widely among different vegetable crops, based on factors like plant population density, growth habits (e.g., deep-rooted vs. shallow-rooted), and total biomass production. Perennial vegetables or those used in agroforestry systems generally offer higher, longer-term sequestration potential compared to annual monocultures.

In essence, while vegetable cultivation can be a net emitter of greenhouse gases under conventional, input-intensive systems, shifting to “carbon-smart” or organic farming methods transforms it into a viable and essential part of the climate solution.

Carbon sequestration through vegetable crops is that they can play a crucial, yet variable, role in climate change mitigation when integrated with specific sustainable management practices. While individual vegetable plants may sequester less carbon than perennial woody crops due to their shorter lifespans and smaller root systems, the implementation of carbon farming techniques at scale can result in significant soil organic carbon (SOC) accumulation.

The primary factor determining the success of carbon sequestration in vegetable farming is the adoption of specific management practices, rather than the crop type alone. Practices such as conservation tillage, cover cropping, organic amendments (manure/compost), and crop rotation are essential for enhancing SOC.

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