International Research Journal of Education and Technology

Peer Reviewed Journal

ISSN 2581-7795

Carbon Sequestration in Soils: Engineering Solutions for Land Sustainability

Akash B Jadhav[1], Tejaswini Daware,

[1]HOD Civil Engineering, Shatabdi Institute Of Engineering
[2]Professor, Shatabdi Institute of Techanology

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Abstract - *Soil carbon sequestration presents a promising pathway to mitigate climate change, enhance soil health, and improve ecosystem services. This paper explores the mechanisms, engineering applications, benefits, challenges, and future directions of soil carbon sequestration. The integration of natural processes with advanced geotechnical and agricultural practices is emphasized as a sustainable solution for reducing atmospheric CO_2 levels. Key applications in construction, land management, and climate resilience are also discussed.*

Key Words: Soil, Carbon, Sequestration, Sustainability

1.INTRODUCTION *(Size 11 , cambria font)*

This paper explores the role of engineering in advancing carbon sequestration in soils, examining cutting-edge technologies, strategies for land management, and the broader implications for climate change mitigation and environmental sustainability. By enhancing our understanding of soil carbon dynamics and applying targeted engineering solutions, we can pave the way for a more sustainable and resilient future, where soil plays a crucial role in stabilizing global carbon levels and supporting the health of the planet.

1.1 Objective

To investigate the potential of soil-based carbon sequestration and its integration into civil engineering practices

Examine the Mechanisms of Soil Carbon Sequestration: To provide an in-depth understanding of the natural processes through which soils store carbon, including the biological, chemical, and physical factors influencing carbon capture and storage in soil.

Assess Engineering Innovations and Techniques: To review and evaluate recent advancements in engineering technologies and strategies that can optimize soil's capacity for carbon sequestration, such as soil amendments, biochar, controlled traffic farming, and other soil management practices.

Identify Synergies between Carbon Sequestration and Land Sustainability: To investigate how enhanced carbon sequestration can contribute to broader environmental goals, such as improving soil health, boosting agricultural productivity, and enhancing ecosystem services.

Evaluate the Feasibility and Impact of Large-Scale Implementation: To critically analyze the scalability of soil carbon sequestration technologies, their cost-effectiveness, and the practical challenges associated with their widespread adoption in both developed and developing regions.

Provide Policy and Management Recommendations: To offer insights into how governments, industries, and land managers can integrate soil carbon sequestration into climate change mitigation strategies and land use policies, fostering a sustainable and climate-resilient future.

1.2 Scope and problem statement

Scope: Focus on organic and inorganic sequestration methods, engineering applications, and interdisciplinary strategies.
Background: Importance of mitigating climate change; global carbon cycle dynamics.
Problem Statement: Rising atmospheric CO_2 levels and the need for scalable carbon capture solutions.

2. Engineering Applications

- Carbon-Embedded Soils for Construction

Using carbon-rich materials (e.g., biochar, fly ash) in geotechnical projects.
Applications in embankments, retaining walls, and green infrastructure.

- Enhanced Weathering in Civil Engineering

Incorporation of silicate rock dust in urban landscaping.
Accelerated carbonation processes in landfills and reclaimed lands.

- Urban Development and Green Spaces

Soil-based carbon capture in urban parks, green roofs, and bioswales.
Integrating sequestration strategies into urban planning.

- Land Reclamation Projects

Using carbon sequestration techniques to rehabilitate degraded lands.Potential for integrating into floodplain restoration and erosion control.

Benefits of Soil Carbon Sequestration

- Climate Mitigation

Reduction of greenhouse gas emissions.
Potential to store 1–3 Gt CO_2 annually.

- Soil Health and Productivity

Enhanced nutrient availability and water retention.
Improved agricultural sustainability.

- Erosion Control and Resilience

Better soil structure and reduced vulnerability to erosion.
Increased resilience to climate extremes.

3. Methods of Soil Carbon Sequestration

Soil Organic Matter (SOM) Enhancement

Description: Increasing the amount of organic matter in the soil through the addition of organic materials like crop residues, manure, compost, or cover crops.
Mechanism: Organic matter is a major carbon pool in soils, and its addition helps store more carbon through the process of decomposition, where carbon is stabilized in the soil over time.
Examples:
Adding crop residues and green manures to the soil.
Using compost and animal manures as soil amendments.
Practicing agroforestry or reforestation to increase organic matter in the soil.

Fig 1

Biochar Application

Description: Biochar is a form of charcoal produced by heating organic materials (like wood, crop residues, or waste) in a low-oxygen environment. When applied to soils, it can act as a long-term carbon sink.
Mechanism: Biochar has a high surface area and is chemically stable, allowing it to store carbon for hundreds to thousands of years.
Examples:Applying biochar to agricultural soils to increase soil fertility while sequestering carbon.Using biochar in degraded soils to improve soil structure and water retention.

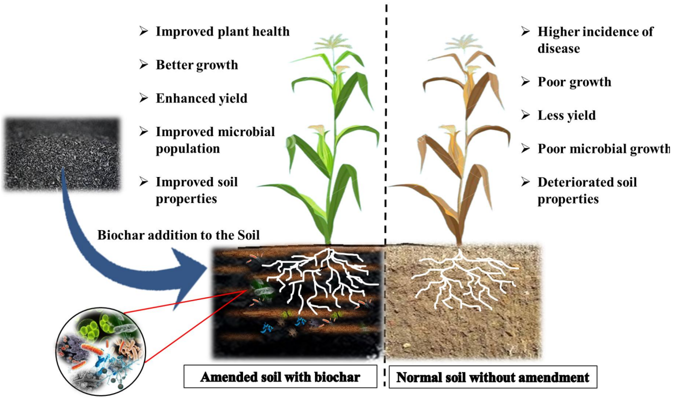

Fig 2

Cover Cropping

Description: Planting crops specifically designed to cover the soil surface during fallow periods or between cash crop cycles.
Mechanism: Cover crops, such as legumes, grasses, or deep-rooted plants, enhance carbon sequestration by increasing organic matter in the soil and preventing erosion. They also promote soil microbial activity, which helps convert organic material into stable forms of carbon.
Examples:Planting clover, rye, or other fast-growing cover crops to increase soil organic matter.
Implementing rotation and intercropping with legumes to fix nitrogen and add organic carbon.

Fig 3

Incorporation of Carbon-Rich Materials

Description: Adding carbon-rich materials such as crop residues, food waste, or municipal waste into the soil to increase the carbon content.
Mechanism: These materials decompose slowly, providing a long-term source of organic carbon for the soil.
Examples:
Adding mulch or crop residues to soil to improve carbon storage and soil structure.

Land Restoration and Soil Erosion Control

Description: Restoring degraded land through soil conservation practices and reducing soil erosion.

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Mechanism: Soil erosion removes topsoil, which is rich in organic carbon. Restoring vegetation and stabilizing soil through techniques like contour plowing, terracing, and planting ground cover reduces erosion and increases carbon storage in the soil.
Examples: Using contour farming and terracing on slopes to prevent erosion. Restoring wetlands or grasslands that store significant amounts of carbon in the soil.

Fig 4

DISCUSSION

Which Method is better?

For Immediate Impact on Degraded Land:

Land Restoration and Soil Erosion Control is highly beneficial, especially for land that has been degraded by erosion or poor management. It helps restore ecosystems and prevents further loss of carbon stored in the soil.

For Enhancing Agricultural Soil Health:

Cover Cropping and Soil Organic Matter (SOM) Enhancement are very effective. Cover cropping provides both short-term and long-term benefits, improving soil structure and organic matter, while SOM enhancement offers significant carbon storage and fertility improvements over time.

For Long-Term, Stable Carbon Storage:

Biochar Application is the best for long-term carbon sequestration. It provides a stable form of carbon storage that lasts for centuries, especially in soils that are otherwise deficient in organic matter.

Combination of Methods:

Often, a combination of these methods works best. For example:

Cover cropping and SOM enhancement can work together to increase organic matter and improve soil fertility.

Biochar application can be integrated into these practices to enhance carbon storage in the soil.

Land restoration techniques can be applied to degraded soils to improve their carbon sequestration capacity, with cover cropping and SOM enhancement complementing restoration efforts.

In summary, each method has its strengths, and the choice of method depends on the specific context and goals. For immediate agricultural benefits, cover cropping and SOM enhancement are excellent choices. For long-term carbon sequestration, biochar and land restoration may offer more enduring solutions.

4 . CONCLUSIONS

Soil carbon sequestration represents a vital and practical approach to mitigating climate change while promoting land sustainability. The methods explored in this paper—Land Restoration and Soil Erosion Control, Cover Cropping, Biochar Application, and Soil Organic Matter (SOM) Enhancement—each offer distinct advantages in enhancing the soil's capacity to store carbon and improve soil health.

Among these methods, Land Restoration and Soil Erosion Control proves particularly effective in regions impacted by land degradation and erosion, preventing the loss of valuable topsoil and promoting long-term ecological restoration. Cover Cropping is a versatile and accessible practice that can be readily integrated into agricultural systems, providing immediate benefits in terms of soil health, organic matter enhancement, and carbon storage. Biochar Application, although requiring initial investment, offers a promising long-term solution for stable carbon sequestration and soil fertility improvement, making it an appealing choice for carbon-intensive industries. Lastly, Soil Organic Matter (SOM) Enhancement, through practices like adding compost or crop residues, represents a fundamental and cost-effective method that can significantly improve soil carbon content over time.

Ultimately, the combination of these methods may offer the most effective strategy for maximizing soil carbon sequestration. Tailoring these practices to specific land types, climatic conditions, and agricultural systems is essential for their successful implementation.

In conclusion, enhancing soil carbon sequestration not only contributes to mitigating climate change by reducing atmospheric CO_2 levels but also promotes soil health, increases agricultural productivity, and fosters sustainable land management practices. By continuing to advance research, technology, and policy support in this field, we can unlock the full potential of soils as a critical tool in the fight against climate change, while simultaneously ensuring the long-term sustainability of our agricultural landscapes.

Challenges and Limitations

Measurement and Monitoring

Difficulties in quantifying soil carbon stocks and changes.

Need for advanced tools like remote sensing and IoT sensors.

- Stability and Permanence

Risk of carbon re-release due to land use changes or soil disturbance. Ensuring long-term carbon storage.

- Scaling and Adoption

High costs and technical barriers for large-scale implementation. Policy and financial challenges in promoting sequestration practices.

- Interdisciplinary Knowledge Gaps

Limited collaboration between soil science, civil engineering, and policy-making.Need for integrated research frameworks.

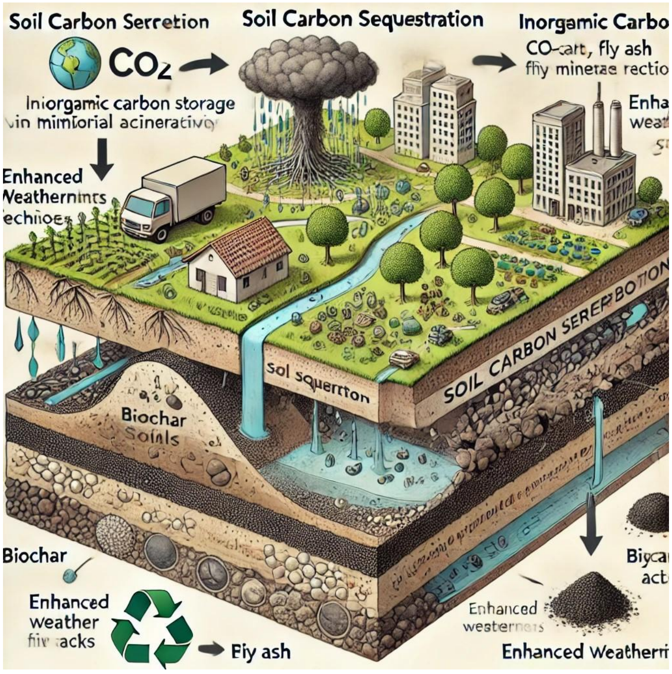

Fig 5- showing final soil carbon sequestration

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