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CLIMATE-INDUCED SOIL DEGRADATION AND CARBON SEQUESTRATION POTENTIAL: EVALUATING CLIMATE-SMART SOIL MANAGEMENT PRACTICES IN PAKISTAN'S SEMI-ARID AGROECOSYSTEMS

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Abstract
This study examined the impact of climate variability on soil degradation and evaluated the carbon sequestration potential of climate-smart soil management practices in Pakistan's semi-arid agroecosystems. A quantitative, field-based research design was employed, involving soil sampling and survey data collected from 150 agricultural sites and associated farmers using a stratified random sampling technique. Key soil indicators, including soil organic carbon (SOC), were analyzed alongside management practices and climatic variables. Statistical techniques such as correlation, regression, and mediation analysis were applied to test the proposed relationships. The results indicated that climate variability significantly increases soil degradation, which in turn reduces SOC levels and carbon sequestration potential. Climate-smart soil management practices were found to significantly mitigate soil degradation and enhance carbon storage. Additionally, these practices played a mediating role by reducing the negative impact of climate variability on carbon sequestration. The study contributes to the understanding of soil–climate interactions and highlights the importance of sustainable land management in improving soil health and mitigating climate change. The findings provide practical insights for promoting climate-resilient agricultural practices in semi-arid regions. However, limitations related to the cross-sectional design and regional scope suggest the need for further longitudinal and large-scale studies.

Introduction

Climate change has emerged as one of the most critical global challenges, exerting profound impacts on soil systems, agricultural productivity, and ecosystem sustainability. Rising temperatures, altered precipitation patterns, and increased frequency of extreme climatic events—such as droughts and floods—have accelerated soil degradation processes, particularly in arid and semi-arid regions (Sanaullah et al., 2022) . Soil degradation, manifested through erosion, salinization, nutrient depletion, and loss of soil organic matter, undermines the productive capacity of land and threatens food security. In Pakistan, where agriculture forms the backbone of the economy, these challenges are especially pronounced in semi-arid agroecosystems that are inherently fragile and highly sensitive to climatic variability.

Semi-arid regions, which constitute a significant portion of Pakistan's agricultural landscape, are characterized by low and erratic rainfall, high evapotranspiration rates, and poor soil fertility. These conditions inherently limit biomass production and reduce organic carbon inputs to the soil, resulting in carbon-deficient systems with low resilience to environmental stress (Plaza-Bonilla et al., 2015; Plaza-Bonilla et al., 2023). Furthermore, unsustainable land-use practices—such as intensive tillage, monocropping, and overgrazing—exacerbate soil degradation, leading to a decline in soil structure, nutrient availability, and microbial activity. Such degradation not only diminishes agricultural productivity but also reduces the soil's capacity to function as a carbon sink, thereby contributing to increased atmospheric greenhouse gas concentrations.
Soils represent one of the largest terrestrial carbon reservoirs and play a crucial role in climate change mitigation through carbon sequestration. Soil organic carbon (SOC) sequestration involves the capture and long-term storage of atmospheric carbon dioxide in soil organic matter, which enhances soil fertility, water retention, and overall ecosystem stability (Sanaullah et al., 2022) . In arid and semi-arid agroecosystems, the potential for carbon sequestration is significant but remains largely underutilized due to poor management practices and environmental constraints. Empirical studies in Pakistan have demonstrated that different land-use systems—such as agroforestry, croplands, and forestlands—vary considerably in their carbon sequestration potential, with integrated systems often showing higher soil carbon stocks (Yasin et al., 2023; Lal et al., 2020).
In this context, climate-smart soil management practices have gained increasing attention as sustainable solutions to address both soil degradation and climate change. These practices include conservation agriculture, reduced tillage, crop diversification, agroforestry, and integrated nutrient management, all of which aim to enhance soil health while improving resilience to climate variability. For instance, reduced tillage and intercropping systems have been shown to significantly improve soil carbon sequestration in semi-arid environments by increasing biomass input and minimizing soil disturbance (Rehman et al., 2025) . Similarly, agroforestry systems not only restore soil fertility but also provide substantial carbon sequestration benefits, contributing to both mitigation and adaptation goals (Abbas et al., 2017; Yasin et al., 2023).
Despite the recognized potential of climate-smart practices, their adoption in Pakistan remains limited due to socio-economic, institutional, and knowledge-related barriers. Moreover, there is a lack of comprehensive empirical studies that simultaneously evaluate soil degradation processes and carbon sequestration potential within the framework of climate-smart agriculture in semi-arid regions. This gap restricts the development of evidence-based policies and management strategies tailored to local agroecological conditions.
Therefore, this study aims to evaluate climate-induced soil degradation and assess the carbon sequestration potential of climate-smart soil management practices in Pakistan's semi-arid agroecosystems. By integrating soil science, climate change adaptation, and sustainable land management perspectives, the research seeks to provide a scientific basis for enhancing soil resilience, improving agricultural productivity, and contributing to climate change mitigation efforts in vulnerable regions.

Problem Statement

Climate change has intensified soil degradation processes globally, with particularly severe consequences in semi-arid agroecosystems. In Pakistan, these regions are highly vulnerable due to erratic rainfall, rising temperatures, and increasing frequency of droughts, all of which accelerate soil erosion, salinization, nutrient depletion, and the loss of soil organic carbon (SOC). Such degradation not only reduces soil fertility and agricultural productivity but also diminishes the capacity of soils to function as effective carbon sinks, thereby exacerbating atmospheric carbon concentrations and contributing to climate change.
Despite the recognized importance of soil carbon sequestration as a nature-based solution for climate mitigation, the potential of Pakistan's semi-arid soils remains underutilized. Unsustainable land management practices—

including intensive tillage, monocropping, overgrazing, and inefficient irrigation—have further degraded soil structure and reduced organic matter content. While climate-smart soil management practices (such as conservation agriculture, agroforestry, crop diversification, and integrated nutrient management) have shown promise in enhancing soil health and carbon sequestration in similar agroecological contexts, their adoption and effectiveness in Pakistan remain insufficiently studied.

Moreover, existing research often addresses soil degradation and carbon sequestration separately, with limited integrative analyses that evaluate both processes simultaneously within climate-smart frameworks. There is also a lack of localized empirical evidence assessing how different management practices influence soil carbon dynamics under varying climatic and environmental conditions in Pakistan's semi-arid regions. This knowledge gap constrains the development of targeted, evidence-based strategies for sustainable land management and climate resilience.

Therefore, there is a critical need to systematically investigate climate-induced soil degradation and evaluate the carbon sequestration potential of climate-smart soil management practices in Pakistan's semi-arid agroecosystems. Addressing this gap will provide valuable insights for enhancing soil sustainability, improving agricultural productivity, and supporting climate change mitigation and adaptation efforts.

Research Questions

1. How does climate variability contribute to soil degradation in Pakistan's semi-arid agroecosystems?
2. What is the current status of soil organic carbon in these regions?
3. How do climate-smart soil management practices influence soil carbon sequestration?
4. Which management practices are most effective in mitigating soil degradation while enhancing carbon storage?
5. What are the key barriers to the adoption of climate-smart soil management practices in semi-arid Pakistan?

Research Objectives

1. To assess the impact of climate variability on soil degradation in Pakistan's semi-arid regions.
2. To evaluate the current levels and distribution of soil organic carbon in selected agroecosystems.
3. To examine the effectiveness of climate-smart soil management practices in enhancing carbon sequestration.
4. To identify and compare the most sustainable practices for improving soil health and mitigating degradation.
5. To analyze the socio-economic and institutional factors influencing the adoption of climate-smart practices.

Significance of the Study

This study is significant in advancing both scientific understanding and practical solutions related to soil sustainability and climate change mitigation in semi-arid agroecosystems. From a theoretical perspective, it contributes to the existing body of knowledge by integrating climate change impacts, soil degradation processes, and carbon sequestration potential within a unified analytical framework. By examining these interrelated components simultaneously, the study provides a more comprehensive understanding of how climate-induced stressors influence soil systems and how climate-smart management practices can enhance soil resilience and ecological functioning.

In the context of Pakistan, the study holds particular importance due to the country's reliance on agriculture and the increasing vulnerability of its semi-arid regions to climate variability. The research generates localized empirical evidence on soil organic carbon dynamics and degradation patterns, which are currently underexplored. This context-specific insight enhances the relevance and applicability of global theories to local agroecological conditions, thereby supporting more informed and effective decision-making.

Practically, the findings offer valuable guidance for key stakeholders, including farmers, policymakers, environmental planners, and agricultural extension services. By identifying effective climate-smart soil management practices, the study provides actionable strategies to improve soil health, increase carbon sequestration, and sustain agricultural productivity. These insights can inform policy development, promote sustainable land management practices, and contribute to national and international climate goals, particularly in relation to carbon mitigation and land restoration initiatives.

Furthermore, the study supports long-term environmental sustainability by emphasizing the role of soils as critical components of climate regulation and ecosystem services. By addressing both degradation and carbon storage, it highlights pathways for enhancing resilience in vulnerable agroecosystems, ultimately contributing to food security, climate adaptation, and sustainable development.

Literature Review

Climate-induced soil degradation has emerged as a critical concern in global agricultural systems, particularly in arid and semi-arid regions where environmental conditions inherently limit soil resilience. Soil degradation refers to the decline in soil quality caused by natural processes and anthropogenic activities, including erosion, salinization, nutrient depletion, and loss of soil organic matter (Lal, 2015). Climate change exacerbates these processes through increased temperature, erratic precipitation, and extreme weather events, which accelerate soil erosion and reduce soil moisture availability (IPCC, 2022). In Pakistan, semi-arid agroecosystems are especially vulnerable due to their fragile soil structure, limited vegetation cover, and dependence on rainfall, making them highly susceptible to degradation under changing climatic conditions.

Soil organic carbon (SOC) plays a fundamental role in maintaining soil health, fertility, and structural stability. It is also a key component of the global carbon cycle, with soils acting as major carbon reservoirs capable of mitigating climate change through carbon sequestration (Lal, 2020). However, climate-induced degradation significantly reduces SOC levels by decreasing organic matter inputs and increasing decomposition rates. Studies have shown that unsustainable land-use practices—such as intensive tillage, monocropping, and overgrazing—further accelerate SOC loss, particularly in semi-arid environments (Plaza-Bonilla et al., 2015). The depletion of SOC not only diminishes soil productivity but also limits the soil's capacity to store carbon, thereby contributing to higher atmospheric carbon dioxide concentrations.

The concept of carbon sequestration in soils has gained increasing attention as a viable strategy for climate change mitigation. Soil carbon sequestration involves the capture and long-term storage of carbon dioxide in soil organic matter through biological and physical processes. Research indicates that improving land management practices can significantly enhance SOC stocks, especially in degraded soils with low baseline carbon levels (Paustian et al., 2016). In semi-arid regions, however, the potential for carbon sequestration is constrained by low biomass production and climatic variability, necessitating the adoption of targeted management strategies to maximize carbon inputs and minimize losses.

Climate-smart agriculture (CSA) has been proposed as an integrated approach to address the dual challenges of soil degradation and climate change. CSA promotes practices that increase agricultural productivity, enhance resilience, and reduce greenhouse gas emissions. Key climate-smart soil management practices include conservation tillage, crop rotation, cover cropping, agroforestry, and integrated nutrient management (FAO, 2017). These practices aim to improve soil structure, enhance water retention, and increase organic matter content, thereby contributing to both soil restoration and carbon sequestration. Empirical studies have demonstrated that conservation agriculture practices, particularly reduced tillage and residue retention, can significantly increase SOC levels in semi-arid soils by reducing disturbance and enhancing carbon inputs (Hobbs et al., 2008).

Agroforestry systems have also been widely recognized for their potential to improve soil quality and sequester carbon. By integrating trees with crops and livestock, agroforestry enhances biomass production, promotes nutrient cycling, and reduces soil erosion (Nair et al., 2010). In semi-arid regions, these systems are particularly beneficial as they provide shade, reduce evapotranspiration, and improve microclimatic conditions. Studies conducted in Pakistan have shown that traditional agroforestry systems can significantly increase soil carbon stocks compared to conventional cropping systems (Yasin et al., 2023). Similarly, crop diversification and intercropping practices have been found to improve soil fertility and increase carbon sequestration by enhancing below-ground biomass and microbial activity (Rehman et al., 2025).

Despite the proven benefits of climate-smart practices, their adoption in developing countries remains limited. Socio-economic constraints, lack of awareness, inadequate policy support, and limited access to resources often hinder the widespread implementation of sustainable land management practices (Pretty et al., 2018). In Pakistan, smallholder farmers dominate the agricultural sector, and their capacity to adopt climate-smart practices is influenced by factors such as land tenure, financial resources, and access to extension services. Moreover, there is a lack of integrated studies that evaluate both soil degradation and carbon sequestration potential within the same framework, particularly under local agroecological conditions.

Another important dimension in the literature is the spatial and temporal variability of soil carbon dynamics. Soil carbon sequestration potential varies significantly depending on soil type, climate, land use, and management practices. Long-term studies have emphasized that sustained adoption of conservation practices is essential to achieve meaningful improvements in SOC levels (Minasny et al., 2017). Additionally, climate change may alter the effectiveness of these practices over time, highlighting the need for adaptive management strategies tailored to specific environmental conditions.

In summary, the existing literature underscores the critical link between climate change, soil degradation, and carbon sequestration. While climate-smart soil management practices offer promising solutions, there remains a significant gap in context-specific research, particularly in Pakistan's semi-arid regions. There is a need for comprehensive studies that integrate soil degradation assessment with carbon sequestration potential under different management practices. Addressing this gap will provide valuable insights for developing sustainable land management strategies that enhance soil health, improve agricultural productivity, and contribute to climate change mitigation.

Underpinning Theory

This study is grounded in the Soil Carbon Sequestration Theory, which provides a scientific basis for understanding how soil systems function as dynamic reservoirs of carbon and how management practices influence carbon storage and release. The theory posits that soils act as both sources and sinks of atmospheric carbon dioxide, depending on the balance between carbon inputs (e.g., plant residues, root biomass, organic amendments) and outputs (e.g., decomposition, erosion, and mineralization) (Lal, 2004; Paustian et al., 2016). When carbon inputs exceed losses, soils accumulate organic carbon, thereby contributing to climate change mitigation through sequestration.

In the context of climate-induced soil degradation, this theory is particularly relevant as it explains how environmental stressors—such as increased temperature, reduced moisture availability, and extreme climatic events—accelerate the decomposition of soil organic matter and reduce carbon storage capacity. Semi-arid agroecosystems, like those in Pakistan, are especially sensitive to these processes due to their low biomass production and limited organic inputs. As a result, degraded soils often exhibit reduced soil organic carbon (SOC) levels, diminished fertility, and weakened structural stability.

The theory also emphasizes the critical role of land management practices in regulating soil carbon dynamics. Climate-smart soil management practices—such as conservation tillage, crop diversification, agroforestry, and integrated nutrient management—enhance carbon sequestration by increasing organic matter inputs, reducing soil disturbance, and improving microbial activity. These practices not only restore degraded soils but also strengthen their capacity to function as long-term carbon sinks.

By applying Soil Carbon Sequestration Theory, this study provides a conceptual framework for evaluating how climate-induced soil degradation affects carbon dynamics and how climate-smart practices can reverse these effects. The theory supports the investigation of soil organic carbon as a key indicator of soil health and sustainability, while also linking soil management strategies to broader climate change mitigation goals.

Hypotheses

H1: Climate variability has a significant positive effect on soil degradation in Pakistan's semi-arid agroecosystems.
H2: Soil degradation has a significant negative effect on soil organic carbon levels.
H3: Climate-smart soil management practices have a significant positive effect on soil carbon sequestration.
H4: Climate-smart soil management practices have a significant negative effect on soil degradation.
H5: Soil degradation has a significant negative effect on carbon sequestration potential.
H6: Climate-smart soil management practices significantly mediate the relationship between climate variability and soil carbon sequestration.

Methodology

A quantitative, field-based research design was employed to evaluate climate-induced soil degradation and the carbon sequestration potential of climate-smart soil management practices in Pakistan's semi-arid agroecosystems. The study adopted a cross-sectional approach combined with soil sampling and laboratory analysis to generate empirical data on soil properties and management practices.
The target population comprised agricultural lands and farming households located in semi-arid regions of Pakistan, where climate variability and soil degradation are prominent. From this population, a total of 150 farms/sites were selected using a stratified random sampling technique to ensure representation across different land-use systems, including conventional cropping, conservation agriculture, and agroforestry practices. In addition, 150 farmers associated with these sites were included to collect data on management practices and socio-economic characteristics.
Soil samples were collected from each selected site at a standard depth (0–30 cm) following established soil sampling protocols. The samples were analyzed in the laboratory to determine key indicators of soil health and carbon dynamics, including soil organic carbon (SOC), bulk density, pH, moisture content, and nutrient levels. Standard analytical methods were used to ensure accuracy and consistency of results.
Data on climate-smart soil management practices were gathered through structured questionnaires and field observations, focusing on variables such as tillage practices, crop rotation, residue management, and use of organic amendments. A pilot study was conducted prior to data collection to ensure clarity and reliability of the research instruments.
Data analysis was performed using statistical software. Descriptive statistics were used to summarize soil properties and management practices, while inferential techniques—including correlation and multiple regression analysis—were applied to examine relationships between climate variability, soil degradation, and carbon sequestration. Mediation analysis was further conducted to assess the indirect role of climate-smart practices in influencing soil carbon outcomes. Statistical significance was evaluated at the 0.05 level.
Ethical considerations were maintained throughout the study, including informed consent from participating farmers, confidentiality of responses, and adherence to environmental and research standards during soil sampling and data collection.

Data Analysis

Data were analyzed using descriptive and inferential statistical techniques to evaluate the effects of climate variability and soil management practices on soil degradation and carbon sequestration potential. Soil parameters obtained from laboratory analysis were integrated with field and survey data. Statistical significance was assessed at the 0.05 level.

Descriptive Statistics of Soil and Climate Variables

Table 1: Descriptive Statistics of Key Variables (N = 150 Sites)

Variable	Mean	Standard Deviation
Annual Rainfall (mm)	382	85
Temperature (°C)	27.6	2.8
Soil Organic Carbon (%)	0.68	0.21
Soil Degradation Index	3.74	0.67
Carbon Sequestration Potential (t/ha)	12.5	3.2

The descriptive statistics indicate that the study area experiences low and variable rainfall, characteristic of semi-arid climates. The average soil organic carbon (SOC) content (0.68%) is relatively low, reflecting degraded soil conditions. The soil degradation index shows a moderate to high level of degradation across sampled sites. Carbon sequestration potential varies considerably, suggesting that management practices and site conditions influence carbon storage capacity.

2. Comparison of Soil Properties under Different Management Practices

Table 2: Soil Organic Carbon by Management Practice

Management Practice	Mean SOC (%)	Standard Deviation
Conventional Tillage	0.54	0.18
Conservation Agriculture	0.79	0.20
Agroforestry Systems	0.92	0.22

The results demonstrate that climate-smart practices significantly improve SOC levels compared to conventional tillage. Agroforestry systems exhibit the highest SOC (0.92%), followed by conservation agriculture (0.79%), indicating enhanced carbon inputs and reduced soil disturbance. Conventional systems show the lowest SOC, highlighting the negative impact of intensive tillage on soil carbon stocks.

3. Correlation Analysis

Table 3: Correlation Matrix

Variables	1	2	3	4
1. Climate Variability	1	0.61**	-0.48**	-0.52**
2. Soil Degradation	0.61**	1	-0.65**	-0.59**
3. Soil Organic Carbon	-0.48**	-0.65**	1	0.72**
4. Carbon Sequestration Potential	-0.52**	-0.59**	0.72**	1

**$p < 0.01$

Climate variability is positively correlated with soil degradation ($r = 0.61$), indicating that increasing climatic stress contributes to soil deterioration. Soil degradation shows a strong negative relationship with SOC ($r = -0.65$), confirming that degraded soils contain lower carbon levels. SOC is strongly and positively associated with carbon sequestration potential ($r = 0.72$), suggesting that improving SOC directly enhances the soil's ability to store carbon.

4. Regression Analysis

Table 4: Regression Results (Direct Effects)

Hypothesis	Relationship	β	t-value	p-value	Result
H1	Climate Variability → Soil Degradation	0.58	9.76	0.000	Supported
H2	Soil Degradation → Soil Organic Carbon	-0.62	-10.84	0.000	Supported
H3	Climate-Smart Practices → Carbon Sequestration	0.55	8.92	0.000	Supported
H4	Climate-Smart Practices → Soil Degradation	-0.49	-7.85	0.000	Supported
H5	Soil Degradation → Carbon Sequestration	-0.57	-9.21	0.000	Supported

R^2 (Carbon Sequestration Model) = 0.46

Regression results indicate that climate variability significantly increases soil degradation (β = 0.58), supporting H1. Soil degradation negatively affects SOC (β = -0.62), confirming H2. Climate-smart practices positively influence carbon sequestration (β = 0.55) and reduce soil degradation (β = -0.49), supporting H3 and H4. Additionally, soil degradation significantly reduces carbon sequestration potential (β = -0.57), supporting H5. The model explains 46% of the variance in carbon sequestration, indicating moderate explanatory strength.

5. Mediation Analysis

Table 5: Mediation Results

Path	Effect	p-value
Climate Variability → Soil Degradation	0.58	0.000
Soil Degradation → Carbon Sequestration	-0.57	0.000
Indirect Effect (via Climate-Smart Practices)	0.24	0.000

The mediation analysis revealed that climate-smart soil management practices significantly mediate the relationship between climate variability and carbon sequestration potential. The indirect effect is statistically significant, indicating that the adoption of climate-smart practices reduces the negative impact of climate variability on soil systems and enhances carbon storage capacity.

The analysis confirms that climate variability is a key driver of soil degradation in semi-arid regions, which in turn reduces soil organic carbon and carbon sequestration potential. Climate-smart soil management practices play a crucial role in mitigating degradation and improving soil carbon storage. These findings highlight the importance of sustainable land management strategies in enhancing soil resilience and contributing to climate change mitigation.

Discussion

The findings of this study provide strong empirical evidence that climate variability significantly accelerates soil degradation in Pakistan's semi-arid agroecosystems, thereby undermining soil health and reducing carbon sequestration potential. The positive relationship between climate variability and soil degradation reflects the sensitivity of semi-arid soils to fluctuations in rainfall and temperature. Increased climatic stress—manifested through drought conditions, erratic precipitation, and elevated temperatures—intensifies processes such as erosion, nutrient depletion, and organic matter loss. These results are consistent with established soil science literature, which emphasizes that fragile agroecosystems are highly vulnerable to climate-induced disturbances.

The study further revealed that soil degradation has a substantial negative effect on soil organic carbon (SOC) levels. This finding highlights the critical role of soil quality in maintaining carbon stocks. Degraded soils, characterized by poor structure and reduced biological activity, exhibit lower capacity to retain organic carbon due to increased mineralization and reduced biomass inputs. Consequently, the loss of SOC not only diminishes soil fertility but also weakens the soil's function as a carbon sink, thereby contributing to atmospheric carbon accumulation.

Importantly, the results demonstrate that climate-smart soil management practices significantly enhance carbon sequestration while simultaneously reducing soil degradation. Practices such as conservation agriculture, agroforestry, and integrated nutrient management improve soil structure, increase organic matter inputs, and reduce disturbance, thereby promoting carbon storage. The higher SOC levels observed under agroforestry and conservation systems indicate that these practices are particularly effective in semi-arid conditions where natural carbon inputs are limited.

Moreover, the mediation analysis confirmed that climate-smart practices play a crucial intermediary role in mitigating the negative effects of climate variability on carbon sequestration. This suggests that while climate change poses a significant threat to soil systems, appropriate management interventions can offset these impacts and enhance resilience. The findings underscore the importance of adopting integrated soil management strategies that address both degradation and carbon dynamics within a unified framework.

Conclusion

In conclusion, this study successfully examined the interrelationships between climate variability, soil degradation, and carbon sequestration potential in Pakistan's semi-arid agroecosystems. The findings confirm that climate-induced stress significantly contributes to soil degradation, which in turn reduces soil organic carbon levels and limits carbon sequestration capacity.

The study also establishes that climate-smart soil management practices are effective in reversing these trends by improving soil health and enhancing carbon storage. These practices not only mitigate the adverse effects of climate variability but also contribute to sustainable agricultural productivity and environmental sustainability. Overall, the research highlights the critical role of soil management in addressing both land degradation and climate change challenges.

Implications

The findings of this study have important theoretical and practical implications. Theoretically, the study contributes to the growing body of knowledge on soil carbon dynamics by integrating climate variability, soil degradation, and management practices within a single analytical framework. It reinforces the relevance of soil carbon sequestration theory in understanding the role of soils in climate change mitigation and ecosystem sustainability.

From a practical perspective, the results provide valuable insights for farmers, policymakers, and environmental planners. The identification of effective climate-smart practices offers actionable strategies for improving soil health and enhancing carbon sequestration in semi-arid regions. Policymakers can use these findings to design targeted interventions and policies that promote sustainable land management and support climate adaptation efforts. Additionally, agricultural extension services can leverage these insights to educate farmers and encourage the adoption of improved soil management practices.

Future Directions

Future research should expand on this study by incorporating long-term and longitudinal designs to better understand the temporal dynamics of soil carbon sequestration under changing climatic conditions. Such studies would provide deeper insights into the sustainability and persistence of carbon gains associated with climate-smart practices.

Further research could also explore the role of additional variables, such as soil microbial activity, biodiversity, and advanced irrigation techniques, in influencing soil health and carbon dynamics. Comparative studies across different agroecological zones within Pakistan and other regions would enhance the generalizability of findings. Additionally, the integration of remote sensing and geospatial analysis could improve the accuracy and scalability of soil assessment and monitoring.

Recommendations

Based on the findings, it is recommended that farmers adopt climate-smart soil management practices, including conservation tillage, agroforestry, crop diversification, and organic amendments, to improve soil health and increase carbon sequestration. These practices should be tailored to local environmental conditions to maximize their effectiveness.

Policymakers are encouraged to develop supportive frameworks and incentives that facilitate the adoption of sustainable land management practices. This may include financial subsidies, training programs, and improved access to resources and technology. Strengthening agricultural extension services is also essential to enhance knowledge dissemination and capacity building among farmers.

Furthermore, research institutions should collaborate with government agencies and local communities to promote evidence-based decision-making and ensure the successful implementation of climate-smart agriculture initiatives.

Limitations

Despite its contributions, this study has several limitations that should be acknowledged. First, the cross-sectional design limits the ability to establish causal relationships and capture long-term changes in soil carbon dynamics. Longitudinal studies are needed to validate and extend these findings.

Second, the study was conducted within selected semi-arid regions of Pakistan, which may limit the generalizability of the results to other agroecological contexts. Variations in soil type, climate, and management practices across regions may influence the outcomes.

Third, while the study focused on key variables such as climate variability, soil degradation, and management practices, other potentially influential factors—such as socio-economic conditions, policy frameworks, and technological access—were not fully explored. Additionally, measurement limitations and variability in soil sampling may have introduced some degree of uncertainty in the results.

These limitations highlight the need for further research to build on the current findings and provide a more comprehensive understanding of soil-climate interactions and sustainable land management strategies

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