Review Article
DOI: https://doi.org/10.70749/ijbr.v3i10.2410

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://ijbr.com.pk
ISSN: 2960-2793/ 2960-2807

Crossref

OPEN ACCESS

Carbon Sequestration through Conservation Tillage Practices under Cereal-Legume Intercropping Systems: A Review

Hazib Ali[1], Sadaf Saeed Ullah[2], Muqadas Batool[3], Mehmood Ul Hassan[4], Khalil Ali[5,6], Shah Mulk[7], Tooba Zia[8], Rifat Naseem[9]

[1]College of Agriculture, Guizhou University, China.
[2]Department of Botany, Government College University Lahore, Katchery Road, Lahore, Punjab, Pakistan.
[3]College of Life Sciences, Guizhou University, China.
[4]Department of Agriculture, Hazara University, Mansehra, KP, Pakistan.
[5]Department of Biological Sciences, The Superior University, Lahore, Punjab, Pakistan.
[6]Senior Research Analyst Environment Biodiversity, The Urban Unit, Planning & Development Board Punjab, Lahore, Pakistan.
[7]Department of Biological Sciences, International Islamic University, Islamabad, Pakistan.
[8]Institute of Botany, University of the Punjab, Lahore, Punjab, Pakistan.
[9]Department of Plant Sciences, Faculty of Biological Sciences, Quaid-I-Azam University, Islamabad, Pakistan.

ARTICLE INFO

Keywords: Cereal-legume Inter Cropping, Soil Organic Matter, Carbon Sequestration, Conservation Tillage, Carbon storage, Soil Organic Carbon, Sustainable Agriculture.

Correspondence to: Khalil Ali,
Department of Biological Sciences, The Superior University, Lahore, Punjab, Pakistan.
Email: khalilali2101@gmail.com

Declaration
Authors' Contribution
All authors equally contributed to the study and approved the final manuscript

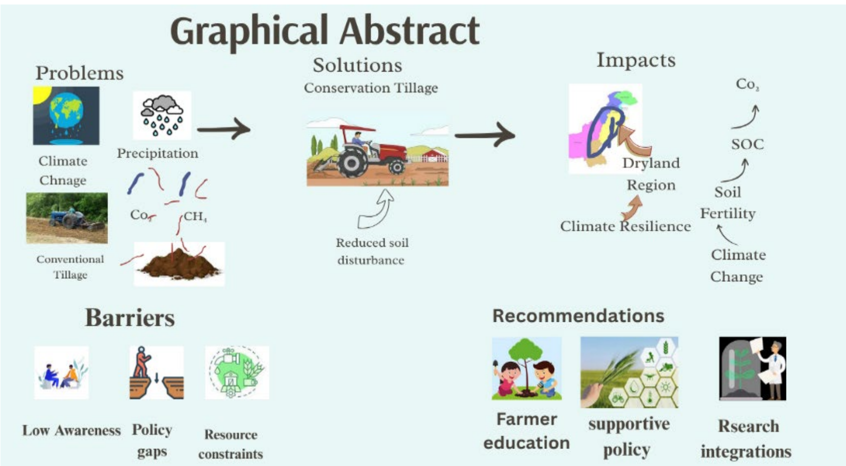
Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History
Received: 03-07-2025 Revised: 26-09-2025
Accepted: 03-10-2025 Published: 30-10-2025

ABSTRACT

Greenhouse gas emissions are widely considered a major threat to agriculture, yet carbon sequestration offers a potential solution to food shortages driven by climate change. This study evaluates the effects of conservation tillage and cereal–legume intercropping in Pakistan's subtropical dryland agricultural systems on improving soil organic carbon quality. Conservation tillage, or no-till farming, enhances soil organic carbon retention by minimizing disturbance and reducing topsoil loss. Pulse–cereal intercropping strengthens soil ecology through improved nitrogen fixation and increased biomass production. The synergistic interaction between intercropping and cereal residue management optimizes nutrient dynamics, thereby maximizing carbon storage and enhancing agricultural resilience. However, widespread adoption of these technologies in Pakistan remains limited due to policy constraints, insufficient information dissemination, and socio-economic barriers. The study recommends scaling up these climate-smart practices through farmer training, supportive policy interventions, and integrated research efforts. Intercropping and mixed cereal–legume systems represent significant strategies for improving food security in Pakistan and sustaining global soil organic carbon pools for climate change mitigation.



INTRODUCTION

Agriculture has a complex and significant influence on the global climate system. Although it contributes considerably to global CO_2 emissions, it also holds substantial potential for carbon sequestration (Adekiya et al. 2023). This dual role of agriculture necessitates urgent interventions to transition from conventional farming methods to environmentally sustainable practices. Nonintegrated agricultural activities such as intensive tillage, monoculture, and excessive agrochemical use have reduced soil organic matter. Consequently, carbon stored in soil organic matter is released back into the atmosphere, contributing to global climate change (Akmal et al. 2018). These practices diminish the soil's carbon storage capacity, lower the amount of greenhouse gases fixed in the atmosphere, and disrupt the natural carbon cycle (Hussain et al. 2021). Conservation tillage, reduced tillage, chemical fertilizer optimization, and intercropping systems have emerged as promising management practices to enhance carbon sequestration and mitigate greenhouse gas emissions (Pierre et al. 2022). Such approaches minimize soil disturbance, increase cropping system diversity, and promote nutrient cycling, which collectively improve soil health, increase soil carbon sequestration, and reduce the environmental footprint of agriculture (Junod et al. 2024). Soil organic matter (SOM) is the largest terrestrial carbon pool and plays a critical role in regulating greenhouse gas exchange between land and the atmosphere. Soil carbon sequestration functions by capturing atmospheric carbon dioxide and storing it in the soil, thereby contributing to climate regulation and soil integrity (Junod et al. 2024). Increasing soil organic carbon can therefore enhance soil fertility, water-holding capacity, and ecosystem service provision, ultimately contributing to sustainable agricultural productivity (Anyebe et al. 2025).

Conservation agriculture follows principles of sustainability and enhances soil organic carbon, improves soil properties, and reduces erosion and land degradation. It emphasizes minimal soil disturbance, permanent soil cover, and diversified crop rotations, all of which benefit soil health and crop performance (Jayaraman et al. 2021). Conservation tillage, a major component of conservation agriculture, reduces soil disturbance, retains crop residues, and improves soil structure, thereby enhancing carbon sequestration by increasing soil carbon stocks (Hussain et al. 2021). Intercropping, particularly cereal–legume systems, is another climate-smart approach that diversifies cropping systems, increases productivity, and reduces greenhouse gas emissions.

Pakistan's agricultural sector plays a vital role in ensuring national food security and providing livelihoods for millions of rural households (Usman et al. 2025). However, the country's subtropical dryland agricultural systems are highly vulnerable to climate change (Rehman et al. 2023). Land degradation remains a major concern, intensifying climate change impacts by increasing greenhouse gas emissions and reducing carbon sequestration capacity (Hailu and Teka 2024; Saeed Ullah et al. 2024a, b).

This review aims to synthesize current knowledge on carbon sequestration under conservation tillage in cereal–legume intercropping systems, with an emphasis on their relevance to Pakistan. The main objectives of this review are: to investigate the effects of conservation tillage on soil organic carbon accumulation and soil health indicators; to assess the effectiveness of cereal–legume intercropping systems in nitrogen fixation, nutrient uptake, and crop yield improvement; to evaluate the interaction between conservation tillage and cereal–legume intercropping in enhancing carbon sequestration, soil fertility, and crop productivity; to identify the challenges and opportunities associated with implementing these systems in Pakistan; and to propose strategies that support the adoption of sustainable agricultural practices in Pakistan and similar regions.

Climate Change Impacts on Food Security

Climate change remains one of the most powerful threats to global food and nutrition security, directly influencing crop yields, water availability, and the long-term sustainability of agricultural systems (Saleem et al. 2024). Extensive evidence shows that rising temperatures, shifts in precipitation patterns, and the increasing frequency of extreme weather events have already significantly reduced crop productivity in many regions, resulting in food shortages and market instability. Land degradation, intensified by climate change, further reduces carbon sequestration rates and thus creates a negative feedback loop that worsens food security outcomes (Rehman et al. 2024). Key factors such as the loss of fertile topsoil, reduced water-holding capacity, and limited nutrient availability lower agricultural production and increase vulnerability to climatic shocks (Brempong et al. 2023).

Sustainable agricultural practices, however, offer a pathway to enhance climate resilience and safeguard livelihoods, particularly for smallholder farmers who are most affected by climatic stressors (Das and Ansari 2021). Conservation tillage can improve soil health, increase water-use efficiency, and support diversified production systems that strengthen resilience to climatic variability when combined with intercropping and other climate-smart strategies (Jat et al. 2022). These practices contribute not only to improved food security but also to long-term landscape sustainability and the protection of ecosystem services.

Focus on Pakistan's Subtropical Drylands

High temperatures, irregular rainfall, and rising drought incidence threaten the dryland cropping systems of subtropical Pakistan (Ahmed et al. 2022). Existing challenges including soil erosion, water scarcity, and unsustainable farming practices further aggravate these vulnerabilities (Rehman et al. 2022). This places significant pressure on the agricultural sector to enhance climate resilience, increase productivity, and reduce greenhouse gas emissions through a shift toward climate-smart agriculture.

In Pakistan, conservation tillage and cereal–legume intercropping represent highly feasible and beneficial approaches (Kotorová et al. 2018). These practices form part of broader soil carbon storage strategies that enhance food security and contribute to global climate change mitigation. Conservation tillage and intercropping systems have demonstrated improvements in climate resilience, soil health, erosion control, and water management (Koushika et al. 2024). Adoption of conservation tillage can lead to increased crop yields, reduced production costs, and improved livelihoods for smallholder farmers, thereby strengthening rural well-being and contributing to sustainable agricultural development.

Conservation Tillage and Carbon Sequestration

Conservation tillage is widely promoted within sustainable agriculture frameworks (Hussain et al. 2021). It reduces soil disturbance, improves soil structure, decreases erosion, and facilitates carbon sequestration (Mandal et al. 2022). According to Mohammad et al. (2012), conventional tillage practices rely on high-intensity soil turning and removal or incorporation of crop residues, whereas conservation tillage systems such as no-till (NT), reduced tillage (RT), and variable depth tillage (VDT) maintain soil cover and minimize disruption of soil aggregates (Singh et al. 2023).

Reduced tillage and no-tillage approaches are beneficial for improving soil structure and enhancing carbon sequestration (Al-Shammary et al. 2024). Variable depth tillage functions as an important precision agriculture technique that integrates soil characteristics, crop requirements, and machinery efficiency, enabling significant fuel savings by optimizing tillage depth.

Conservation tillage methods increase the amount of soil organic carbon and improve soil fertility and water retention (Kumar and Babalad 2018). Enhanced infiltration increases water availability to crops (Hussain et al. 2021). Higher soil organic carbon improves soil aggregate formation, strengthens resistance to erosion, and increases carbon sequestration rates (Naorem et al. 2023).

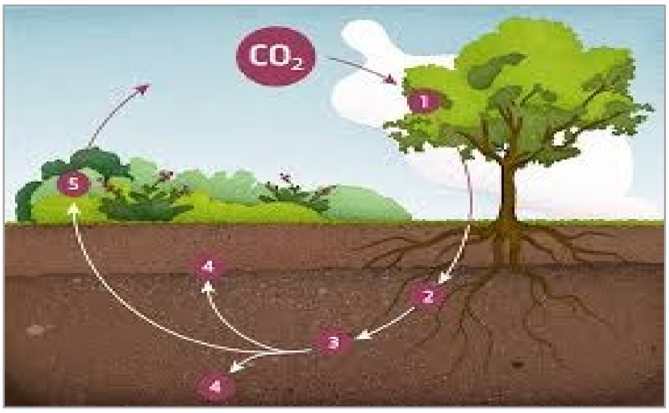
Cereal–legume intercropping the joint cultivation of cereals and legumes is a sustainable practice that enhances cropping intensity. Legumes fix atmospheric nitrogen, enriching soil nitrogen levels and reducing dependence on synthetic fertilizers, which are major contributors to greenhouse gas emissions (Akchaya et al. 2025b). Intercropping improves system productivity and optimizes resource use (Zhanbota et al. 2022). Compared with sole cropping systems, legume-based intercropping enhances biomass production, increases soil organic carbon through residue inputs, and accelerates nitrogen-rich organic matter decomposition (Zhang et al. 2024). Elevated soil carbon levels improve soil fertility, water retention, and overall carbon sequestration (Liu et al. 2024).

As illustrated in Figure 1, the carbon sequestration pathway under conservation tillage and intercropping includes:

1. Plants absorb atmospheric CO_2 through photosynthesis;
2. Carbon enters the soil via plant roots and root exudates;
3. Decomposed plant residues contribute to soil organic matter;
4. Organic carbon becomes physically protected from decomposition, particularly under reduced tillage; and
5. A stable carbon pool is formed, enabling long-term carbon storage within the soil ecosystem.

Figure 1

Carbon Sequestration through Conservation Tillage in a Cereal-Legume Intercropping System.



Combined Effects of Conservation Tillage and Cereal–Legume Intercropping

Conservation tillage and legume-based strip intercropping, although still under extensive research, interact synergistically to enhance soil carbon sequestration (Rehman et al. 2025). Reduced tillage limits soil disturbance, while intercropping increases biomass production and biological nitrogen fixation, contributing jointly to improved soil quality (Akchaya et al. 2025a). This combination promotes greater soil organic carbon storage and reduces greenhouse gas emissions (Hussain et al. 2021). In semi-arid environments, strip intercropping of legumes under conservation tillage has been identified as one of the most effective methods for increasing soil organic carbon sequestration and strengthening soil health (Rehman et al. 2025). Integrating these practices supports improved crop rotations and enhances overall system functioning, contributing to healthier soils and increased carbon storage capacity (Xing and Wang 2024).

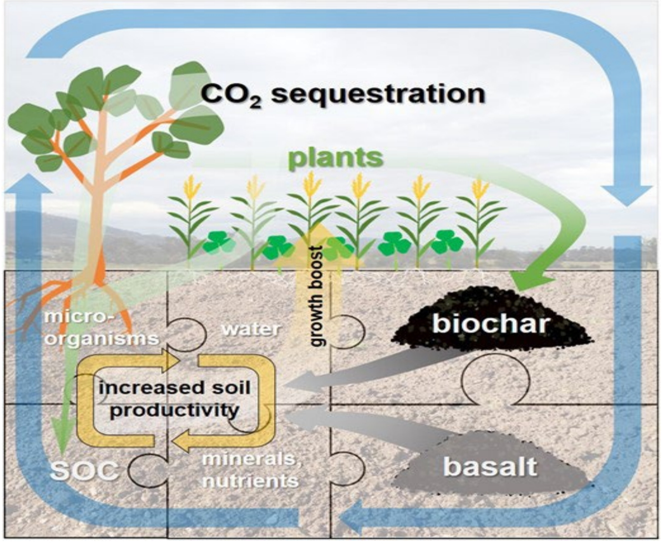
Concept of Carbon Sequestration in Soils

Soil carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2) in the soil, thereby reducing greenhouse gas concentrations and mitigating climate change (Komal et al. 2024). Agricultural practices play an essential role in influencing soil carbon dynamics, and the adoption of sustainable management strategies can substantially increase soil carbon storage.

Soil carbon occurs in both organic and inorganic forms. Soil Organic Carbon (SOC) comprises carbon compounds originating from living organisms, including plant residues, animal remains, and microbial biomass. SOC is fundamental to soil health because it regulates soil structure, water-holding capacity, and nutrient availability (Sombrero and De Benito 2010). Conservation tillage enhances SOC by minimizing soil disturbance and encouraging organic matter accumulation. In contrast, Soil Inorganic Carbon (SIC) consists primarily of carbonates and bicarbonates, typically found in arid and semi-arid regions (Virto et al. 2022). While SOC plays a more direct role in agricultural productivity, SIC also contributes to long-term carbon storage. Conservation tillage primarily aims to increase SOC due to its immediate benefits for soil fertility and crop performance (Niu et al. 2024).

Figure 2 illustrates the soil carbon sequestration potential of vegetation, biochar, basalt, and microorganisms. Plants capture CO_2 from the atmosphere and increase SOC through biomass inputs. Biochar stabilizes carbon and improves soil physical properties. Basalt weathering promotes inorganic carbon formation and mineral enrichment. Microorganisms facilitate the transformation and stabilization of organic matter. Collectively, these processes enhance soil productivity and contribute to climate change mitigation.

Figure 2
A model for soil carbon sequestration through sustainable practices

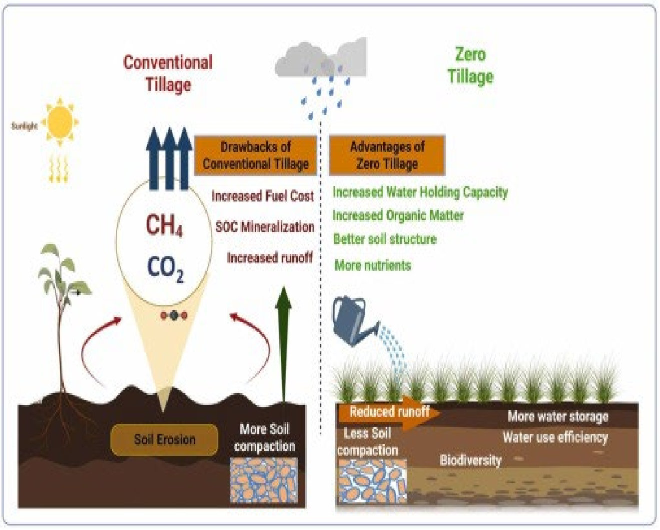


Sequestration Potential in Arid and Semi-Arid Regions
Arid and semi-arid regions such as Pakistan present both challenges and opportunities for soil carbon sequestration (Rehman et al. 2025). Soil organic carbon storage in these regions is generally restricted by low rainfall, high temperatures, and inherently poor soil fertility (Farooqi et al. 2020). However, conservation tillage practices integrated within cropping systems can enhance the potential for carbon sequestration even under such limiting conditions (Hussain et al. 2021). Minimum tillage has been shown to effectively reduce carbon dioxide emissions and influence soil organic carbon fractions in subtropical dryland ecosystems of Pakistan (Hassan et al. 2015).
Cereal–legume intercropping also contributes to soil organic carbon sequestration by improving soil nitrogen availability, thereby increasing biomass input and organic matter accumulation (Raseduzzaman et al. 2024). In regions where water availability is scarce, the selection of appropriate tillage and cropping practices becomes essential for maximizing carbon uptake and improving soil function (Ghimire et al. 2022).

Conservation Tillage
Conservation tillage encompasses a range of soil management practices designed to minimize soil disturbance, conserve soil and water resources, and enhance soil carbon sequestration (Khan and Wang 2023). Unlike conventional tillage—which involves extensive ploughing, soil inversion, and residue removal—conservation tillage maintains crop residues on the soil surface, thereby reducing erosion, improving soil structure, and supporting long-term soil quality.

No-Till
No-till, or zero tillage, eliminates soil disturbance entirely. In no-till systems, seeds are directly placed into undisturbed soil while crop residues remain on the surface as mulch, as illustrated in Figure 3 (Wasaya et al. 2019). No-till farming improves soil water retention, increases organic matter, enhances biodiversity, and reduces runoff and erosion (Wasaya et al. 2019). A comparative pictorial representation of conventional and zero tillage highlights the major differences in soil management, environmental impacts, and agronomic benefits. Long-term studies indicate that no-till systems can lead to substantial carbon accumulation in the upper soil layers (Mohammad et al. 2012).

Figure 3
Comparative Overview of Conventional Tillage vs. Zero Tillage



Minimum Tillage
Reduced tillage (RT), commonly referred to as minimum tillage (MT), involves lower intensity and frequency of soil disturbance compared to conventional tillage (CT), as illustrated in Figure 4 (Rehman et al. 2025). Shallow tillage (ST) and/or direct seeding (DS) may be conducted under crop residue cover on the soil surface (Sarker et al. 2022). The primary objective of minimum tillage is to balance conservation and productivity: while some soil disturbance is allowed to prepare a seedbed, the detrimental effects of intensive tillage on soil properties are minimized (Sarker et al. 2022). When combined with straw mulching, minimum tillage can significantly enhance soil carbon accumulation (Qin et al. 2024).

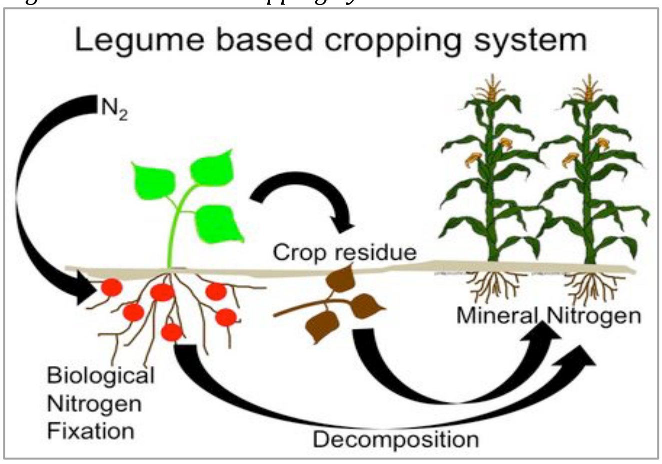
Mulch Tillage
Mulch tillage is a conservation practice that maintains crop residues or other organic materials on the soil surface (Busari et al. 2015). Mulches reduce soil erosion, conserve moisture, suppress weed growth, and moderate soil temperature fluctuations (El-Beltagi et al. 2022). They also enhance soil organic matter and microbial activity, contributing to soil organic carbon sequestration (Yuexuan et al. 2025). Additionally, organic mulches help structure soil bacterial communities, improving overall soil health (Wang et al. 2020). Figure 4 presents an experimental scheme demonstrating various organic mulch treatments in agronomic and horticultural trials (Labarga et al. 2024).

Cereal–Legume Intercropping: Enhancing Soil Health and Carbon Storage

Definition and Advantages of Intercropping
Intercropping involves the simultaneous cultivation of two or more crops of different types in the same field (Maitra et al. 2019). This ancient practice provides multiple ecological and agronomic benefits, including higher total yields, improved land use efficiency, and enhanced biodiversity. Intercropping supports diversified cropping systems and mitigates the biodiversity losses commonly associated with monocultures (Singh et al. 2023). The cereal–legume mixture is a common form of intercropping (Demie et al. 2022). Intercropping improves yield productivity and optimizes resource use, such as sunlight, water, and nutrients, as different crops utilize resources differently (Gebru 2015; Seran and Brintha 2010). For example, taller crops may provide shade to shorter crops, reducing water stress, while deep-rooted crops access nutrients from lower soil layers and make them available to shallow-rooted crops (Rehman et al. 2025).

Role of Legumes in Nitrogen Fixation
Legumes play a key role in intercropping systems by fixing atmospheric nitrogen, enriching the soil, and benefiting intercropped cereals (Figure 4) (Duchene et al. 2017). Through a symbiotic relationship with rhizobia bacteria, legumes convert atmospheric nitrogen into plant-usable forms, reducing the need for synthetic nitrogen fertilizers (Abd-Alla et al. 2023). This natural nitrogen input lowers fertilizer costs and reduces the carbon footprint associated with fertilizer production and application (Soumare et al. 2020). Enhanced nitrogen availability promotes vigorous plant growth, increasing both above- and belowground biomass. As plant residues decompose, they contribute to soil organic carbon accumulation (Li et al. 2017). The presence of legumes in intercropping systems also improves soil structure, increases infiltration capacity, and further enhances carbon sequestration (Belel et al. 2014; Maitra et al. 2023).

Figure 4
Legume Based Inter Cropping System



Impact on Biomass Production and Soil Carbon
Cereal–legume intercropping systems outperform monocultures in terms of biomass productivity (Bedoussac et al. 2018). This increased productivity is attributed to synergistic interactions between the crops, including improved nutrient cycling, reduced pest and disease pressure, and more efficient resource utilization. Higher biomass production contributes more crop residues to the soil (Soussana et al. 2010), providing a direct source of organic matter that enhances soil organic carbon (SOC) and improves soil structure. The diversification inherent in cereal–legume intercropping significantly influences soil carbon dynamics (Kumar et al. 2020). Moreover, increased crop diversity fosters a more diverse soil microbial community, enhancing organic matter decomposition and nutrient recycling. Legumes, through biological nitrogen fixation, further enrich the soil, promote plant growth, and facilitate carbon sequestration (Kumar et al. 2020).

Synergistic Effects of Conservation Tillage and Intercropping
Enhanced Soil Carbon Sequestration
Soil carbon levels are generally higher in intercropped systems under conservation tillage (CT) compared to conventional tillage (Maia et al. 2019). Reduced soil disturbance preserves existing SOC and slows decomposition, while intercropping and nitrogen fixation contribute additional organic matter to the soil (Blesh 2019). This increased SOC deposition improves soil quality and contributes to climate change mitigation (Deb et al. 2015).
Intercropping combined with conservation tillage revives degraded soils by promoting carbon accumulation. Reduced soil disturbance allows organic matter to accumulate on the soil surface, while crop residues and root biomass from intercropping systems provide a continuous supply of organic material, gradually increasing SOC and improving soil structure, water retention, and nutrient availability (Utomo et al. 2013).

Improved Soil Health and Nutrient Cycling
Conservation tillage enhances soil structure, minimizes erosion, and increases water infiltration, which benefits plant growth and SOC storage (Hussain et al. 2021). Legumes in intercropping systems improve nutrient cycling, enhance microbial activity, and contribute to healthier soils, promoting carbon sequestration (Kumar et al. 2020). Intercropping increases resource use efficiency and crop yields while reducing the need for synthetic inputs (Maitra et al. 2021).
By combining intercropping with conservation tillage, soils with low fertility can be revitalized. Nitrogen-fixing legumes provide a natural nitrogen source, while conservation tillage improves nutrient uptake through enhanced soil structure and infiltration, resulting in higher yields and more effective carbon capture (Villat and Nicholas 2024).

Increased Crop Productivity and Resilience
Conservation tillage and intercropping strengthen soil health and optimize crop performance under stress conditions such as drought or nutrient deficiency. These practices stabilize crop yields over the long term and reduce the vulnerability of agricultural systems to climate variability and extreme weather events (Elias et al. 2019). Synergistic effects of improved soil health, nutrient cycling, and pest and disease reduction enhance productivity. Legumes provide natural nitrogen, reducing reliance on synthetic fertilizers and improving crop

quality. By adopting these climate-smart practices, agricultural systems can achieve greater resilience to climate change, ensuring food security and improving smallholder livelihoods.

Carbon Sequestration Potential in Arid and Semi-Arid Regions

Challenges in Water-Limited Environments

Arid and semi-arid regions face unique constraints for soil carbon sequestration due to low rainfall, high temperatures, and degraded soils (Lal 2009). These conditions limit SOC accumulation, hinder soil restoration, and reduce soil carbon storage potential. Cycles of drought and intense rainfall, along with temperature extremes, further constrain crop growth and soil health (Wang and Gao 2019).

Water scarcity limits plant growth and biomass production, reducing organic matter inputs into the soil. High temperatures accelerate organic matter decomposition, further decreasing SOC. Degraded, structurally weak, and saline soils are less capable of supporting vegetation and SOC turnover. These challenges highlight the need for innovative, site-specific strategies to improve SOC sequestration in water-limited environments (Thapa et al. 2023; Saeed Ullah et al. 2025b).

Conservation Strategies for Drylands

By integrating conservation tillage with suitable cropping systems, some of the possible difficulties anticipated in improving the capacity of carbon sequestration can be mitigated in the arid to semi-arid regions (Thapa et al. 2023). Integration of cereals and legumes in farming systems contribute in increasing soil nitrogen supply for the growth of plants and in carbon input. Hence, the carbon sequestration of these water scarce regions can be maintained through appropriate tillage and cropping (Ghimire et al. 2022). No-till and reduced tillage (conservation tillage) can help maintain soil moisture, reduce soil erosion, and accumulate soil structure. Examples of intercrops are planting drought-resistant legumes, which may boost soil nitrogen levels, crop productivity, and carbon addition (Somasundaram et al. 2020). The decision on the optimal land preparation techniques and cropping systems will be determined by local agro-ecological conditions, farmers and agricultural market alternatives. They can enhance soil health, soil sustenance and carbon capture in dryland agriculture.

Case Studies on Conservation Tillage in Pakistan

Trials conducted in the subtropical dry regions of Pakistan indicate that conservation tillage can indirectly reduce atmospheric carbon dioxide by altering soil organic carbon fractions and improving soil health (Zahid et al. 2020). Similarly, studies in Punjab have demonstrated that legumes grown under conservation tillage techniques enhance soil organic carbon fixation, thereby improving soil fertility and crop yields (Zahid et al. 2020). In Sindh, a semi-arid region, minimum tillage practices have been shown to increase biomass carbon, enhance soil health, and support sustainable agriculture, contributing to effective carbon sequestration (Zhang et al. 2021).

These findings highlight the potential for conservation tillage and intercropping to improve soil productivity and carbon sequestration in arid regions of Pakistan. Wider adoption of these climate-smart agricultural practices could mitigate climate change impacts, enhance food security, and benefit smallholder farmers. However, increased engagement through research and extension services is necessary to scale up these practices in dryland areas (Al-Shammary et al. 2024).

Examples of Common Cereal-Legume Intercropping in Pakistan

Wheat–Chickpea

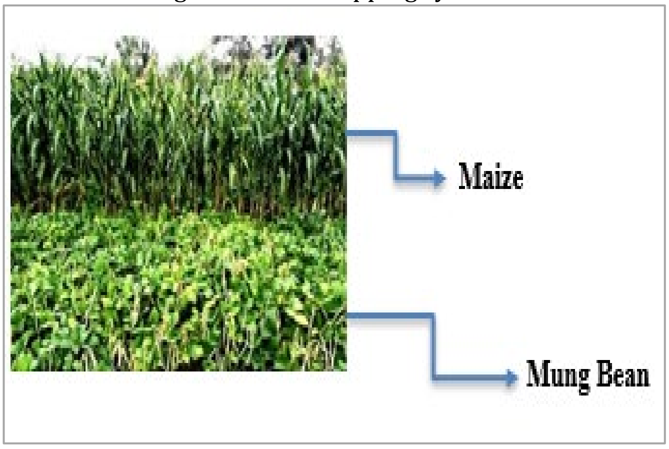
Wheat–chickpea intercropping is widespread in Pakistan's rain-fed regions, providing benefits in soil health, crop yield, and carbon sequestration (Pramanick et al. 2024; Saeed Ullah et al. 2025a). Chickpea, a leguminous cover crop, fixes atmospheric nitrogen, enriching the soil for subsequent wheat crops (Kumar et al. 2020). The complementary root systems improve soil structure, enhance water retention, and increase nutrient uptake. Nitrogen released from decomposing chickpea residues reduces the need for synthetic fertilizers, thereby lowering environmental impacts.

Maize–Mung Bean

Maize–mung bean intercropping is common in Pakistan's irrigated areas (Figure 5), contributing additional nitrogen to the soil and enhancing overall productivity (Ali et al. 2016). Short-duration mung bean is sown between maize rows, efficiently utilizing available resources, suppressing weeds, and improving soil health (Ullah et al. 2022). The mung bean matures before maize harvest, providing an additional source of income for farmers. Upon decomposition, mung bean residues release nitrogen into the soil, benefiting the subsequent maize crop as a natural nutrient source.

Figure 5

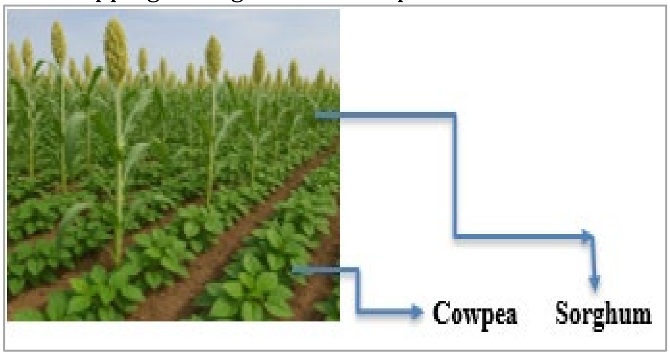
Maize and Mung bean inter cropping system



Sorghum–Cowpea Intercropping

Intercropping sorghum with cowpea is widely practiced in the arid and semi-arid regions of Pakistan (Figure 6), contributing to enhanced carbon sequestration and promoting sustainable agriculture in marginal environments. Cowpea, a drought-tolerant legume, not only improves soil fertility through biological nitrogen fixation but also provides valuable fodder for livestock. This intercropping system is particularly well-suited to areas with limited water availability and degraded soils (Layek et al. 2018). Nitrogen fixed by cowpea is gradually released into the soil as plant residues decompose, supplying a natural nitrogen source for subsequent sorghum crops. By combining increased biomass production with soil fertility improvement, sorghum–cowpea intercropping supports both carbon storage and sustainable crop-livestock production in resource-constrained environments.

Figure 6
Intercropping of sorghum and cowpea



Challenges in Adoption and Farmer Perceptions

Thus, there are some social and economic limitations regarding the adoption of this practice, not to mention the perception of farmers in and around areas where, it would thus take intervention in such things as smallholder farmer accessibility to equipment, as well as improved knowledge through extension service provision to overcome these issues. Further, understanding and addressing these barriers will lead to appropriate mass adoption and maximization of benefits from the practices (Jellason et al. 2021).

Constraints and Challenges in Pakistan

Socioeconomic Barriers

Most smallholder farmers in the country do face significant socioeconomic barriers, such as limited access to conservation tillage equipment and little or no tangible financial resources, making it difficult to adopt sustainable agricultural practices. New machines require such a fist investment, but they cannot access credit facilities. Unlike mostly extensive investments for specific machinery, the cost can be a barrier, thus making it difficult for smallholder farmers to adopt the technology (Stevenson et al. 2014). Thus, by removing barriers to access to equipment for smallholder farmers, financial support, and the promotion of affordable and accessible technology. Resources are important to making such efforts a reality credit facilities and the development of affordable loans. Connecting access to such credit facilities and affordable loans by the smallholder farmers in the developing world would lessen their current situation. Government and development agencies around the globe should also help farm-level financing schemes so as to develop low-cost and readily available conservation tillage technologies and farm machinery rental services (Wafula et al. 2016).

Knowledge Gaps and Extension Services

However, there is a lack of knowledge among farmers about the benefits of using conservation tillage and intercropping techniques. This has acted as a barrier to the widespread adoption of these practices. This has been driven by inadequate extension services and no training programs, thus limiting the sharing of information and best agricultural practices. Thus, improving knowledge through extension services, farmer training programs, and participatory research becomes a pillar for the adoption of sustainable agricultural practices (Somasundaram et al. 2020) . Most farmers do not know of the benefits of adopting conservation tillage and intercropping: soil health, reduced erosion and higher crop productivity. They likely do not have the foreign information or experience that would enable these practices to work for them. This information gap can be bridged through government and development agencies investment in extension to farmers via training and participatory research. These projects are expected to build farmers' skills and working knowledge regarding the advantages of conservation tillage and intercropping (Ketema and Bauer 2012).

Policy and Institutional Constraints

Conservation tillage and intercropping are very dependent on constraining policies and institutions if they are to be taken to scale. The uncertainties in policy related to the agricultural practices and lack of explicit support for these novel technologies have hindered the farmers to accept them. The majority of farmers are not given any kind of direct incentive to use sustainable technology (sunken cost, subsidies, tax exemption. Lack of policy formulation and government communication and coordination can lead to conflicting policies and sometimes even poor implementation. Therefore, the government needs to formulate a clear policy framework and regulations to support conservation tillage and intercropping, and encourage farmers to practice conservation tillage and intercropping through incentives and better coordination among government agencies (Giller et al. 2009).

Tools and Techniques for Measuring Carbon Sequestration

Soil Sampling and Soil Organic Carbon Measurement Protocols

Accurate soil sampling and standardized protocols for measuring soil organic carbon (SOC) are essential for assessing carbon sequestration and monitoring the effectiveness of agricultural management practices. Standardized analytical methods, such as the dry combustion technique, ensure that SOC data are reliable, comparable, and reproducible across studies (Lal 2001). Representative soil samples should be collected from locations that reflect variability in soil type, topography, and management practices, and at multiple depths to account for vertical distribution of organic carbon. Good quality control during sampling and analysis minimizes errors and strengthens the reliability of results (Ma et al. 2023).

Remote Sensing and GIS Technologies

Remote sensing and Geographic Information Systems (GIS) provide cost-effective, spatially explicit tools for mapping carbon sequestration over large areas (Issa et al. 2020). Satellite imagery and aerial photographs allow monitoring of vegetation cover, land use changes, and soil properties, thereby enabling assessment of carbon dynamics and identification of sites suitable for carbon storage. GIS-based analyses help characterize spatial patterns of soil organic carbon and vegetation biomass, supporting evaluation of the efficacy of different agricultural interventions (Aroca-Fernandez et al. 2025). These technologies also facilitate tracking changes over time, informing targeted management strategies to enhance carbon sequestration.

Modelling Tools and Isotopic Techniques

Simulation models, such as the Denitrification-Decomposition model, Rothamsted Carbon Model, and CENTURY, allow prediction of long-term effects of various management practices on soil carbon dynamics (Farooqi et al. 2023). Isotopic techniques, including carbon tracing, provide detailed insights into carbon cycling processes, tracking the movement and fate of organic carbon within soil ecosystems (Ali et al. 2023). Due to variations in climate, soils, and agricultural practices across Pakistan, region-specific measurement protocols, equipped with appropriate tools and expertise, are essential for accurate carbon monitoring (Shaukat et al. 2023).

Implications for Climate Change Mitigation and Food Security

Conservation tillage and intercropping practices enhance the carbon sequestration potential of soils, contributing to climate change mitigation and sustainable land management (Adil et al. 2023). Improved soil health under these practices enhances water infiltration, nutrient cycling, and soil structural stability, which collectively support stable crop yields and food security (Komal et al. 2024). By conserving soil moisture and improving nutrient availability, these approaches also increase resilience to droughts and extreme weather events, while reducing reliance on synthetic fertilizers, lowering input costs, and improving farmer incomes (Raveloaritiana and Wanger 2024). Over time, these practices promote biodiversity, ecosystem services, and long-term sustainability of agro-ecosystems (Koushika et al. 2024; Zubair et al. 2025).

Future Research Directions and Policy Recommendations

Long-Term Field Trials and Agro-Ecological Zones

Long-term comparative field trials are crucial to evaluate the integrated effects of conservation tillage and intercropping across diverse agro-ecological zones. Trials should include multiple tillage practices (no-till, reduced tillage, and conventional tillage) combined with intercropping systems such as wheat–chickpea, maize–mung bean, and sorghum–cowpea. Monitoring SOC, soil health indicators, and crop yields in these trials will provide robust data for evidence-based recommendations tailored to local farming systems (Sharif et al. 2018). Such data are essential for accurate carbon accounting and policymaking (Adil et al. 2023).

Standardized Measurement Protocols and Modelling Tools

Developing standardized, site-specific protocols for measuring SOC, soil health, and crop yields is vital for producing reliable, comparable data. Modeling tools should be applied to simulate the effects of alternative agricultural systems under local climatic and soil conditions. Additionally, building local capacity by providing access to equipment and trained personnel will enable accurate carbon monitoring and facilitate meaningful policy development (Batjes et al. 2024). Addressing social barriers and improving farmer awareness are also key to promoting adoption of conservation tillage and intercropping for sustainable practice (Nasser et al. 2024).

Policy Frameworks and Farmer Engagement

Effective adoption of conservation tillage and intercropping requires supportive policies and incentive structures that promote sustainable land management practices. Engaging farmers in research and extension activities has been shown to facilitate the adaptation of these practices to local farming systems and ecological conditions. Collaborative approaches involving academics, policymakers, and farmers can help scale up climate-smart practices, enhance sustainable agricultural development, and strengthen rural livelihoods (van Asseldonk et al. 2023).

Policy measures should include subsidies, tax incentives, and accessible financing for farmers adopting conservation tillage and intercropping. In addition, participatory research and extension programs should directly involve farmers in the co-implementation of sustainable and environmentally friendly production technologies. Effective collaboration between scientists, policymakers, and farmers is essential to ensure widespread adoption, optimize resource use, and secure the long-term sustainability of these practices (Batjes et al. 2024).

CONCLUSION

Potential mitigation responses to climate change and its adverse effects on sustainable agriculture that can enhance soil carbon sequestration include cereal–legume intercropping and conservation tillage. Improved conservation tillage through the combined application of no-till and minimum-tillage can reduce soil disturbance, increase water retention, enhance soil organic carbon sequestration, and, under suitable conditions, allow legumes to improve nitrogen use efficiency, crop biomass, and microbial activity. These practices strengthen carbon sequestration, soil health, and crop resilience in dryland agrifood systems. However, their implementation is hindered by multiple constraints, including limited technological capacity, inadequate machinery, institutional barriers, and insufficient governmental funding. Interventions to address these challenges should include farmer training, financial incentives, and the adoption of a sustainable land management framework. Applying these methods across Pakistan's diverse agro-ecological zones will require long-term experimental trials and region-specific research. Scientists, policymakers, and farmers must collaborate to ensure effective application of these principles and ultimately achieve improvements in food security under changing climatic conditions.

REFFERNCES

Abd-Alla, M. H., Al-Amri, S. M., & El-Enany, A. E. (2023). Enhancing rhizobium–legume symbiosis and reducing nitrogen fertilizer use are potential options for mitigating climate change. *Agriculture*, *13*(11), 2092. https://doi.org/10.3390/agriculture13112092

Adekiya, A. O., Alori, E. T., Ogunbode, T. O., Sangoyomi, T., & Oriade, O. A. (2023). Enhancing organic carbon content in tropical soils: Strategies for sustainable agriculture and climate change mitigation. *The Open Agriculture Journal*, *17*(1). https://doi.org/10.2174/0118743315282476231124074206

Adil, M., Zhang, C., Yao, Z., Lu, S., Qin, Z., Wang, J., Mahmood, A., Riaz, M. W., & Lu, H. (2023). Interactive effects of intercropping and mulching under conservation tillage as sustainable agriculture increased cotton productivity. *Frontiers in Ecology and Evolution*, *10*. https://doi.org/10.3389/fevo.2022.1092636

Ahmed, M., Hayat, R., Ahmad, M., Ul-Hassan, M., Kheir, A. M., Ul-Hassan, F., Ur-Rehman, M. H., Shaheen, F. A., Raza, M. A., & Ahmad, S. (2022). Impact of climate change on Dryland agricultural systems: A review of current status, potentials, and further work need. *International Journal of Plant Production*, *16*(3), 341-363. https://doi.org/10.1007/s42106-022-00197-1

Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M. R., Rajpoot, S. K., & Choudhary, A. K. (2025). Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: A review. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1527256

Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M. R., Rajpoot, S. K., & Choudhary, A. K. (2025). Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: A review. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1527256

Akmal, M., Shah, A., & Ali, J. (2018). Growth, radiation use efficiency and grain yield of wheat as influenced by nitrogen, tillage, and crop residue management. *Journal of Plant Nutrition*, *41*(16), 2032-2047. https://doi.org/10.1080/01904167.2018.1485161

Al-Shammary, A. A., Al-Shihmani, L. S., Fernández-Gálvez, J., & Caballero-Calvo, A. (2024). Optimizing sustainable agriculture: A comprehensive review of agronomic practices and their impacts on soil attributes. *Journal of Environmental Management*, *364*, 121487. https://doi.org/10.1016/j.jenvman.2024.121487

Ali, N. S., Atee, A. S., & Masood, T. K. (2016). Effect of nitrogen application and amount of water on yield of intercropped Maize-Mung bean and water productivity. *Journal of Agricultural Research and Innovative Technologies*, *1*(1), 1-16.

Ali, S., Zahid, A., Fatima, A., Aziz, M., Maqsood, H., Shezhad, A., Younas, S., & Bushra. (2023). Conservation agriculture a sustainable approach for disaster risk reduction in rice wheat cropping system of Pakistan. *Disaster Resilience and Green Growth*, 311-333. https://doi.org/10.1007/978-981-99-1763-1_15

Anyebe, O., Sadiq, F. K., Manono, B. O., & Matsika, T. A. (2025). Biochar characteristics and application: Effects on soil ecosystem services and nutrient dynamics for enhanced crop yields. *Nitrogen*, *6*(2), 31. https://doi.org/10.3390/nitrogen6020031

Aroca-Fernandez, J. M., Diez-Pastor, J. F., Latorre-Carmona, P., Elvira, V., Camps-Valls, G., Pascual, R., & Garcia-Osorio, C. (2025). A Collaborative Platform for Soil Organic Carbon Inference Based on Spatiotemporal Remote Sensing Data. *arXiv preprint arXiv:2504.13962*. https://doi.org/10.48550/arXiv.2504.13962

Batjes, N. H., Ceschia, E., Heuvelink, G. B., Demenois, J., Le Maire, G., Cardinael, R., Arias-Navarro, C., & Van Egmond, F. (2024). Towards a modular, multi-ecosystem monitoring, reporting and verification (MRV) framework for soil organic carbon stock change assessment. *Carbon Management*, *15*(1). https://doi.org/10.1080/17583004.2024.2410812

Bedoussac, L., Journet, E., Hauggaard-Nielsen, H., Naudin, C., G. Corre Hellou, G., Jensen, E. S., & Justes, E. (2018). Grain legume–cereal intercropping systems. *Burleigh Dodds Series in Agricultural Science*, 243-256. https://doi.org/10.19103/as.2017.0023.14

Belel, M. D., Halim, R. A., Rafii, M. Y., & Saud, H. M. (2014). Intercropping of corn with some selected legumes for improved forage production: A review. *Journal of Agricultural Science*, *6*(3). https://doi.org/10.5539/jas.v6n3p48

Blesh, J. (2019). Feedbacks between nitrogen fixation and soil organic matter increase ecosystem functions in diversified agroecosystems. *Ecological Applications*, *29*(8). https://doi.org/10.1002/eap.1986

Brempong, M. B., Amankwaa-Yeboah, P., Yeboah, S., Owusu Danquah, E., Agyeman, K., Keteku, A. K., Addo-Danso, A., & Adomako, J. (2023). Soil and water conservation measures to adapt cropping systems to climate change facilitated water stresses in Africa. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.1091665

Busari, M. A., Kukal, S. S., Kaur, A., Bhatt, R., & Dulazi, A. A. (2015). Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*, *3*(2), 119-129. https://doi.org/10.1016/j.iswcr.2015.05.002

Das, U., & Ansari, M. (2021). The nexus of climate change, sustainable agriculture and farm livelihood: Contextualizing climate smart agriculture. *Climate Research*, *84*, 23-40. https://doi.org/10.3354/cr01648

Deb, S., Bhadoria, P. B., Mandal, B., Rakshit, A., & Singh, H. B. (2015). Soil organic carbon: Towards better soil health, productivity and climate change mitigation. *Climate Change and Environmental Sustainability*, *3*(1), 26. https://doi.org/10.5958/2320-642x.2015.00003.4

Demie, D. T., Döring, T. F., Finckh, M. R., van der Werf, W., Enjalbert, J., & Seidel, S. J. (2022). Mixture × genotype effects in cereal/Legume intercropping. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.846720

Duchene, O., Vian, J., & Celette, F. (2017). Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. *Agriculture, Ecosystems & Environment*, *240*, 148-161. https://doi.org/10.1016/j.agee.2017.02.019

El-Beltagi, H. S., Basit, A., Mohamed, H. I., Ali, I., Ullah, S., Kamel, E. A., Shalaby, T. A., Ramadan, K. M., Alkhateeb, A. A., & Ghazzawy, H. S. (2022). Mulching as a sustainable water and soil saving practice in agriculture: A review. *Agronomy*, *12*(8), 1881. https://doi.org/10.3390/agronomy12081881

Elias, E. H., Flynn, R., Idowu, O. J., Reyes, J., Sanogo, S., Schutte, B. J., Smith, R., Steele, C., & Sutherland, C. (2019). Crop vulnerability to weather and climate risk: Analysis of interacting systems and adaptation efficacy for sustainable crop production. *Sustainability*, *11*(23), 6619. https://doi.org/10.3390/su11236619

Farooqi, Z. U., Sabir, M., Ahmad, H. R., Shahbaz, M., & Smith, J. (2023). Reclaimed salt-affected soils can effectively contribute to carbon sequestration and food grain production: Evidence from Pakistan. *Applied Sciences*, *13*(3), 1436. https://doi.org/10.3390/app13031436

Farooqi ZUR, M Sabir, M Zia-Ur-Rehman, MM Hussain (2020). Mitigation of climate change through carbon sequestration in agricultural soils. In Climate Change and Agroforestry Systems (pp. 87-118). Apple Academic Press.

Hailu Gebru, H. G. (2015). A review on the comparative advantages of intercropping to mono-cropping system. *J Biol Agric Healthc 5*(9), 1-13. https://www.cabidigitallibrary.org/doi/full/10.5555/20153225849

Ghimire, R., Clay, D. E., Thapa, S., & Hurd, B. (2022). More carbon per drop to enhance soil carbon sequestration in water-limited environments. *Carbon Management*, *13*(1), 450-462. https://doi.org/10.1080/17583004.2022.2117082

Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research*, *114*(1), 23-34. https://doi.org/10.1016/j.fcr.2009.06.017

Hailu, L., & Teka, W. (2024). Potential of conservation agriculture practice in climate change adaptation and mitigation in Ethiopia: A review. *Frontiers in Climate*, *6*. https://doi.org/10.3389/fclim.2024.1478923

Hassan, A., Ijaz, S., Lal, R., Ali, S., Ansar, M., Hussain, Q., & Bloch, M. (2015). Active soil organic carbon fractions and aggregate stability effected by minimum tillage and crop rotations on a marginal Dryland soil in Punjab, Pakistan. *International Journal of Plant & Soil Science*, *4*(4), 326-337. https://doi.org/10.9734/ijpss/2015/14328

Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstic, D., Aslam, Z., Zulifqar, U., Rauf, A., Hano, C., & El-Esawi, M. A. (2021). Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants*, *10*(10), 2001. https://doi.org/10.3390/plants10102001

Issa, S., Dahy, B., Ksiksi, T., & Saleous, N. (2020). A review of terrestrial carbon assessment methods using geo-spatial technologies with emphasis on arid lands. *Remote Sensing*, *12*(12), 2008. https://doi.org/10.3390/rs12122008

Jat, M. L., Chakraborty, D., Ladha, J. K., Parihar, C. M., Datta, A., Mandal, B., Nayak, H. S., Maity, P., Rana, D. S., Chaudhari, S. K., & Gerard, B. (2022). Carbon sequestration potential, challenges, and strategies towards climate action in smallholder agricultural systems of South Asia. *Crop and Environment*, *1*(1), 86-101. https://doi.org/10.1016/j.crope.2022.03.005

Jayaraman S, K Bandyopadhyay, A Naorem, N Sinha, M Mohanty, K Hati, A Patra, S Chaudhari, RC Dalal, R Lal (2021). Soil Carbon Sequestration Through Conservation Tillage and Residue Management. Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security. Conservation

Agriculture for Sustainable Agriculture. (pp. 299-319). Singapore: Springer Singapore.

Jellason, N. P., Conway, J. S., & Baines, R. N. (2020). Understanding impacts and barriers to adoption of climate-smart agriculture (CSA) practices in north-western Nigerian drylands. *The Journal of Agricultural Education and Extension*, *27*(1), 55-72. https://doi.org/10.1080/1389224x.2020.1793787

Junod, M. F., Reid, B., Sims, I., & Miller, A. J. (2024). Cover crops in cereal rotations: A quantitative review. *Soil and Tillage Research*, *238*, 105997. https://doi.org/10.1016/j.still.2023.105997

Ketema, M., & Bauer, S. (2012). Factors affecting intercropping and conservation tillage practices in eastern Ethiopia. *Agris on-line Papers in Economics and Informatics*, *4*(1), 21-29. https://doi.org/10.22004/ag.econ.131354

Komal N, Qu Zaman, A Pantera, G Yasin, K Ashraf, S Nazir, MB Baig (2024). Climate-Smart Agriculture: Potential Role in Carbon Sequestration and to Address Climate Change Under Irrigated Agro-Ecosystems. In Climate-Smart and Resilient Food Systems and Security (pp. 73-110). Springer.

Kotorová, D., Kováč, L., Jakubová, J., & Balla, P. (2018). The long-term different tillage and its effect on physical properties of heavy soils. *Acta fytotechnica et zootechnica*, *21*(3), 100-107. https://doi.org/10.15414/afz.2018.21.03.100-107

Koushika, S. P., Krishnaveni, A., Pazhanivelan, S., Bharani, A., Arunkumar, V., Devaki, P., & Muthukrishnan, N. (2024). Carbon Economics of Different Agricultural Practices for Farming Soil. *arXiv preprint arXiv:2403.07530*.. https://doi.org/10.48550/arXiv.2403.07530

Kumar, B. N., & Babalad, H. (2018). Soil organic carbon, carbon sequestration, soil microbial biomass carbon and nitrogen and soil enzymatic activity as influenced by conservation agriculture in Pigeonpea and soybean intercropping system. *International Journal of Current Microbiology and Applied Sciences*, *7*(03), 323-333. https://doi.org/10.20546/ijcmas.2018.703.038

Kumar, S., Meena, R. S., Datta, R., Verma, S. K., Yadav, G. S., Pradhan, G., Molaei, A., Rahman, G. K., & Mashuk, H. A. (2019). Legumes for carbon and nitrogen cycling: An organic approach. *Carbon and Nitrogen Cycling in Soil*, 337-375. https://doi.org/10.1007/978-981-13-7264-3_10

Lal, R. (2001). Potential of soil carbon sequestration in forest ecosystems to mitigate the greenhouse effect. *SSSA Special Publication*, *57*, 137-154. https://hero.epa.gov/reference/6978279/

Lal, R. (2009). Sequestering carbon in soils of arid ecosystems. *Land Degradation & Development*, *20*(4), 441-454. https://doi.org/10.1002/ldr.934

Layek, J., Das, A., Mitran, T., Nath, C., Meena, R. S., Yadav, G. S., Shivakumar, B. G., Kumar, S., & Lal, R. (2018). Cereal+Legume intercropping: An option for improving productivity and sustaining soil health. *Legumes for Soil Health and Sustainable Management*, 347-386. https://doi.org/10.1007/978-981-13-0253-4_11

Li, X. G., Jia, B., Lv, J., Ma, Q., Kuzyakov, Y., & Li, F. (2017). Nitrogen fertilization decreases the decomposition of soil organic matter and plant residues in planted soils. *Soil Biology and Biochemistry*, *112*, 47-55. https://doi.org/10.1016/j.soilbio.2017.04.018

Liu, L., Liu, D., Ding, X., Chen, M., & Zhang, S. (2023). Straw incorporation and nitrogen fertilization enhance soil carbon sequestration by altering soil aggregate and microbial community composition in saline-alkali soil. *Plant and Soil*, *498*(1-2), 341-356. https://doi.org/10.1007/s11104-023-06439-z

Ma, Y., Woolf, D., Fan, M., Qiao, L., Li, R., & Lehmann, J. (2023). Global crop production increase by soil organic carbon. *Nature Geoscience*, *16*(12), 1159-1165. https://doi.org/10.1038/s41561-023-01302-3

Maia, S. M., Otutumi, A. T., Mendonça, E. D., Neves, J. C., & Oliveira, T. S. (2019). Combined effect of intercropping and minimum tillage on soil carbon sequestration and organic matter pools in the semiarid region of Brazil. *Soil Research*, *57*(3), 266-275. https://doi.org/10.1071/sr17336

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A low input agricultural strategy for food and environmental security. *Agronomy*, *11*(2), 343. https://doi.org/10.3390/agronomy11020343

Maitra,, S. (2019). Potential of intercropping system in sustaining crop productivity. *International Journal of Agriculture Environment and Biotechnology*, *12*(01). https://doi.org/10.30954/0974-1712.03.2019.7

MAITRA, S., SAHOO, U., SAIRAM, M., GITARI, H. I., REZAEI-CHIYANEH, E., BATTAGLIA, M. L., & HOSSAIN5, A. (2023). Cultivating sustainability: A comprehensive review on intercropping in a changing climate. *Research on Crops*, *VOLUME 24*(ISSUE 4 (DEC)). https://doi.org/10.31830/2348-7542.2023.roc-1020

Mandal, A., Majumder, A., Dhaliwal, S. S., Toor, A. S., Mani, P. K., Naresh, R. K., Gupta, R. K., & Mitran, T. (2020). Impact of agricultural management practices on soil carbon sequestration and its monitoring through simulation models and remote sensing techniques: A review. *Critical Reviews in Environmental Science and Technology*, *52*(1), 1-49. https://doi.org/10.1080/10643389.2020.1811590

Mohammad, W., Shah, S. M., Shehzadi, S., & Shah, S. A. (2012). Effect of tillage, rotation and crop residues on wheat crop productivity, fertilizer nitrogen and water use efficiency and soil organic carbon status in dry area (rainfed) of north-west Pakistan. *Journal of soil science and plant nutrition*, *12*(4), 715-727. https://doi.org/10.4067/s0718-95162012005000027

Naorem, A., Jayaraman, S., Sinha, N. K., Mohanty, M., Chaudhary, R., Hati, K., Mandal, A., Thakur, J., Patra, A., Srinivasarao, C., Chaudhari, S., Dalal, R. C., & Lal, R. (2023). Eight-year impacts of conservation agriculture on soil quality, carbon storage, and carbon emission footprint. *Soil and Tillage Research*, *232*, 105748. https://doi.org/10.1016/j.still.2023.105748

Nasser, V., Dechow, R., Helfrich, M., Meijide, A., Rummel, P. S., Koch, H., Ruser, R., Essich, L., & Dittert, K. (2024). Managing Soil Nitrogen Surplus: The Role of Winter Cover Crops in N 2 O Emissions and Carbon Sequestration. https://doi.org/10.5194/egusphere-2024-2849-supplement

Niu, X., Zhang, S., Zhang, C., Yan, P., Wang, H., Xu, W., Song, M., & Aurangzeib, M. (2024). Key factors influencing the spatial distribution of soil organic carbon and its fractions in Mollisols. *CATENA*, *247*, 108522. https://doi.org/10.1016/j.catena.2024.108522

Pierre, J. F., Latournerie-Moreno, L., Garruña-Hernández, R., Jacobsen, K. L., Guevara-Hernández, F., Laboski, C. A., & Ruiz-Sánchez, E. (2022). Maize legume intercropping systems in southern Mexico: A review of benefits and challenges. *Ciência Rural*, *52*(11). https://doi.org/10.1590/0103-8478cr20210409

Ponce-Hernandez R, P Koohafkan, J Antoine (2004). Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land-use changes (Vol. 1). Food & Agriculture Org.

Pramanick, B., Kumar, M., Naik, B. M., Singh, S. K., Kumar, M., & Singh, S. V. (2024). Soil carbon-nutrient cycling, energetics, and carbon footprint in calcareous soils with adoption of long-term conservation tillage practices and cropping systems diversification. *Science of The Total Environment*, *912*, 169421. https://doi.org/10.1016/j.scitotenv.2023.169421

Qin, W., Niu, L., You, Y., Cui, S., Chen, C., & Li, Z. (2024). Effects of conservation tillage and straw mulching on crop yield, water use efficiency, carbon sequestration and economic benefits in the Loess Plateau region of China: A meta-analysis. *Soil and Tillage Research*, *238*, 106025. https://doi.org/10.1016/j.still.2024.106025

Raseduzzaman, M., Dong, W., Gaudel, G., Aluoch, S. O., Timilsina, A., Li, X., & Hu, C. (2024). Maize-soybean intercropping reduces greenhouse gas emissions from the fertilized soil in the north China plain. *Journal of Soils and Sediments*, *24*(8), 3115-3131. https://doi.org/10.1007/s11368-024-03859-x

Raveloaritiana E, TC Wanger (2024). Decades matter: Agricultural diversification increases financial profitability, biodiversity, and ecosystem services over time. arXiv preprint arXiv:2403.05599

Rehman, A., Batool, Z., Ma, H., Alvarado, R., & Oláh, J. (2024). Climate change and food security in South Asia: The importance of renewable energy and agricultural credit. *Humanities and Social Sciences Communications*, *11*(1). https://doi.org/10.1057/s41599-024-02847-3

Rehman, A., Farooq, M., Lee, D., & Siddique, K. H. (2022). Sustainable agricultural practices for food security and ecosystem services. *Environmental Science and Pollution Research*, *29*(56), 84076-84095. https://doi.org/10.1007/s11356-022-23635-z

Rehman, H. U., Mahmood, A., Ishfaq, F., Javaid, M. M., Haider, A., Asif, M., Nadeem, M. A., & Nargis, J. (2023). Sustainable crop management for Drylands. *Climate-Resilient Agriculture, Vol 1*, 435-464. https://doi.org/10.1007/978-3-031-37424-1_20

Rehman, S. U., Ijaz, S. S., Ud Din, A. M., Al-Dosary, M. A., Ansar, M., Fatima, S., Siddiqa, A., Ashraf, M. N., Haider, I., Junaid, M. B., Raza, M. A., & Yang, H. (2025). Correction: Combined effects of reduced tillage and strip intercropping on soil carbon sequestration in semi-arid environment. *Journal of Soil Science and Plant Nutrition*, *25*(2), 4090-4090. https://doi.org/10.1007/s42729-025-02385-0

Saleem, A., Anwar, S., Nawaz, T., Fahad, S., Saud, S., Ur Rahman, T., Khan, M. N., & Nawaz, T. (2024). Securing a sustainable future: The climate change threat to agriculture, food security, and sustainable development goals. *Journal of Umm Al-Qura University for Applied Sciences*, *11*(3), 595-611. https://doi.org/10.1007/s43994-024-00177-3

Sarker, M. R., Galdos, M. V., Challinor, A. J., Huda, M. S., Chaki, A. K., & Hossain, A. (2022). Conservation tillage and residue management improve soil health and crop productivity—Evidence from a rice-maize cropping system in Bangladesh. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.969819

Seran, T. H., & Brintha, I. (2010). Review on maize based intercropping. *Journal of Agronomy*, *9*(3), 135-145.

https://doi.org/10.3923/ja.2010.135.145

Sharif, M., Ijaz, S. S., Ansar, M., Ahmad, I., & Sadiq, S. A. (2018). Evaluation of conservation tillage system performance for Rainfed wheat production in upland of Pakistan. *Pakistan Journal of Agricultural Research*, *31*(1). https://doi.org/10.17582/journal.pjar/2018/31.1.37.44

Shaukat, M., Hoshide, A. K., Muhammad, S., Arshad, I. A., Mushtaq, M., & De Abreu, D. C. (2023). Predicting soil carbon sequestration and Harvestable C-biomass of rice and wheat by DNDC model. *Crops*, *3*(3), 220-240. https://doi.org/10.3390/crops3030021

Singh, P., Nazir, G., & Dheri, G. S. (2022). Influence of different management practices on carbon sequestration of agricultural soils – a review. *Archives of Agronomy and Soil Science*, *69*(12), 2471-2492. https://doi.org/10.1080/03650340.2022.2158326

Somasundaram, J., Sinha, N. K., Dalal, R. C., Lal, R., Mohanty, M., Naorem, A. K., Hati, K. M., Chaudhary, R. S., Biswas, A. K., Patra, A. K., & Chaudhari, S. K. (2020). No-till farming and conservation agriculture in South Asia – Issues, challenges, prospects and benefits. *Critical Reviews in Plant Sciences*, *39*(3), 236-279. https://doi.org/10.1080/07352689.2020.1782069

Sombrero, A., & De Benito, A. (2010). Carbon accumulation in soil. ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain. *Soil and Tillage Research*, *107*(2), 64-70. https://doi.org/10.1016/j.still.2010.02.009

Soumare, A., Diedhiou, A. G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., & Kouisni, L. (2020). Exploiting biological nitrogen fixation: A route towards a sustainable agriculture. *Plants*, *9*(8), 1011. https://doi.org/10.3390/plants9081011

Saeedullah, S., Nawaz, M., Yousaf, N., Rukhsar, S., Malhi, K., & Hanif, M. (2024). Ganoderma curtisii, firstly reported from districts Lahore and Gujranwala of Punjab province, Pakistan. *Lahore Garrison University Journal of Life Sciences*, *8*(3), 360-378. https://doi.org/10.54692/lgujls.2024.0803351

Yousaf, N. (2024). Ganoderma tsugae (Polyporales; Ganodermataceae), a new record from Pakistan. *PLANTARUM*, *6*(2). https://doi.org/10.46662/plantarum.v6i2.119

Soussana, J., Tallec, T., & Blanfort, V. (2010). Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal*, *4*(3), 334-350. https://doi.org/10.1017/s1751731109990784

Stevenson, J. R., Serraj, R., & Cassman, K. G. (2014). Evaluating conservation agriculture for small-scale farmers in sub-Saharan Africa and South Asia. *Agriculture, Ecosystems & Environment*, *187*, 1-10. https://doi.org/10.1016/j.agee.2014.01.018

Thapa, V. R., Ghimire, R., Adhikari, K. P., & Lamichhane, S. (2023). Soil organic carbon sequestration potential of conservation agriculture in arid and semi-arid regions: A review. *Journal of Arid Environments*, *217*, 105028. https://doi.org/10.1016/j.jaridenv.2023.105028

Tripathi, S., Soni, S. K., Maurya, A. K., & Soni, P. K. (2010). Calculating carbon sequestration using remote sensing and GIS. *Geospatial world*, 1-8. https://geospatialworld.net/article/calculating-carbon-sequestration-using-remote-sensing-and-gis/

Ullah, R., Aslam, Z., Attia, H., Sultan, K., Alamer, K. H., Mansha, M. Z., Althobaiti, A. T., Al Kashgry, N. A., Algethami, B., & Zaman, Q. U. (2022). Sorghum allelopathy: Alternative weed management strategy and its impact on mung bean productivity and soil rhizosphere properties. *Life*, *12*(9), 1359. https://doi.org/10.3390/life12091359

Usman, M., Ali, A., Baig, S. A., Radulescu, M., Abbas, A., & Akram, R. (2025). Food security in Punjab, Pakistan: Rural views on climate disasters and their impacts. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-025-06047-0

Utomo, M., Banuwa, I. S., Buchari, H., Anggraini, Y., & Berthiria, .. (2013). Long-term tillage and nitrogen fertilization effects on soil properties and crop yields. *JOURNAL OF TROPICAL SOILS*, *18*(2), 131. https://doi.org/10.5400/jts.2013.v18i2.131-139

Van Asseldonk, M., Girvetz, E., Pamuk, H., Wattel, C., & Ruben, R. (2023). Policy incentives for smallholder adoption of climate-smart agricultural practices. *Frontiers in Political Science*, *5*. https://doi.org/10.3389/fpos.2023.1112311

Villat, J., & Nicholas, K. A. (2024). Quantifying soil carbon sequestration from regenerative agricultural practices in crops and vineyards. *Frontiers in Sustainable Food Systems*, *7*. https://doi.org/10.3389/fsufs.2023.1234108

Virto, I., de Soto, I., Antón, R., & Poch, R. M. (2022). Management of carbonate-rich soils and trade-offs with soil inorganic carbon cycling. *Burleigh Dodds Series in Agricultural Science*, 707-736. https://doi.org/10.19103/as.2022.0106.22

Wafula, L., Oduol, J., Oluoch-Kosura, W., Muriuki, J., Okello, J., & Mowo, J. (2015). Does strengthening technical capacity of smallholder farmers enhance adoption of conservation practices? The case of conservation agriculture with trees in Kenya. *Agroforestry Systems*, *90*(6), 1045-1059. https://doi.org/10.1007/s10457-015-9882-y

Wang, X., & Gao, Y. (2019). Advances in the mechanism of cereal/legume intercropping promotion of symbiotic nitrogen fixation. *Chinese Science Bulletin*, *65*(2-3), 142-149. https://doi.org/10.1360/tb-2019-0138

Wang, Y., Liu, L., Luo, Y., Awasthi, M. K., Yang, J., Duan, Y., Li, H., & Zhao, Z. (2020). Mulching practices alter the bacterial-fungal community and network in favor of soil quality in a semiarid orchard system. *Science of The Total Environment*, *725*, 138527. https://doi.org/10.1016/j.scitotenv.2020.138527

Wasaya, A., Yasir, T. A., Ijaz, M., & Ahmad, S. (2019). Tillage effects on agronomic crop production. *Agronomic Crops*, 73-99. https://doi.org/10.1007/978-981-32-9783-8_5

Zubair, M., Farooq, U., Sandhu, A. S., Ali, W., Shakeel, F., & Ullah, S. S. (2025). Role of bacillus subtilis in plant growth promotion and disease suppression: A review. *Indus Journal of Bioscience Research*, *3*(8), 468-472. https://doi.org/10.70749/ijbr.v3i8.2199

Ullah, S. S., Iqbal, R., Ghafoor, A., Batool, S. A., Bashir, T., & Mehmood, A. (2025). Next-generation CRISPR biotechnology for Pakistan: AI-driven, climate-resilient super crops and the future of food security. *Futuristic Biotechnology*, 28-35. https://doi.org/10.54393/fbt.v5i3.189

Ullah, S. S., Arshad, A., Yousaf, N., Rasheed, S., Amin, N., & Mulk, S. (2025). Revolutionizing sustainable agriculture: Harnessing Macrofungi and bacterial systems for eco-friendly silver Nanoparticle synthesis and enhanced plant growth. *Indus Journal of Bioscience Research*, *3*(10), 15-27. https://doi.org/10.70749/ijbr.v3i10.2317

Xing, Y., & Wang, X. (2024). Impact of agricultural activities on climate change: A review of greenhouse gas emission patterns in Field crop systems. *Plants*, *13*(16), 2285. https://doi.org/10.3390/plants13162285

Yuexuan M, Z Guixin, L Yiyan, D Zhengze, D Ke, W Yi, M Shouyi (2025). Effects of long-term modified conservation tillage on carbon sequestration, microbial communities, and crop productivity in northeastern Chinese Mollisols. Pedosphere.

Zahid, A., Ali, S., Ahmed, M., & Iqbal, N. (2020). Improvement of soil health through residue management and conservation tillage in rice-wheat cropping system of Punjab, Pakistan. *Agronomy*, *10*(12), 1844. https://doi.org/10.3390/agronomy10121844

Zhanbota, A., Noor, R. S., Khan, A. I., Wang, G., Waqas, M. M., Shah, A. N., & Ullah, S. (2022). A two-year study on yield and yield components of maize-white bean intercropping systems under different sowing techniques. *Agronomy*, *12*(2), 240. https://doi.org/10.3390/agronomy12020240

Zhang, J., Ning, Y., Wu, H., Gao, G., Wu, Z., Peng, Y., Huang, Z., & Zhang, X. (2024). Intercropping shapes the metabolome and microbiome of medicinal giant lily (Cardiocrinum giganteum) in bamboo, Chinese fir, and mixed forests. *Forests*, *15*(12), 2201. https://doi.org/10.3390/f15122201

Zhang, J., Pannell, J. L., Case, B. S., Hinchliffe, G., Stanley, M. C., & Buckley, H. L. (2021). Interactions between landscape structure and bird mobility traits affect the connectivity of agroecosystem networks. *Ecological Indicators*, *129*, 107962. https://doi.org/10.1016/j.ecolind.2021.107962