AGRIFRONTLINE
The Voice of Agriculture

Soil Health under Climate Stress: Carbon Loss, Degradation, and Restoration Pathways.

M Shantha Murthy B[1], Sai Shree Pattnaik[2], Lalita[3]*

Introduction

Climate change has intensified environmental degradation at an unprecedented scale, with ecosystem destruction occurring 1,000–10,000 times faster than natural background rates. Soil degradation represents a critical dimension of this crisis, undermining ecosystem stability, biodiversity, and agricultural productivity through land-use change, intensive farming, and climatic aberrations. Restoring soil ecosystems has therefore become essential for counteracting both anthropogenic pressures and climate-induced stresses, positioning soil health as a central pillar of sustainability under changing climate scenarios (Bhaduri *et al.,* 2022).

Soil health under climate stress is increasingly threatened by widespread degradation, manifested through erosion, organic carbon loss, contamination, compaction, and salinization, all of which compromise the soil's capacity to support plant growth, regulate water, sustain biodiversity, and buffer environmental change. Soil degradation can be broadly categorized into biological, chemical, ecological, and physical forms, ranging from declines in microbial activity and nutrient imbalances to climate-driven productivity losses and structural damage from erosion and heavy machinery use (Nunes *et al.,* 2020). Globally, the most serious threats to soil function include loss of soil organic carbon (SOC), erosion, and nutrient imbalance, while regions such as Europe additionally face soil sealing, salinization, contamination, and significant SOC changes (Montanarella *et al*., 2016). As the largest terrestrial carbon reservoir, SOC plays a decisive role in soil fertility and agricultural productivity, maintaining a dynamic equilibrium between carbon inputs and decomposition under stable management conditions. In this context, Conservation Agriculture (CA) has gained recognition as a sustainable pathway to restore and maintain soil health through minimal soil disturbance, permanent soil cover, and diversified crop rotations, enhancing water retention, soil structure, carbon sequestration, and climate resilience. While CA contributes significantly to Sustainable Development Goals related to food security, land restoration, and climate action (McElwee *et al*., 2020), its outcomes remain context specific, shaped by agroecological conditions, technological adoption, and socioeconomic factors. Advancing soil health research and integrating innovations

[1] PhD Scholar, Division of Soil Science, University of Agricultural Sciences, Bangalore
[2] PhD Scholar, Disha University of Agriculture and Technology,Bhubaneswar, Odisha
[3] M.Sc., Department of Soil Science and Agricultural Chemistry, Banaras Hindu University, Varanasi, Uttar Pradesh

such as precision agriculture, biotechnology, and digital tools are therefore critical for refining restoration pathways, mitigating carbon loss, and enabling a resilient, environmentally sustainable agricultural future under climate stress (Wen *et al.,* 2025).

2. Concept of Soil Health and Soil Carbon

Soil health, often referred to as soil quality, denotes the soil's capacity to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and support plant and animal health. Its evaluation relies on an integrated set of physical, chemical, and biological indicators. Among these, soil organic carbon (SOC) is a central and unifying indicator, as it regulates microbial activity, nutrient cycling, soil aggregation, infiltration, and water-holding capacity. As the largest terrestrial carbon pool, soil plays a decisive role in agricultural ecosystem stability and the global greenhouse gas balance. However, SOC stocks are highly vulnerable to climate stress and land degradation. Rising temperatures accelerate the decomposition of soil organic matter more rapidly than net primary production, leading to a net decline in SOC, particularly in agricultural systems where crop yields—and thus carbon inputs—may stagnate. Anthropogenic soil erosion further intensifies SOC losses by reducing total ecosystem carbon pools and enhancing mineralization of organic matter in eroded sediments compared to intact topsoil, while also degrading biodiversity and long-term land productivity (Ghisman *et al*., 2025).

Restoration pathways for soil health under climate stress increasingly emphasize management practices and emerging technologies that enhance soil carbon inputs while slowing carbon mineralization. Conservation Agriculture (CA) significantly improves soil health by increasing SOC through reduced tillage, residue retention, and diversified crop rotations, which collectively strengthen soil structure, water retention, nutrient availability, and microbial diversity. SOC accumulation under CA is widely recognized as a key indicator of improved soil fertility, resilience, and long-term sustainability. Collectively, these strategies align with a comprehensive soil health framework that integrates physical, chemical, and biological indicators such as structural stability, nutrient status, organic matter, microbial diversity, biomass carbon, and enzyme activity to support resilient and climate-smart agricultural systems (Wen *et al.,* 2025).

3. Climate Stressors Affecting Soil Systems

Global climate change, marked by rising temperatures, altered precipitation regimes, and an increasing frequency of extreme weather events, poses multifaceted challenges to soil systems, including heightened moisture variability, loss of organic matter, and disruptions in microbial balance (Liu *et al.,* 2024). Climatic aberrations such as prolonged droughts, intense rainfall and flooding, salinization driven by sea-level rise, and permafrost thawing exacerbate soil degradation and contamination by altering soil structure, nutrient cycling, and contaminant mobility. These stresses not only undermine soil resistance and resilience but also interact with land-use intensification, compounding soil vulnerability and accelerating biodiversity loss in both above- and below-ground ecosystems.

Climate variability also amplifies soil erosion, moisture stress, and yield instability, particularly in rainfed

agricultural systems. Evidence from a 12-year comparative study (2010–2022) demonstrates that no-till systems maintained higher soil moisture and greater yield stability under drought conditions than conventional tillage, offering resilience against precipitation variability during critical autumn and late-spring periods (Das *et al*., 2022). Conservation Agriculture (CA), through improved soil structure and enhanced water retention, is therefore designed to buffer agricultural systems against drought, erratic rainfall, and temperature fluctuations, stabilizing production under climate stress. These findings underscore the need for climate-resilient soil management strategies that are locally adapted to mitigate climate stressors while sustaining soil health and productivity.

4. Soil Carbon Loss under Climate Change

Soil organic matter is fundamental to carbon storage and overall ecosystem functioning, yet it is increasingly threatened by the combined impacts of climate change and unsustainable land management. Elevated temperatures accelerate microbial respiration and organic matter decomposition, while moisture stress alters carbon turnover rates, collectively destabilizing soil organic matter pools and reducing the soil's capacity to function as a long-term carbon sink (Smith, 2004). As a result, soil organic carbon (SOC) depletion has become widespread, leading to declines in soil fertility, microbial activity, productivity, and ecosystem functionality. The loss of organic matter and nutrients is closely associated with erosion, altered microbial processes, and poor land management, reinforcing feedbacks between soil degradation and climate change (Ghisman *et al.*, 2025).

Soil erosion is a particularly significant pathway of SOC loss under climate stress, directly linking land degradation to carbon emissions. Evidence indicates that while Conservation Agriculture (CA) may not always substantially reduce surface runoff compared to conventional tillage, it can markedly lower sediment loss and associated SOC losses, while increasing SOC concentrations in eroded sediments (Xiao *et al*., 2025). These findings highlight that climate-induced disturbances, when coupled with inappropriate management, accelerate organic matter loss and weaken soil buffering capacity, whereas targeted conservation practices can play a critical role in slowing SOC loss and stabilizing soil carbon stocks under changing climatic conditions.

4.1 Mechanisms of Carbon Loss

Soil organic carbon (SOC) loss under climate stress occurs through multiple, interlinked mechanisms driven by both environmental change and land management practices. Rising temperatures enhance microbial activity and accelerate the mineralization of organic matter, resulting in increased CO_2 emissions from soils. At the same time, physical processes such as soil erosion remove carbon-rich topsoil through sediment transport and surface runoff, directly depleting SOC stocks. Together, enhanced mineralization, erosion, and reduced carbon inputs significantly diminish the soil's long-term carbon storage capacity.

Agricultural practices play a critical role in accelerating these mechanisms of carbon loss. Each tillage operation can release up to 300 kg CO_2e ha^{-1}, while soil erosion may contribute an additional 300 kg CO_2e ha^{-1} annually, underscoring the substantial climate impact of soil disturbance (Freitag *et al*., 2024). These processes highlight the

importance of conservation-oriented practices that minimize soil disturbance, limit erosion, and sustain organic matter inputs to slow carbon loss and preserve soil health under changing climatic conditions.

4.2 Feedbacks between Soil Carbon and Climate

Soil organic carbon (SOC) plays a critical buffering role in regulating soil–climate interactions, and its decline initiates reinforcing feedbacks that intensify both climate change and land degradation. Reduced SOC weakens soil structure, biological activity, and water- and nutrient-holding capacity, making soils more vulnerable to drought, erosion, and nutrient loss. This diminished resilience accelerates ecosystem and agricultural vulnerability, creating a cycle of degradation and declining carbon sequestration potential under persistent climatic stress (Bhaduri *et al*., 2022). Conversely, improved soil carbon management can generate stabilizing feedbacks that enhance climate resilience. Conservation Agriculture (CA) has been shown to increase SOC stocks by approximately 0.3–1.2 t C ha^{-1} yr^{-1} relative to conventional tillage systems (Paustian *et al.,* 2016), while no-till combined with residue retention can raise SOC by an average of 0.57 t ha^{-1} yr^{-1}, particularly in wetter climates (Powlson *et al.,* 2014). Healthy, carbon-rich soils enhance crop adaptation and recovery by improving water and nutrient retention, stabilizing soil aggregates, and optimizing the rhizosphere microenvironment. Strengthening soil health management is therefore a key pathway for breaking negative soil–climate feedbacks and transitioning agricultural systems toward greater climate resilience and long-term carbon sequestration (Liu *et al.,* 2024).

5. Impacts of Soil Degradation on Agroecosystems and Ecosystem Services

Soil degradation exerts profound impacts on agroecosystems and the ecosystem services they provide, affecting soil fertility, biodiversity, water regulation, food safety, and climate regulation. Degradation driven by erosion, salinization, acidification, and contamination reduces soil organic matter, weakens soil structure, impairs water infiltration, and increases dependence on external inputs such as nitrogen and phosphate fertilizers, which only temporarily offset yield losses. Large-scale studies demonstrate that conventional tillage accelerates erosion and surface runoff, whereas conservation management practices—including soil bunds, contour cultivation, mulching, afforestation, no-till, and broader Conservation Agriculture (CA) systems—significantly reduce soil loss, enhance water infiltration, improve soil fertility, and support crop productivity across diverse agroecological regions (Eze *et al*., 2020; Das *et al.,* 2022). In contrast, erosion-driven nutrient runoff contributes to freshwater eutrophication, biodiversity loss, and the weakening of soil-mediated ecosystem services essential for agricultural resilience.

Soil contamination further compounds degradation impacts by disrupting soil biocenosis and threatening food security and human health. Heavy metals, pesticides, industrial chemicals, petroleum hydrocarbons, and persistent organic pollutants impair microbial activity, reduce crop productivity, and pose risks through bioaccumulation and biomagnification in food chains (Ghisman *et al.,* 2025). Given the limitations of traditional remediation measures in restoring ecological function in degraded soils (Zhang and Wu, 2024), ecosystem restoration has emerged as the

most viable response to large-scale soil degradation, aiming to rebuild soil resistance and resilience so that agroecosystems can sustain functionality without continuous intervention.

6. Role of Soil in Climate Change Mitigation and Adaptation

Soils play a pivotal role in climate change mitigation and adaptation by functioning as major carbon sinks and regulators of greenhouse gas fluxes. Enhanced soil organic carbon (SOC) improves soil water-holding capacity and nutrient retention, thereby strengthening resilience to droughts, floods, and climate variability while simultaneously reducing atmospheric carbon concentrations (Song *et al.*, 2015). Conservation agriculture (CA) provides an integrated framework for restoring degraded soils by improving soil structure, increasing organic matter inputs, and enhancing biological activity, leading to sustained SOC accumulation and long-term ecosystem functioning (Francaviglia *et al.,* 2023).

Recent advances in soil restoration increasingly emphasise the integration of sustainable practices with innovative technologies. Achieving a green agricultural transition requires systematic evaluation and adoption of such integrated restoration strategies that combine agronomic management, biological regulation, and technological tools to rebuild soil structure, organic matter, and biological stability, thereby enhancing the role of soils in climate mitigation and adaptation (Zhang and Wu, 2024).

6.1 Carbon-Centred Soil Management

Carbon-centred soil management enhances soil carbon sinks by increasing carbon inputs and slowing mineralization, strengthening soil health and climate resilience. Biochar improves soil structure, water retention, and microbial activity, while organic fertilizers and green manuring promote aggregate formation and rhizo-spheric carbon inputs (Chen *et al*., 2025). CA enhances SOC through residue retention, cover cropping, and reduced tillage, with accumulation influenced by soil type, climate, initial carbon, root biomass, and erosion history (Francaviglia *et al*., 2023; Rodrigues *et al*., 2023). SOC gains of 18–25% under conservation practices have been reported across tropical, subtropical, and semi-arid regions (Tadiello *et al*., 2023).

6.2 Organic Amendments and Bio-inputs

Organic amendments and bio-inputs improve soil carbon dynamics, nutrient cycling, and microbial activity. Cover crops, crop residues, organic fertilisers, and green manure stabilise nutrients and enhance SOC, particularly when combined with biochar (Khangura *et al*., 2023; Chen *et al.*, 2025; Zou *et al*., 2024). Biofertilizers, including Rhizobium, Azospirillum, and phosphate-solubilising bacteria, increase crop yields by 10–40%, reduce chemical inputs, and enrich soil microbiomes.

Table 1 summarizes key soil restoration strategies under climate stress, their mechanisms, benefits, and supporting references.

Soil Restoration Strategy	Mechanism	Benefits	Key References
Conservation Agriculture (CA)	Reduced tillage, residue retention, cover cropping	Increases SOC, improves soil structure, water retention	Francaviglia *et al.*, 2023; Dey *et al*., 2020

		, and nutrient cycling	
Carbon-Centred Management (Biochar, Organic Fertilizers, Green Manure)	Enhances carbon inputs, slows mineralization, improves aggregation	Enhances SOC, microbial activity, soil fertility, and climate resilience	Ghisman *et al.,* 2025; Tadiello *et al*., 2023
Organic Amendments & Bio-inputs	Cover crops, crop residues, biofertilizers, CQDs-coated fertilizers	Stabilizes nutrients, improves microbial activity, increases yields, reduces chemical inputs	Khangura *et al.,* 2023; Chen *et al*., 2025
Nature-Based & Agroecological Practices	Mulching, crop rotation, phytoremediation, myco-remediation	Reduces erosion, improves biodiversity, remediates contaminants, enhances soil resilience	Zhang & Wu, 2024; Sadiq *et al.,* 2025
Technological Interventions	Precision agriculture, drones, GPS, nanotechnology (CQDs, nano-iron)	Optimizes inputs, reduces contamination, enhances monitoring, supports CA	Aijaz *et al.,* 2025
Policy & Institutional Support	Incentives, subsidies, land-use planning, digital monitoring	Facilitates adoption of sustainable practices, scaling of CA, soil health protection	Wen *et al.,* 2025; Münzel *et al.,* 2023

6.3 Nature-Based and Agroecological Approaches

Nature-based practices mimic ecosystem processes to enhance biological regulation. Residue mulching, cover cropping, diversified rotations, and reduced tillage improve nutrient cycling, microbial activity, and erosion control. CA-based interventions, including sodic soil reclamation and subsurface drip irrigation, increase SOC and nutrient availability. Plants and microorganisms regulate the rhizosphere, while phytoremediation, bioremediation, and myco-remediation remove contaminants and heavy metals, with multi-omics tools identifying functional communities for restoration (Ali *et al.,* 2013; Chaudhary *et al.,* 2021; Xie *et al*., 2021).

6.4 Technological and Policy Interventions

Precision agriculture tools (GPS, GIS, drones, soil sensors, AI, IoT) optimize inputs and enhance CA efficiency (Aijaz *et al*., 2025). Low-disturbance machinery preserves soil structure and reduces carbon loss (Singh, 2021). Engineered nanomaterials such as nano zero-valent iron and TiO_2 aid contaminant remediation, but require risk assessment and monitoring. Policy frameworks, digital monitoring, incentives, and institutional support improve CA adoption, especially for smallholders. Integrated land and water management addressing pollution and precision agriculture is essential for sustaining soil and water quality (An & Li, 2025; El Bakali *et al.,* 2023; Münzel *et al.,* 2023).

7. Role of Soil in Climate Change Mitigation and Adaptation

Healthy soils are central to both climate change mitigation and adaptation, as they enhance crop resilience by improving water and nutrient retention, stabilizing soil aggregate structures, and optimizing the rhizosphere microenvironment. These functions support faster crop recovery from climate extremes such as droughts and heat stress, while also increasing the capacity of agricultural systems to sequester carbon. Soils can act as either sources or sinks of greenhouse gases depending on management practices, moisture and oxygen availability, and organic matter content.

Conservation Agriculture (CA) provides a practical and scalable pathway for leveraging soils in climate mitigation and adaptation. Reduced and no-till systems lower CO_2 emissions by decreasing fuel consumption and limiting soil organic matter mineralization associated with intensive soil disturbance, while also reducing N_2O emissions by up to 11% compared with conventional tillage, particularly in humid environments and soils with low initial carbon content. CA further enhances climate adaptation by improving soil structure, residue cover, and moisture retention, resulting in greater yield stability under drought conditions in rainfed systems (M'hamed *et al.,* 2025).

8. Challenges and Knowledge Gaps

Despite growing recognition of soil health as a cornerstone of climate resilience, significant challenges and knowledge gaps remain in restoring and managing soils under climate stress. Traditional land management practices such as intensive fertilizer use, shortened fallow periods, and repeated residue burning continue to accelerate soil degradation by depleting organic matter, disrupting microbial communities, and increasing erosion. Conventional restoration approaches, including chemical amendments and deep plowing, often provide only short-term improvements in soil physicochemical properties while failing to restore ecological functions. These limitations highlight the need for a deeper understanding of multi-stress interactions, long-term restoration dynamics, and region-specific adaptation strategies to guide effective soil restoration engineering (DuPont *et al*., 2021).

Emerging technologies and management frameworks also face important uncertainties. Similar uncertainties

surround nanomaterials more broadly, including risks of ecotoxicity, bioaccumulation, and secondary contamination from soil amendments and industrial by-products, as well as food safety concerns when phytoremediation leads to accumulation of toxic elements in edible plant tissues (Kumar *et al*., 2021). Conservation Agriculture (CA) exhibits variable outcomes across agroecological zones, soil types, and management systems, with mixed findings on bulk density, pH, cation exchange capacity, nutrient stratification, and initial nitrogen immobilization during early adoption. Moreover, increases in soil organic carbon under CA may, under certain conditions, elevate N_2O emissions, underscoring the need for careful nutrient and residue management (Guenet *et al.*, 2021). Addressing these gaps requires long-term, site-specific monitoring, development of regionally appropriate soil health indicators, and integrated socio-ecological research to ensure sustainable soil restoration under climate stress.

9. Future Perspectives and Research Priorities

Future research on soil health under climate stress must prioritize long-term, systems-oriented approaches integrating biophysical, technological, and socioecological dimensions. Long-term field experiments, multi-scale comparative studies, and dynamic monitoring of restoration interventions are essential to capture temporal variability and cumulative effects on soil carbon, ecosystem services, and climate resilience (Wiesmeier *et al.,* 2015). Advancing context-specific management models and elucidating coupling mechanisms between tillage–fertilization systems and soil ecosystem services will be critical for translating scientific knowledge into effective restoration strategies and policy frameworks (Bhaduri *et al.,* 2022).

Innovation in sustainable technologies and management practices represents another key research frontier Similarly, future research should advance context-specific Conservation Agriculture (CA) adaptations, low-cost seeding and residue-management equipment suitable for smallholder farmers, and bio-based inputs that enhance soil biological processes, SOC stabilization, and greenhouse gas mitigation (Kabato et al., 2025). Integrated remediation strategies for contaminated and degraded soils, combined with improved industrial waste management, sustainable agricultural practices, and long-term soil health monitoring, are urgently needed to safeguard ecosystem services, food safety, and climate resilience.

10. Conclusion

Climate change poses a serious and escalating threat to soil health through accelerated carbon loss, degradation, and contamination, undermining soil fertility, biodiversity, water quality, food security, and climate regulation. Carbon-centred soil management, agroecological practices, and climate-adaptive strategies offer viable pathways to counteract these challenges by enhancing soil organic carbon (SOC) stocks, restoring ecological functions, and improving agricultural resilience under climate stress. Recent advances in phytoremediation, bioremediation, myco-remediation, nanotechnology, bio-based inputs, precision agriculture, and organic amendments demonstrate strong potential

for rehabilitating degraded and contaminated soils. Conservation Agriculture (CA) emerges as a holistic and scalable pathway for restoring soil health, enhancing carbon sequestration, reducing degradation, and building climate-resilient agroecosystems. By improving soil physical, chemical, and biological properties, CA supports sustainable food production, ecosystem services, and climate change mitigation. In parallel, carbon quantum dots represent promising multifunctional nanomaterials with emerging applications in soil microbial modulation, nutrient delivery, and plant stress management, offering additional tools for climate-resilient agriculture. Integrating ecological principles, technological innovation, and inclusive policy frameworks will be essential for strengthening soil health, enhancing carbon sequestration capacity, and ensuring long-term agricultural and ecosystem resilience under changing climate scenarios.

References

Aijaz, N., Lan, H., Raza, T., Yaqub, M., Iqbal, R., & Pathan, M. S. (2025). Artificial intelligence in agriculture: Advancing crop productivity and sustainability. *Journal of Agricultural and Food Research, 20*, 101762. https://doi.org/10.1016/j.jafr.2025.101762

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. *Chemosphere, 91*(7), 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075

An, L., & Li, Z. (2025). The effects of different tillage and crop rotation patterns on soil organic carbon accumulation and distribution characteristics in arid regions: A case study of field experiments in northwest China. *Geographical Research Bulletin, 4*, 135–157.

Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B. C., Munda, S., & Dari, B. (2022). A review on effective soil health bio-indicators for ecosystem restoration and sustainability. *Frontiers in Microbiology, 13*, 938481.

Chaudhary, D. K., Bajagain, R., Woo, S., & Jaisoo, J. (2021). Effect of consortium bioaugmentation and biostimulation on remediation efficiency and bacterial diversity of diesel-contaminated aged soil. *World Journal of Microbiology and Biotechnology, 37*, Article 46. https://doi.org/10.1007/s11274-021-03019-1

Chen, Y., Wu, S., & Hu, C. (2025). The synergistic effects of soil acidification and carbon sequestration technologies: Mechanism analysis, research progress, and application prospects. *Geographical Research Bulletin, 4*, 56–91.

Das, S., Chatterjee, S., & Rajbanshi, J. (2022). Responses of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: A meta-analysis. *Science of the Total Environment, 805*, 150428.

Dey, A., Dwivedi, B. S., Bhattacharyya, R., Datta, S. P., Meena, M. C., Jat, R. K., Gupta, R. K., Jat, M. L., Singh, V. K., Das, D., et al. (2020). Effect of conservation agriculture on soil organic and inorganic carbon sequestration and lability in a rice–wheat cropping

DuPont, S. T., Kalcsits, L., & Kogan, C. (2021). Soil health indicators for central Washington orchards. *PLOS ONE, 16*, e0258991. https://doi.org/10.1371/journal.pone.0258991

El Bakali, I., Ait El Mekki, A., Maatala, N., & Harbouze, R. (2023). A systematic review on the impact of incentives on the adoption of conservation agriculture: New guidelines for policymakers and researchers.

International Journal of Agricultural Sustainability, 21, 2290415. https://doi.org/10.1080/14735903.2023.2290415

Eze, S., Dougill, A. J., Banwart, S. A., Hermans, T. D., Ligowe, I. S., & Thierfelder, C. (2020). Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. *Soil & Tillage Research, 201*, 104639.

Francaviglia, R., Almagro, M., & Vicente-Vicente, J. L. (2023). Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. *Soil Systems, 7*(1), 17.

Freitag, M., Friedrich, T., & Kassam, A. (2024). The carbon footprint of conservation agriculture. *International Journal of Agricultural Sustainability, 22*, 2331949. https://doi.org/10.1080/14735903.2024.2331949

Ghisman, V., Muresan, A. C., Bogatu, N. L., Herbei, E. E., & Buruiana, D. L. (2025). Recent advances in the remediation of degraded and contaminated soils: A review of sustainable and applied strategies. *Agronomy, 15*(8), 1920.

Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., & Zhou, F. (2021). Can N_2O emissions offset the benefits from soil organic carbon storage? *Global Change Biology, 27*(2), 237–256.

Kabato, W., Getnet, G. T., Sinore, T., Nemeth, A., & Molnár, Z. (2025). Towards climate-smart agriculture: Strategies for sustainable agricultural production, food security, and greenhouse gas reduction. *Agronomy, 15*, 565. https://doi.org/10.3390/agronomy15030565

Khangura, R., Ferris, D., Wagg, C., & Bowyer, J. (2023). Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. *Sustainability, 15*, 2338. https://doi.org/10.3390/su15042338

Kumar, A., Yadav, N., Mondal, R., Kour, D., Subrahmanyam, G., Shabnam, A. A., Khan, S. A., Yadav, K. K., Sharma, G. K., & Cabral Pinto, M. (2021). Mycoremediation: A mechanistic understanding of contaminants alleviation from natural environment and future prospect. *Chemosphere, 284*, 131325. https://doi.org/10.1016/j.chemosphere.2021.131325

Liu, L., Gao, M., & Cao, E. (2024). Agricultural measures to address climate change: Enhancing adaptability and sustainable development strategies. *Geographical Research Bulletin, 3*, 88–95.

M'hamed, H. C., Rezgui, M., Ferchichi, N., Toukabri, W., Somrani, O., Rezgui, M., et al. (2025). Resilience of conservation agriculture to rainfall deficits: A long-term study on durum wheat yield in Tunisia. *Italian Journal of Agronomy, 20*(1), 100031.

McElwee, P., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., et al. (2020). The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. *Global Change Biology, 26*(9), 4691–4721.

Montanarella, L., Pennock, D. J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., et al. (2016). World's soils are under threat. *Soil, 2*, 79–82. https://doi.org/10.5194/soil-2-79-2016

Münzel, T., Hahad, O., & Daiber, A., et al. (2023). Soil and water pollution and human health: What should cardiologists worry about? *Cardiovascular Research, 119*, 440–449. https://doi.org/10.1093/cvr/cvad012

Nunes, F. C., Alves, L. J., Cseko, C., de Carvalho, N., Gross, E., de Soares, T. M., Narasimha, M., & Prasad, V. (2020). Soil as a complex ecological system for meeting food and nutritional security. In M. N. V. Prasad & M. Pietrzykowski (Eds.), *Climate change and soil interactions* (1st ed.). Elsevier.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature, 532*(7597), 49–57.

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change, 4*(8), 678–683.

Sadiq, F. K., Anyebe, O., Tanko, F., Abdulkadir, A., Manono, B. O., Matsika, T. A., et al. (2025). Conservation agriculture for sustainable soil health management: A review of impacts, benefits and future directions. *Soil Systems, 9*(3), 103.

Singh, R. C. (2021). Machinery for conservation agriculture: Indian perspective. In *Conservation agriculture for sustainable agriculture* (pp. 499–509). Springer. https://doi.org/10.1007/978-981-33-6393-8_36

Smith, P. (2004). Soils as carbon sinks: The global context. *Soil Use and Management, 20*, 212–218. https://doi.org/10.1111/j.1475-2743.2004.tb00361.x

Song, Z., Gao, H., Zhu, P., Peng, C., Deng, A., Zheng, C., et al. (2015). Organic amendments increase corn yield by enhancing soil resilience to climate change. *The Crop Journal, 3*, 110–117. https://doi.org/10.1016/j.cj.2015.01.004

Tadiello, T., Acutis, M., Perego, A., Schillaci, C., & Valkama, E. (2023). Soil organic carbon under conservation agriculture in Mediterranean and humid subtropical climates: A global meta-analysis. *European Journal of Soil Science, 74*, e13338.

Wen, G., Cao, Y., & Wei, X. (2025). The data-driven analysis of soil health and crop adaptability: Technologies, impacts, and optimization strategies. *Advances in Resources Research, 5*(1), 350–368.

Wiesmeier, M., Hübner, R., & Kögel-Knabner, I. (2015). Stagnating crop yields: An overlooked risk for the carbon balance of agricultural soils? *Science of the Total Environment, 536*, 1045–1051. https://doi.org/10.1016/j.scitotenv.2015.07.061

Xiao, L., Zhao, K., Wang, Y., Zhao, R., Xie, Z., & Hu, Q. (2025). Effects of conservation agriculture on carbon dynamics across eroded slopes: A global synthesis. *Agriculture, Ecosystems & Environment, 389*, 109696.

Xie, T., Li, F., Chen, J., & Wang, Y. (2021). Role of organic matter in soil heavy metal immobilization. *Journal of Environmental Sciences, 101*, 12–23. https://doi.org/10.1016/j.jes.2020.09.002

Zhang, Z., & Wu, B. (2024). Soil health and sustainable agriculture: Key research directions and practical pathways. *Geographical Research Bulletin, 3*, 298–301.

Zou, Y., Liu, Z., Chen, Y., Wang, Y., & Feng, S. (2024). Crop rotation and diversification in China: Enhancing sustainable agriculture and resilience. *Agriculture, 14*, 1465. https://doi.org/10.3390/agriculture14121465