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# Regenerative Agriculture for Climate-Resilient and Sustainable Food Systems: Global Perspective with Special Focus on Pakistan

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**Abstract:** As the planet faces unprecedented environmental and climatic pressures, regenerative agriculture offers a framework for radically rethinking how food is produced. In contrast to most industrial forms of farming that damage soils and increase greenhouse gas emissions, regenerative practices harness nature's processes to enhance soil health, promote biodiversity, and strengthen ecosystem functions that support resilient food systems. Building on practices such as cover cropping, diverse crop rotations, minimal tillage, and agroforestry, regenerative agriculture increases the capacity to sequester carbon in soils and resources. Not only does it improve water retention, but it also buffers agricultural landscapes against extreme weather events, which are essential pillars of climate resilience and sustainability. However, barriers to adoption, such as economic considerations, knowledge gaps between scientists and farmers on regenerative practices, and disconnected governance policies, need to be addressed via an integrated framework that reinforces linkages among science, efficiency, and evidence-based framing of incentives provided to growers (e.g., Marketplace providers), whilst ensuring informed policy support by decision makers towards scaling aligned, transformative outcomes across agrifood systems. This review consolidates the latest research on regenerative principles, climate mitigation and adaptation effectiveness. Its main goal is to critically assess current scientific understanding of regenerative agriculture, exploring opportunities and challenges for its adoption in developing countries such as Pakistan. Additionally, it integrates agronomic, socio-economic, and ecological perspectives, emphasizing regenerative agriculture as a key strategy for developing climate-resilient and sustainable food systems, rather than presenting it as a one-size-fits-all solution.

**Keywords:** regenerative agriculture, climate resilience, soil health, sustainable food systems, carbon sequestration, biodiversity conservation, agroecology

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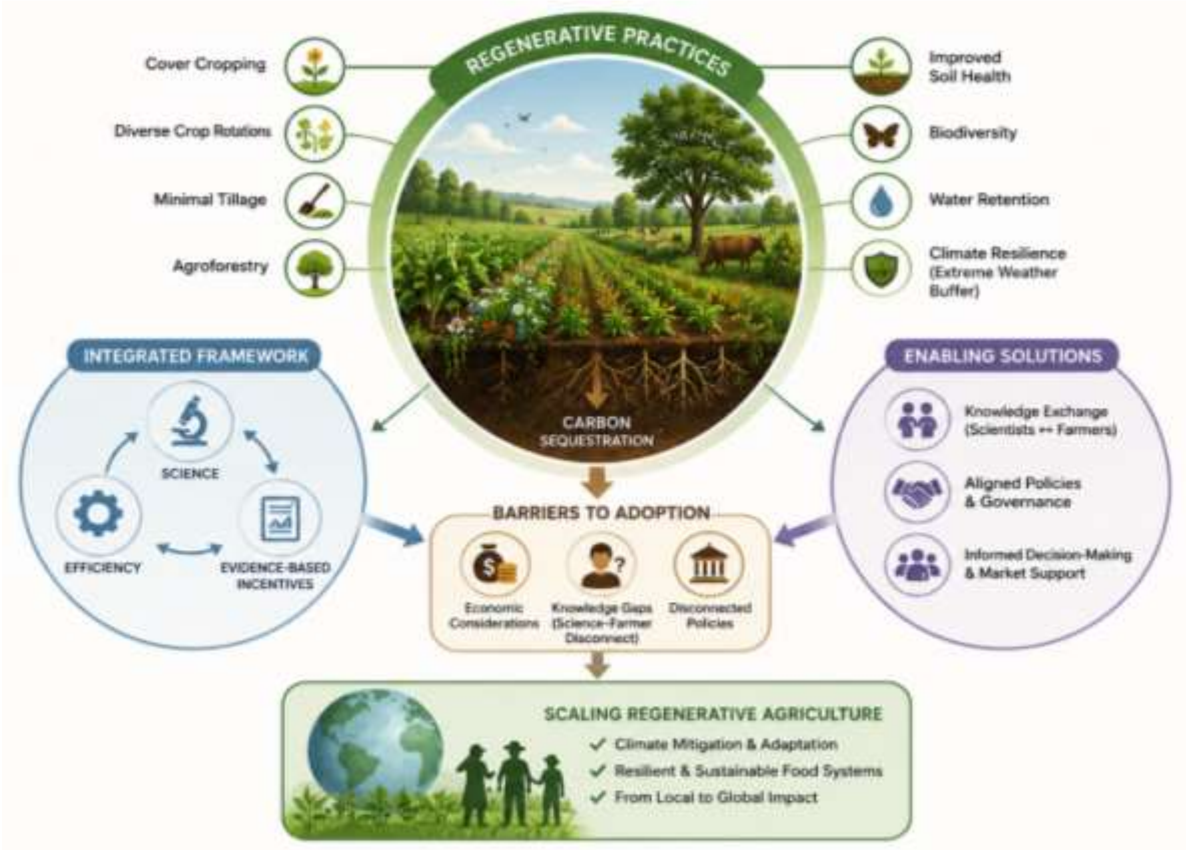


*Figure 1: The figure illustrates different regenerative practices, the barriers in adoption of regenerative agriculture, and its benefits*

*Source: The image has been created using Canva based on the information presented in the published literature*

## 1. Introduction

Rising sustainability and climate change risks threaten the global agri-food system (Kumar et al., 2025). Traditional agricultural methods frequently cause significant ecological degradation, including soil erosion, loss of organic matter, declining microbial diversity, and major GHG (greenhouse gas) emissions (Shahriar et al., 2025). Transformative approaches are needed because these issues threaten food security and ecosystem health. To this end, regenerative agriculture (RA), a holistic and novel paradigm that seeks to provide food production while building soil health, enhancing biodiversity and ecosystem services, reducing input costs, and improving climate resilience, has gained momentum and traction in recent years to steadily curb the aforementioned factors perturbing the stability of agroecosystems (Akhil and Sowjanya, 2025).

The main characteristic that sets regenerative agriculture apart from other sustainable farming practices is its clear framework that emphasizes soil health, biodiversity, and social equity, and that can be easily scaled up (Lal, 2020). It transforms the very notion of farms from simple centers of production to multifunctional ecosystems, moving away from an extractive model and toward a regenerative one that builds biological capital and ecosystem services (Jamil and Pearce, 2025). RA emphasizes practices like minimal soil disturbance (such as no-till or minimal tillage), maintaining over 30% plant cover and living roots most of the year, enhancing species diversity through crop rotation, intercropping, and cover cropping, and incorporating livestock to supply manure. These methods boost soil organic carbon (SOC), improve nutrient cycling, and enhance water retention (Khan and Benik, 2025).

Regenerative agriculture offers substantial benefits across environmental, economic, and social dimensions. RA mitigates climate change by sequestering atmospheric CO2 in the soil (via increased SOC), i.e., by increasing carbon storage that captures atmospheric CO2 (Ghosh et al., 2024). The same approach also minimizes GHG emissions associated with conventional farming, including nitrous oxide from synthetic fertilizers and methane (when farmed adaptively) emitted by livestock (Choudhari et al., 2024). At the ecological level, RA increases diversity among plants and soil organisms above- and below ground, enhancing ecosystem resilience and improving water quality and resource-use efficiency. Microbial diversity in soils also contributes to nutrient cycling and disease suppression, thereby promoting healthier plants (Grelet et al., 2021).

Across the economy, RA can reduce dependence on external inputs such as synthetic fertilizers and pesticides, lowering production costs for farmers while making their outputs more profitable and/or stabilizing income. This is especially important as climate change affects productivity and farm incomes. Socially, RA helps strengthen rural communities and food security by promoting sustainable, fair food production systems (James et al., 2024). This fosters farmer engagement by aligning agricultural practices with environmental stewardship and sustainability goals.

Despite growing recognition and enormous potential, regenerative agriculture exhibits considerable heterogeneity in its application due to its varied definitions and assessment methods. Nevertheless, its precise goals are still largely agreed upon as (i) increasing soil health, (ii) supporting ecosystem biodiversity or the healthy functioning of ecosystems and/or habitats, and (iii) improving climate change adaptability/resilience/functioning for overall environmental/eco-systemic benefits to society/climate regulation (Islam, 2025). To provide a compelling case for the generalization of RA, research efforts have increasingly focused on measuring socio-economic and environmental impacts across multiple spatio-temporal scales (Kumar et al., 2025). In addition, RA is being merged with other emerging technologies to enhance sustainable food and energy systems such as agrivoltaics, whereby solar electricity production is co-located with agricultural production (Moodley et al., 2024) to achieve these goals.

The current review adopts a global perspective on the mechanisms and principles, benefits, and limitations of RA as a pathway toward climate-resilient and sustainable food systems. Along with a global perspective, the review presents the relevance and applicability of RA in Pakistan, where water scarcity, soil degradation, and climate vulnerability are major challenges to achieving food security. The major objectives include, a) to analyze the scientific literature available on RA, b) to examine research gaps and methodological limitations in research work, and c) to identify opportunities for adopting RA in developing countries like Pakistan.

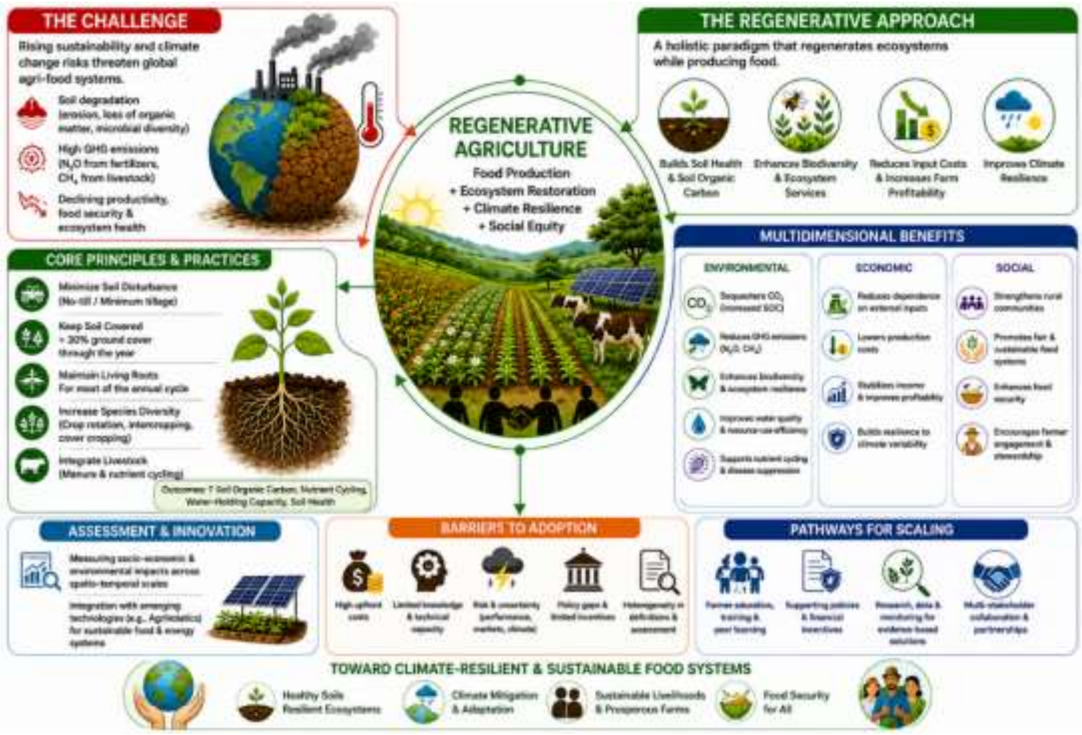


*Figure 2. Figure demonstrates how regenerative agriculture transforms conventional agri-food systems into climate-resilient and sustainable ecosystems through ecological restoration, carbon sequestration, biodiversity enhancement, and integrated socio-economic pathways.*

*Source: The image has been created using Canva based on the information presented in the published literature*

## 2. Review Methodology

This review employs a narrative synthesis approach, systematically analyzing existing research on RA. It explores various keyword combinations, including "regenerative agriculture," "RA and climate resilience," "RA and carbon sequestration," "RA and soil health," and "sustainable food systems," with an emphasis on Pakistan. The selected topics are based on scientific relevance and include research articles, review papers, peer-reviewed journal articles, research reports, and some policy documents identified through searches on Google Scholar, Web of Science, Scopus, ScienceDirect, Elsevier, JSTOR, Wiley Online Library, SpringerLink, and Taylor and Francis primarily from 2017 to 2025. Grey literature sources, such as IFOAM, were also useful. The focus is on studies that discuss the benefits and challenges of adopting RA in developing countries, particularly Pakistan, and those presenting quantitative evidence on RA impacts. The literature is thematically synthesized to highlight key trends, research gaps, benefits, limitations, and future directions of RA.

## 3. Foundational Principles of Regenerative Agriculture

### 3.1 Minimum Soil Disturbance

Regenerative agriculture (RA) is built around core ecological logic, centering restoration of soil function to promote desired production system resilience while minimizing reliance on off-site inputs. RA is also largely aimed at mitigating the soil disturbance of conventional agricultural practices that literally shatter aggregates (and, as such, further promotes faster mass microbial colonization and loss of organic matter), while creating a total habitat discontinuity in space, if not time itself (Rhodes, 2017). One of the pillars of conservation or zero-tillage systems is maintaining soil structure and promoting carbon capture. Research has additionally discovered that the use of cropping techniques such as reduced disturbance promotes soil aggregation, enhances infiltration and biological activity while also pre-conditioning soils for stable crop production with lower greenhouse gas emissions (Gordon et al., 2022).

### 3.2 Permanent Soil Cover

Another core principle is to always keep soil covered, most often achieved with a cover crop and/or mulch or by leaving residue on the soil. Permanent or near-permanent surface cover protects soil from erosion and dampens temperature fluctuations that can trigger destabilizing processes, while also providing organic substrates for microbial activity (Adetunji et al., 2020). Cover crops, in particular, provide a pathway for root exudates that stimulate microbial metabolism and help decompose large organic molecules into stabilized soil-carbon stocks. Given the increasing variability in climate (Koudahe et al., 2022), enhancing soil and climate protection by improving nutrient cycling efficiency through carbon inputs is crucial.

### 3.3 Biodiversity Enhancement

Additionally, as with regenerative systems, maximizing plant diversity in time and space is emphasized through diversified rotations, intercropping, and agroforestry configurations. Biodiversity is not simply treated as a conservation objective but has functional attributes that drive agroecosystem function. Plant assemblages composed of diverse species produce heterogeneous residue inputs, which can support greater diversity and a larger number of microbial niche environments in the soil, thereby enhancing beneficial insects that support biological pest suppression (Kidane et al., 2019). Based on global field experiments, large-scale syntheses provide evidence of the power of diversified cropping arrangements to enhance predator and parasitoid communities while simultaneously lowering pest pressure, highlighting biodiversity as a major driver of ecological regulation in farming systems (Chen et al., 2022).

### 3.4 Integration of Livestock

RA is characterized by improved integration of livestock with cropping enterprises. Adaptive multi-paddock grazing and other well-managed rotational grazing systems recycle nutrients, stimulate regrowth of grazed grasses, and enhance soil biological activity by depositing manure from animals or root turnover. Livestock integration reconnects often decoupled nutrient loops in monoculture systems, fostering more circular soil-nutrient economies. Paired with crop rotations and cover cropping, it accelerates soil organic matter buildup and boosts productivity (Sher et al., 2024).

### 3.5 Reducing Synthetic Inputs

Another key aspect is minimizing chemical inputs and emphasizing biologically driven nutrient cycling through organic amendments, biological nitrogen fixation, and microbially mediated nutrient transformations. This approach emphasizes restoring self-regulating processes in soils rather than relying solely on external inputs (Moodley et al., 2024). Over time, this biologically intensive management cannot only improve nutrient-use efficiency and reduce losses of fertilizer and pesticides into the environment but also increase farm-level economic resilience (Grelet et al., 2021). Table 1 below presents various impacts of regenerative agriculture

Table 1: Evidence-Based Impacts of Regenerative Agriculture Across Agroecosystems

| Component | Reported Benefit | Contradictions / Limitations | Key References |
|---|---|---|---|
| Soil Organic Carbon | Increase under reduced tillage and cover crops | Saturation limits; slow accumulation | Lal (2020); Villat and Nicholas (2024) |
| Crop Yield | Stable or improved long-term | Short-term yield decline is common | Kumar et al. (2024); Gordon et al. (2022) |
| Biodiversity | Enhanced microbial and insect diversity | Depends on the system diversity level | Chen et al. (2022); Grelet et al. (2021) |
| Water Retention | Improved infiltration and moisture holding | Soil-type dependent | Koudahe et al. (2022); Xu et al. (2019) |
| Carbon Sequestration | Potential climate mitigation | Measurement uncertainty; reversibility | Wiltshire and Beckage (2022); Rehberger et al. (2023) |
| Input Reduction | Lower fertilizer/pesticide use | Requires knowledge-intensive management | Vamshi et al. (2024); Moodley et al. (2024) |

The mechanistic pathways used in regenerative agriculture are summarized in Table 2 highlighting their limitations and benefits to the ecosystem.

Table 2: Mechanistic Pathways of Regenerative Practices

| Practice | Mechanism | Ecosystem Outcome | Limitation | References |
|---|---|---|---|---|
| Cover Crops | Root exudates feed microbes | Increased SOM and nutrient cycling | Water competition | Koudahe et al. (2022) |
| No-Tillage | Reduces soil disturbance | Carbon retention | Weed pressure | Gordon et al. (2022) |
| Crop Rotation | Diversifies inputs | Pest suppression | Requires planning | Chen et al. (2022) |
| Livestock Integration | Nutrient recycling | Soil fertility improvement | Management complexity | Sher et al. (2024) |
| Organic Amendments | Adds carbon substrates | Microbial growth | Variable quality | Xu et al. (2019) |

## 4. Environmental Benefits of Regenerative Agriculture

### 4.1 Soil Organic Matter Improvements

Regenerative agriculture (RA) emphasizes building soil organic matter (SOM) through practices such as cover cropping, reduced tillage, diversified rotations, and organic amendments. Additional examples of sustainable production systems (SPS), supported by empirical evidence showing measurable SOM gains under regenerative management, have emerged, and these practices improve soil aggregation, nutrient cycling, and biological activity indicative of healthy ecosystems (Colley et al., 2020). Recent meta-analyses show that conservation and regenerative practices, particularly cover cropping and organic inputs, can substantially increase soil carbon and microbial biomass compared with conventional systems (Torrús-Castillo et al., 2025). These functional enhancements are significant because SOM fractions such as particulate organic matter (POM) and microbially derived carbon help regulate nutrient retention and stabilize soil structure. The gains in SOM, as well as their magnitude and persistence, are context-dependent on baseline soil conditions, climate, management intensity, and elapsed time since adoption, which motivates the need for long-term monitoring to confirm the durability of benefits.

### 4.2 Carbon Sequestration Potential

Enhanced soil carbon sequestration is a major climate-related promise of regenerative systems. As reported in contemporary reviews and modeling studies, regenerative practices can cumulatively increase soil organic carbon stocks by increasing plant inputs (i.e., labile carbon supply), reducing disturbance, and fostering microbial stabilization pathways (Xu et al., 2019). Previous studies have shown that many practices affect land use and soil carbon sequestration synergistically or additively, such as cover cropping alongside agroforestry or extensive livestock compared with single interventions. This work suggests that at larger scales, diversification-based systems can improve a multitude of soil quality indicators and carbon sequestration over time, providing possible mitigation to climate change. Sequestration rates across sites differ substantially and depend greatly on the (sometimes fine grained) details of measurement; this has led recent literature to suggest standardized verification frameworks rather than short-term trials alone (Villat and Nicholas, 2024).

### 4.3 Biodiversity and Pest Resilience

Regenerative management is closely linked to higher levels of above- and below ground biodiversity, enabling ecological pest regulation and system resilience. Across systems, lower chemical disturbance, crop diversity, and organic matter inputs enhance soil microbial biomass, enzyme activity, and functional diversity. Microbial communities improve soil health, enhance nutrient cycling, and suppress disease, while diversified plant systems promote populations of natural enemies that can help regulate pest outbreaks in crops. Evidence from long-term diversification studies shows that these improvements in ecosystem services accrue, with more substantial gains in biological community metrics. Even with the positive trends described above, outcomes depend on whole-system implementation; opting only for piecemeal adoption of isolated practices may yield weak or inconsistent responses in biodiversity (Torrús-Castillo et al., 2025).

### 4.4 Water Retention and Soil Physical Benefits

Regenerative systems generally enhance key soil properties, such as aggregate stability, porosity, and infiltration capacity, by promoting organic matter buildup and reducing mechanical disturbance. Higher SOM increases soil water-holding capacity and reduces bulk density, which is especially helpful in coarse-textured or degraded soils. Cover crops, when combined with organic practices, can improve soil water retention, but their success is limited even over short timeframes relative to soil age (Rhodes, 2017). However, hydrological contributions are not homogeneous nor effective without higher soil textures achieved through amendment strategy and prevalent rainfall regime while also requiring continual regenerative management across timescales.

### 4.5 Reduced Synthetic Chemical Inputs and Co-benefits

One of the hallmarks of regenerative agriculture is a growing reduction in reliance on synthetic fertilizers and pesticides, replaced instead by biologically mediated nutrient cycling and ecological pest management. Replacements with composts, manures, variable rotates and organic tops can increase the natural prosperity of soil while reducing environmental risks. When implemented as a suite of practices, regenerative organic systems have been reported to improve soil biogeochemistry and ecosystem service provision (Esposito et al., 2018; Francis et al., 2005). However, reducing external inputs usually take time and reworking of these systems into one that is still productive. As such, outcomes are diverse based on farmer capacity and type of crop cultivated, as well as local agro-ecologies, suggesting that regenerative agriculture should be viewed as a systems approach rather than an unchanging set of prescriptive practices (Vamshi et al. 2024).

Adopting RA is essential for developing countries dealing with issues like land degradation, climate change, falling soil fertility, water shortages, and other challenges. Pakistan exemplifies this, with many of these problems endangering its productivity and food security. Therefore, Table 3 outlines the challenges and potential solutions involving RA that could be useful for its implementation in Pakistan.

Table 3: Relevance of Regenerative Agriculture in Pakistan

### 4.6 Quantitative Synthesis of Regenerative Agriculture Outcomes

| Challenge | RA Solution | Feasibility | References |
|---|---|---|---|
| Soil degradation | Organic amendments | High | Lal (2020) |
| Water scarcity | Improved infiltration | Moderate | Xu et al. (2019) |
| High input cost | Reduced fertilizers | High | Vamshi et al. (2024) |
| Farmer awareness | Extension services | Low | Rehberger et al. (2023) |
| Climate variability | Diversification | High | Kumar et al. (2025) |

In order to proceed beyond qualitative synthesis, a semi-quantitative meta-analysis was derived from percentage differences in recent peer-reviewed literature comparing regenerative and conventional systems. Effect sizes were standardized using relative percentage differences, given that strict meta-analytic standardization was not possible due to methodological discrepancies.

Analyses focusing on soil or ecological indicators across multiple studies linked regenerative practices to beneficial effects, while agronomic outcomes were variable (Grelet et al., 2021). Song et al. (2016) stated that the specific contributions of soil organic matter (12–35%), microbial biomass carbon (20–60%) and water infiltration capacity (15-40) were higher than under conventional systems.

However, crop yields ranged from 10% lower to 15% higher, mainly during transitional states. These results align with global syntheses show that despite the many ecological benefits of regenerative practices, they have a relatively small effect on productivity (at least at the field level). This highlights the necessity of assessments over long time frames. The quantitative effects of regenerative agriculture are given in Table 4 below.

Table 4: Quantitative Effect Sizes of Regenerative Agriculture

| Parameter | Effect Size (% Change vs Conventional) | Interpretation | References |
|---|---|---|---|
| Soil Organic Carbon | +12 to +35% | Strong improvement | Lal (2020); Villat and Nicholas (2024) |
| Microbial Biomass | +20 to +60% | Highly responsive | Grelet et al. (2021) |
| Water Infiltration | +15 to +40% | Improved hydrology | Xu et al. (2019) |
| Yield | −10 to +15% | Variable | Pittelkow et al. (2015) |
| Input Cost | −20 to −50% | Reduced inputs | Vamshi et al. (2024) |
| Biodiversity Index | +25 to +70% | Strong ecological benefit | Chen et al. (2022) |

While these positive trends are promising, effect sizes vary considerably across agroecological contexts, and many studies lack long-term replication. This limits the generalizability of the findings and underscores the importance of establishing standardized frameworks for meta-analyses.

## 5. Limitations and Challenges

While it is frequently characterized as a boon for climate-resilient food systems, several structural and empirical challenges make excessive optimism unwarranted. The absence of a universally accepted definition is a primary challenge, as scholars and industry participants mean something totally different by it, and pursue sustainability at will. The variety of how they perform, the data that feeds them, and their capabilities make it significantly more difficult to establish common procedures or accreditations throughout a field and infrastructural stack. There are major economic barriers to the transition, including substantial upfront costs for soil and crop management, uncertain short-run payoff timelines (even if longer-run benefits materialize), and potential production declines in certain sectors in the mid-term as soil biological processes reach a new equilibrium. These factors are obstacles to adoption and pose numerous financial challenges (Kumar et al., 2025). Regenerative systems are idiosyncratic, management-sharing, and require specialized ecological knowledge (through extensive training of farmers) as well as assistance – in other words, they scale down to economies simply due to a lack of capacity. While there are many case studies demonstrating positive environmental outcomes of agroecological approaches, skeptics have countered that empirical evidence over time regarding yields and profits, as well as climate benefits, is incomplete and context sensitive. Standardized, multi-year monitoring frameworks (Wiltshire and Beckage, 2022) are rarely in place to meet this demand. In addition, many developing country policies and market systems to establish high-value agriculture fall short of expectations due to underfunded research programs, poor institutional coordination restricting farmer participation, or ineffective access mechanisms for most smallholders linking them with more lucrative markets or certification systems (Rehberger et al., 2023). In our view, regenerative agriculture should be regarded as a public good in progress rather than a universal or one-size-fits-all solution. Accurate, well evidence-based descriptions of preventive measures alongside supportive legal frameworks and ongoing capacity building are key.

Despite RA's increasing significance as a sustainable method for enhancing food security and tackling climate variability, the existing evidence is quite fragmented with diverse methodologies. Most studies focus on short-term experiments using inconsistent indicators, which complicate direct comparisons. Additionally, claims about climate mitigation and carbon sequestration are uncertain, as results can differ depending on climate, soil types, and agricultural practices. Therefore, long-term, multi-location studies are essential to accurately identify the specific benefits RA can provide for different sites and regions.

## 6. Future Research Directions

To help move the field of regenerative agriculture from conceptual potential to scalable, evidence-based solutions, future research should focus on developing a more robust empirical and practical basis for understanding several aspects. Primary goals of this work would include long-term, comparative trials across a range of agroclimatic zones to assess sustainability and resilience traits as well as relative economic performance compared with conventional management over decadal timeframes the slow provision (and spatially variable nature) in the delivery water storage or carbon accumulation writ large must be captured. This relates to the necessity of quantifying soil carbon dynamics in local settings, especially in Pakistan and other comparable developing-country environments that have baseline soils, management histories, and rates of degradation more akin to those of temperate research sites. The systematic measurement and modeling will also help in credible entry into the carbon market. Another issue regarding the aforementioned is the economic modelling of transition phases (e.g., analyses that are typically geared towards short-term costs, yield ranges, and long-run profitability under regenerative scenarios, with poverty due to business instruments undervaluing ecosystem service benefits). There lies a frontier for high-impact research at the juncture of regenerative biology and technology that merges foundations in soil ecology with principles emerging from soil digital (real-time health monitoring, sensor networks) and precision agronomy to drive data-driven decision-making that addresses input inefficiencies while maximizing execution efficiency. At present, policies and regulations tend to favor conventional practices, so there is an important need for policy-incentive design studies that can identify institutional mechanisms, subsidy structures or market incentives which align farmer decision-making with regenerative outcomes. Similarly, investigating nano-enabled regenerative inputs: slow-release nutrient carriers or nano sensors for real-time monitoring of soil properties could provide new opportunities to promote nutrient cycling and soil biology, establishing an interdisciplinary frontier based in advanced materials science as applied to regeneration systems design.

### 6.1 Regenerative Agriculture in Pakistan: Contextual Evidence and Implementation Challenges

In Pakistan, over 60% of soils are degraded, with organic matter levels generally below 1%. In this regard, regenerative agriculture is especially relevant as a solution (Islam, 2025). Published evidence from Pakistan shows an increase in soil organic carbon (SOC) under conservation agriculture practices from 0.1% to 3% over five years in Punjab and Khyber Pakhtunkhwa, which is encouraging; along with better water-use efficiency across provinces, this proves a promising scenario too (Jamil et al., 2025). Like wheat, zero-tillage intensity in water-scarce conditions facilitated yield maintenance and resource savings of 20–30%. In most instances, however, resilient varieties remain below 15% adoption, as farmers are not aware of climate change impacts and adaptation options; extension services have limited reach; and policy assistance is misaligned (Khan et al., 2025).

While conceptually, RA is feasible in Pakistan, it needs to be designed while considering the prevailing institutional arrangement, which can enable its adoption. Few evidences of regenerative practices in Pakistan are presented in Table 5 below.

Table 5: Evidence of Regenerative Practices in Pakistan

| Practice | Region | Observed Impact | Limitation | References |
|---|---|---|---|---|
| Zero Tillage Wheat | Punjab | Yield stability, cost reduction | Weed control issues | Saleem et al., 2022; Naz et al., 2022 |
| Crop Rotation | KP | Improved soil fertility | Knowledge gap | Masud et al., 2023; Afghan et al., 2024 |
| Organic Amendments | Sindh | Increased SOM | Input availability | Saleem et al., 2024 |
| Cover Crops | Punjab | Improved soil moisture | Water competition | Saeed et al., 2023 |

## 7. Conclusion

Although the literature indicates that RA can play a key role in enhancing soil health and ecosystems, and in addressing climate variability, its benefits are highly context-dependent and cannot be universally applied across all agro-ecosystems. Many comparative studies and syntheses have linked restorative practices (cover cropping, reduced tillage, organic amendments and diverse trader) to soil structure quality improvements via their influence on physical axes impacting bulk densities whereby SOC stocks are heightened but end up enhancing the dynamics of water retention itself the resilience afforded over-time relative both directly as well through multiple benefits derived from conventional management spanning all features requiring assessments down 0-120 cm depth germplasm sufficient cultivars ameliorating abiotic stressors amongst others. At the same time, there is an ongoing discussion regarding whether regenerative agriculture can deliver large-scale climate mitigation given persistent systematic worries about soil carbon permanence, lack of long-term evidence and high variability in sequestration rates across ecosystems. Definitional ambiguity and economic transition costs, knowledge gaps in the science of regeneration, and more broadly applicable policy barriers to adoption or scaling; these all pose significant practical challenges for regenerative systems supporters. Perhaps most notably, experimental designs must contend with these limits by means of standardized long-term trials, integrated carbon measurement at scale and a new economic modelling framework paired to sound policy design that aligns incentives with ecological outcomes. To wrap up, even when put under the scientific microscope and realistically contextualized in practice, regenerative agriculture is no silver bullet; it is not a singular call to action for our soil, climate and food systems–it's yet another science-reliant point of view which its embodiment necessitates deep intersectionality between practices with local level adaptation driven by investigations. Therefore, future research should focus on conducting long-term, region-specific experiments using standardized assessment frameworks to support context-specific adoption pathways.

### Declaration of Generative AI and AI-Assisted Technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation, writing, or editing of this manuscript. The authors maintained complete responsibility and oversight throughout the research and writing process, and assume full accountability for the content of the published work.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**References**

Adetunji, A. T., Ncube, B., Mulidzi, R., and Lewu, F. B. (2020). Management impact and benefit of cover crops on soil quality: A review: *Soil and Tillage Research*, *204*, https://doi.org/10.1016/j.still.2020.104717.

Afghan, S., Khan, M. E., Verma, K. K., and Nikpay, A. (2024). Crop rotation and intercropping of sugarcane in Pakistan. In *Biotechnological Transformation for Sugarcane Management* (pp. 167-209). Apple Academic Press. https://doi.org/10.1201/9781003536376.

Akhil, K., and Sowjanya, J. (2025). Revitalizing Soil Health through Regenerative Agriculture: History, Principles, Practices, and Challenges. *International Journal of Environment and Climate Change*, *15*(8), 249-262. https://doi.org/10.9734/ijecc/2025/v15i84969.

Chen, L., Rejesus, R. M., Aglasan, S., Hagen, S. C., and Salas, W. (2022). The impact of cover crops on soil erosion in the US Midwest, *Journal of Environmental Management*, *324*, https://doi.org/10.1016/j.jenvman.2022.116168.

Choudhari, P., Pasumarthi, R., Patil, M., Karanam, P., Singh, R., Sawargaonkar, G., and Jat, M. L. (2024). Compendium of regenerative agriculture: A guide to sustainable and resilient production systems. Compendium of Regenerative Agriculture: A Guide to Sustainable and Resilient Production Systems, Patancheru 502 324, Telangana, India: International Crops Research Institute for the Semi-Arid Tropics. 48 pp.

Colley, T. A., Olsen, S. I., Birkved, M., and Hauschild, M. Z. (2020). Delta Life Cycle Assessment of Regenerative Agriculture in a Sheep Farming System. *Integrated Environmental Assessment and Management*, *16*(2), 282–290. https://doi.org/10.1002/IEAM.4238

Ghosh, S., Saha, A., Kumar, S., and Pathania, S. (2024). Regenerative agriculture for climate change mitigation and food security. In *Regenerative agriculture for sustainable food systems* (pp. 83-133). Singapore: Springer Nature Singapore.

Gordon, E., Davila, F., and Riedy, C. (2022). Transforming landscapes and mindscapes through regenerative agriculture. *Agriculture and Human Values*, *39*(2), 809-826. https://doi.org/10.1007/s10460-021-10276-0

Grelet, G., Lang, S., Merfield, C., Calhoun, N., Robson-Williams, M., Horrocks, A., ... and Kerner, W. (2021). Regenerative agriculture in Aotearoa New Zealand–research pathways to build science-based evidence and national narratives. Next Foundation.

https://www.landcareresearch.co.nz/publications/regenag/regenerative-agriculture-white-paper sets-out-pressing-research-priorities/

Islam, S. (2025). Agriculture, food security, and sustainability: a review. *Exploration of Foods and Foodomics*, *3*, https://doi.org/10.37349/eff.2025.101082.

James, J., Choudhary, P., Singh, S., Archana, Sharma, N. (2024). Regenerative Agriculture: Potential, Progress, Opportunities, and Challenges. In: Kumar, S., Meena, R.S., Sheoran, P., Jhariya, M.K. (eds) *Regenerative Agriculture for Sustainable Food Systems. Springer, Singapore*. https://doi.org/10.1007/978-981-97-6691-8_3.

Jamil, U., and Pearce, J. M. (2025). Regenerative agrivoltaics: integrating photovoltaics and regenerative agriculture for sustainable food and energy systems. *Sustainability*, *17*(11), https://doi.org/10.3390/su17114799.

Koudahe, K., Allen, S. C., and Djaman, K. (2022). Critical review of the impact of cover crops on soil properties. *International Soil and Water Conservation Research*, *10*(3), 343-354. https://doi.org/10.1016/j.iswcr.2022.03.003 .

Kidane, M., Bezie, A., Kesete, N., and Tolessa, T. (2019). The impact of land-use and land-cover (LULC) dynamics on soil erosion and sediment yield in Ethiopia. *Heliyon*, *5*(12). https://doi.org/10.1016/j.heliyon.2019.e02981.

Khan, A. T., and Banik, D. (2025). Climate-Smart Agriculture: Pathways to Resilient Farming Systems. *Vigyan Varta*, *6*, 261-267. https://www.vigyanvarta.in/adminpanel/upload_doc/VV_0725_60.pdf .

Kumar, D., Sheoran, A., Balyan, V., Sharma, P., and Balyan, S. (2025). Regenerative Agriculture: Restoring Ecosystems¢ Resilience and Productivity: A Review. *Agricultural Reviews*, https://doi.org/10.18805/ag.r-2779

Kumar, S., Meena, R. S., Sheoran, P., and Jhariya, M. K. (2024). Regenerative Agriculture for Sustainable Food Systems. https://link.springer.com/book/10.1007/978-981-97-6691-8 pp 1-13.

Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of soil and water conservation*, 75(5), 123A-124A. https://doi.org/10.2489/jswc.2020.0620A.

Masud, H., Haseeb, A., Ahmed, U., Ullah, I., Ali, S., Ur, R. S., ... and Atif, M. (2023). Analyzing the Profitability of Crop Rotation Patterns in Peshawar, Pakistan. *Asian Journal of Advances in Research*, *6*(1), 589-599.

Moodley, V., Phophi, M. M., and Mafongoya, P. L. (2024). Regenerative agriculture: A paradigm shift for food production in South Africa. *Outlook on Agriculture*, *53*(4), 336-350. https://doi.org/10.1177/00307270241292085.

Naz, I., Ijaz, S. S., Habteselassie, M. Y., Ansar, M., and Khan, K. S. (2022). Impact of conservation tillage on organic matter dynamics in loess dryland soil, Punjab, Pakistan. *JAPS: Journal of Animal and Plant Sciences*, *32*(5). https://doi.org/10.36899/JAPS.2022.5.0534.

Rehberger, E., West, P. C., Spillane, C., and McKeown, P. C. (2023). What are the climate and environmental benefits of regenerative agriculture practices? an evidence review. *Environmental Research Communications*, *5*(5), 052001. https://doi.org/10.1088/2515-7620/acd6dc

Rhodes, C. J. (2017). The imperative for regenerative agriculture. *Science progress*, *100*(1), 80-129. https://doi.org/10.3184/003685017x14876775256165.

Saeed, M. Z., Hayat, H., Shafiq, F., and Tareen, W. U. H. (2023). Assessing the prospects and challenges of organic agriculture in the Pothwar region of Punjab, Pakistan. 1-7

Saleem, M. F., Ghaffar, A., Rahman, M. H. U., Imran, M., Iqbal, R., Soufan, W., ... and El Sabagh, A. (2022). Effect of short-term zero tillage and legume intercrops on soil quality and the agronomic and physiological aspects of cotton under an arid climate: land, *11*(2), 289. https://doi.org/10.3390/land11020289.

Saleem, S., Hassan, W., Adil, M., Leghari, A. M., Khaliq, M. A., Bukhar, M. A., and Bashir, S. (2024). Sustainable Management of Saline Soils by Using Organic and Inorganic Amendments: Implications for Wheat Growth and Production. *Plant and Environment*, *5*(01), 100-111. https://doi.org/10.54219/plantenviron.05.01.2024.453.

Shahriar, S., Corradini, M. G., Sharif, S., Moussa, M., and Dara, R. (2025). The role of generative artificial intelligence in digital agri-food. *Journal of Agriculture and Food Research*, *20*, https://doi.org/10.1016/j.jafr.2025.101787.

Sher, A., Li, H., ullah, A., Hamid, Y., Nasir, B., and Zhang, J. (2024). Importance of regenerative agriculture: Climate, soil health, biodiversity and its socioecological impact. *Discover Sustainability*, *5*(1), 462. https://doi.org/10.1007/s43621-024-00662-z.

Song, K., Yang, J., Xue, Y. *et al.* Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. *Sci Rep* **6**, 36602 (2016). https://doi.org/10.1038/srep36602

Torrús-Castillo, M., Macan, G. P. F., Landa, B. B., and Gómez, J. A. (2025). *Assessing the Impact of Six Years of Regenerative Agriculture on a Commercial Olive Orchard in Southern Spain*. https://doi.org/10.5194/egusphere-egu25-422

Vamshi, M., Jagadeesan, R., Lamani, H. D., Rout, S., VijayKumar, R., Jagadesh, M., and Sachan, K. (2024). The revolutionary impact of regenerative agriculture on ecosystem restoration and land vitality: A review. *Journal of Geography, Environment and Earth Science International*, *28*(4), 1-14. https://doi.org/10.9734/jgeesi%2F2024%2Fv28i4760.

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

Wiltshire, S., and Beckage, B. (2022). Soil carbon sequestration through regenerative agriculture in the U.S. state of Vermont. *PLOS Climate*, *1*(4), e0000021. https://doi.org/10.1371/journal.pclm.0000021

Xu, N., Bhadha, J. H., Rabbany, A., and Swanson, S. (2019). Soil Health Assessment of Two Regenerative Farming Practices on Sandy Soils. *Sustainable Agriculture Research*, *8*(4), 61. https://doi.org/10.5539/SAR.V8N4P61