Review Article

Revitalizing Soil Health Through Regenerative Agriculture: A Comprehensive Review

## Abstract

Soil health is the foundation of sustainable agricultural systems, influencing crop productivity, water dynamics, carbon sequestration and ecosystem stability. However, modern industrial agriculture has led to widespread soil degradation, erosion, loss of organic matter and declining microbial diversity. Regenerative agriculture (RA) is a holistic farming approach designed to restore soil health, enhance biodiversity and improve ecosystem resilience. As conventional agricultural practices have led to widespread soil degradation, climate change and biodiversity loss, RA offers a nature-based solution to mitigate these impacts while ensuring long-term food security. RA prioritizes key principles such as minimal soil disturbance, cover cropping, crop diversification, composting, rotational grazing and reduced synthetic inputs, all of which contribute to carbon sequestration, water conservation and soil fertility improvement. Despite its numerous benefits, the large-scale adoption of RA faces challenges, including economic barriers, knowledge gaps and policy constraints. Transitioning to RA often involves short-term yield declines and financial burdens, while the lack of standardized certification limits market access. However, research indicates that RA can significantly enhance soil organic matter, increase drought resilience and improve farm profitability over time. Future efforts should focus on research funding, policy incentives and farmer education programs to accelerate RA adoption. By integrating science-backed regenerative practices into agricultural systems, RA has the potential to combat climate change, restore degraded lands and create a more resilient and sustainable food system for future generations. This review explores the key principles, techniques, benefits, challenges and future directions of RA in revitalizing soil health and ensuring long-term agricultural sustainability.

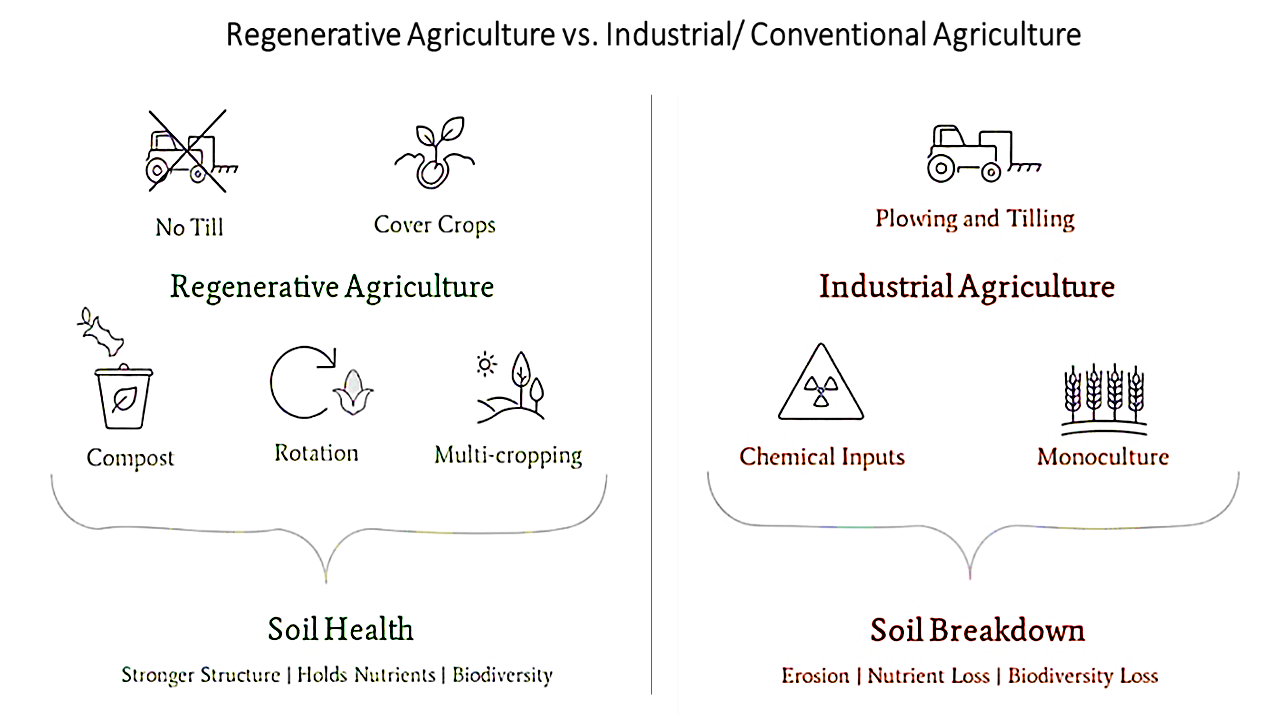
**Keywords**: **Soil Regeneration, Carbon Sequestration, Regenerative Agriculture, Soil Health, Biodiversity Enhancement, Sustainable Farming, No-Till Agriculture** and **Water Conservation.**

## 1. Introduction

Soil is often referred to as the “Skin of the Earth”, covering the planet and supporting plant life, water filtration, carbon storage and biodiversity. However, unsustainable land use, climate change and industrial agriculture have led to a global soil crisis. According to the Food and Agriculture Organization (FAO), approximately 33% of the world's soils are degraded, with nearly 24 billion tons of fertile soil lost annually due to erosion (Schreefel *et al*., 2020). If these trends continue, 90% of soils may become degraded by 2050, jeopardizing global food security and ecosystem stability (Jayasinghe *et al*., 2023).

Soil degradation occurs due to erosion, loss of organic matter, compaction, salinization, acidification, and chemical contamination. These issues are largely driven by modern intensive agriculture, deforestation, urbanization and industrial pollution (Newton *et al*., 2020). The consequences are severe, including declining agricultural productivity, increased desertification, water storage issues, loss of biodiversity and a significant contribution to climate change. As soils lose their organic matter, they also lose their ability to retain nutrients, leading to declining crop yields. Farmers then become increasingly dependent on chemical fertilizers, which further deplete natural soil ecosystems (Giller *et al*., 2021). The loss of soil microbial diversity due to pesticide and herbicide use further compounds the problem, as beneficial microbes are responsible for nutrient cycling, organic matter decomposition, and plant resilience (Jayasinghe *et al*., 2023). Erosion is another major concern, as it removes the nutrient-rich topsoil essential for plant growth. This process, accelerated by deforestation, overgrazing and intensive plowing, leads to desertification, where once-fertile lands turn barren (LaCanne and Lundgren, 2018). Nearly 500 million people worldwide are affected by desertification, particularly in arid and semi-arid regions where agriculture is a primary livelihood. Degraded soils also lose their ability to absorb and store water, making regions more susceptible to drought and flooding (Schreefel *et al*., 2020). This instability in water cycles has contributed to crop failures, food shortages and economic instability, especially in regions already experiencing climate change-induced droughts (Newton *et al*., 2020).

Another major concern is the impact of industrial agriculture on soil health. The shift toward monocropping-growing the same crop year after year on the same land-has severely depleted soil nutrients, leading to an overreliance on synthetic fertilizers (Khangura *et al*., 2023). The excessive use of chemical pesticides and herbicides has also reduced soil biodiversity, harming beneficial organisms such as earthworms, nitrogen-fixing bacteria and mycorrhizal fungi (Jayasinghe *et al*., 2023). Additionally, conventional tillage practices disturb soil aggregates, leading to compaction, poor aeration and increased susceptibility to erosion (Fig. 1) (Newton *et al*., 2020).



**Fig. 1 Depicting Regenerative Agriculture vs. Industrial/ Conventional Agriculture**

(Source: Kim *et al*., 2022; modified by K. Akhil, 2025)

Given the alarming rate of soil degradation, sustainable and regenerative agricultural practices are needed to restore soil health and ensure long-term food security. Regenerative agriculture (RA) provides a nature-based solution to reverse soil damage, improve soil function and increase farm resilience. Unlike conventional methods, which rely on chemical inputs to maintain yields, RA prioritizes restoring soil organic matter, enhancing microbial life and increasing soil structure stability (Schreefel *et al*., 2020). These practices contribute to water conservation, erosion prevention, carbon sequestration, and climate change mitigation. RA promotes cover cropping, crop rotations, no-till farming, compost application, agroforestry and holistic grazing systems, all of which work together to regenerate soil ecosystems (Newton *et al*., 2020). By improving soil carbon sequestration, RA helps mitigate climate change by pulling atmospheric carbon dioxide (CO₂) into the soil (Rhodes, 2017). Research indicates that increasing soil organic matter by just 1% can sequester an additional 3 tons of carbon per hectare annually, significantly reducing greenhouse gas emissions (LaCanne and Lundgren, 2018). Moreover, RA reduces reliance on synthetic inputs, helping farmers save on costs while maintaining or even increasing long-term crop productivity (Jayasinghe *et al*., 2023). The ability of RA to restore soil fertility, increase drought resilience and reduce erosion makes it one of the most effective solutions for degraded lands (Schreefel *et al*., 2020).

## 2. History of Regenerative Agriculture

Regenerative agriculture (RA) is a concept rooted in the broader sustainability movement but has evolved as a distinct agricultural paradigm over the decades.

Several historical events shaped the need for regenerative farming (Heckman *et al*., 2006):

* The Dust Bowl (1930s, USA): Extensive tillage and monoculture farming led to severe soil erosion, prompting the establishment of the Soil Conservation Service (now NRCS) in 1935 to promote soil conservation techniques
* The Green Revolution (1950s-1970s): While boosting crop yields through chemical fertilizers, pesticides, and mechanization, the Green Revolution also resulted in soil degradation, loss of biodiversity and chemical dependency (LaCanne and Lundgren, 2018) ​
* Rise of Organic Agriculture (1960s-1970s): Concerns about soil degradation and environmental pollution led to the development of organic farming, championed by pioneers like J.I. Rodale and Albert Howard, whose principles heavily influenced regenerative agriculture (Rodale, 1983)

The term “Regenerative Agriculture” was first introduced in the early 1980s by Robert Rodale, founder of the Rodale Institute, who emphasized that agriculture should go beyond sustainability to actively regenerate ecosystems and rural communities (Rhodes, 2017).

Rodale outlined key RA principles, which included (Rodale, 1983):

1. Soil Fertility Management through composting, green manure, and cover cropping.
2. Integrated Pest Management (IPM) to reduce reliance on chemical pesticides.
3. Crop-Livestock Integration for nutrient cycling and improved soil health.
4. Diversification of Cropping Systems to enhance resilience and biodiversity (Rhodes, 2017)​.

Although the principles of RA gained some traction, policy frameworks in the 1980s and 1990s largely focused on organic and conservation agriculture, with limited institutional support for RA-specific research and adoption (Kamenetzky and Maybury, 1989)​.

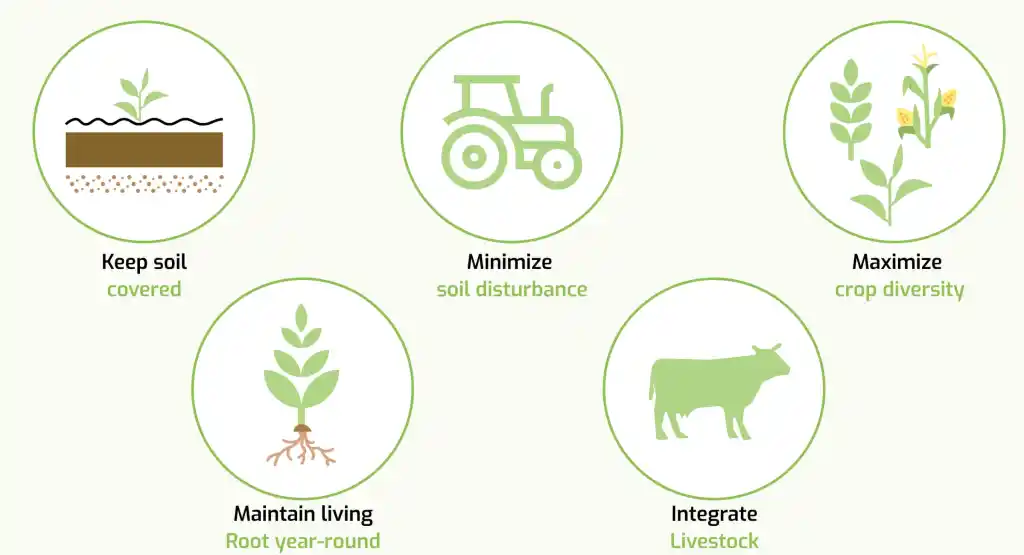
Resurgence and Growth in the 2000s-2010s (Pearson, 2007)

The 21st century saw a renewed focus on RA, driven by global challenges such as climate change, declining soil fertility, and biodiversity loss. Key milestones in this period included:

* The Intergovernmental Panel on Climate Change (IPCC) acknowledged RA’s potential for carbon sequestration and climate change mitigation, highlighting its role in regenerative soil management (IPCC, 2021)​.
* Corporations embraced RA: Companies like General Mills, Danone, and Patagonia invested in regenerative agriculture to reduce their carbon footprint and enhance supply chain sustainability (Giller *et al*., 2021)​.
* Regenerative Organic Certification (ROC) was launched in 2017 by the Rodale Institute, Patagonia, and Dr. Bronner’s, establishing RA as a market-driven movement with defined certification standards (Regenerative Organic Alliance, 2018)​.
* Growing Consumer Awareness: Consumers increasingly demanded sustainable and ethically produced food, driving market incentives for regenerative products (Pooreand Nemecek, 2018)​.

## 3. Principles of Soil Health in Regenerative Agriculture

RA is built upon key soil-regenerative principles (Fig. 2) that improve soil structure, organic matter content, and biological diversity:



**Fig. 2 Principles of Soil Health in Regenerative Agriculture (Source: Geopard Tech, 2024)**

### 3.1. Minimizing Soil Disturbance through Reduced Tillage

Conventional tillage disrupts soil aggregates and reduces microbial populations, making soil prone to erosion and compaction (Newton *et al*., 2020). Frequent tillage also disrupts fungal networks, such as mycorrhizal fungi, which play a crucial role in nutrient exchange between soil and plants (Rhodes, 2017).

Regenerative agriculture emphasizes no-till or reduced tillage methods to preserve soil integrity and microbial life. By reducing mechanical soil disturbance, farmers can maintain soil structure, increase organic matter retention, and promote soil biodiversity (Shah *et al*., 2017). No-till farming helps improve water retention, allowing soil to absorb and store moisture more effectively, which enhances crop resilience during drought periods (Newton *et al*., 2020). Additionally, reducing tillage decreases carbon loss from soil, helping with carbon sequestration and climate change mitigation (Elevitch *et al*., 2018).

### 3.2. Maintaining Permanent Soil Cover

Bare soil is highly susceptible to erosion, moisture loss and temperature fluctuations (Beman *et al*., 2011). When soil is left exposed, it becomes vulnerable to wind and water erosion, leading to the loss of essential nutrients and organic matter. Additionally, direct exposure to sunlight increases soil temperature fluctuations, which can negatively impact microbial activity and root health (Klopfenstein *et al*., 1997).

Regenerative agriculture promotes cover cropping and mulching as effective strategies to protect the soil, increase organic matter, and foster microbial diversity (LaCanne and Lundgren, 2018). Cover crops, such as legumes, grasses and clovers, help stabilize the soil, prevent erosion, and improve soil fertility by fixing nitrogen and adding organic matter. Mulching, on the other hand, provides a protective barrier that reduces evaporation, conserves moisture, and suppresses weed growth. By keeping the soil covered year-round, farmers can enhance soil structure, support beneficial soil microbes and create a more resilient farming system (Elevitch *et al*., 2018). This practice also reduces reliance on synthetic fertilizers and herbicides, contributing to a more sustainable and ecologically balanced agricultural system. Maintaining permanent soil cover is essential for long-term soil health, improved water retention, and increased climate resilience.

### 3.3. Enhancing Crop Biodiversity and Microbial Activity

Enhancing crop biodiversity is crucial for improving soil health, pest resistance, and ecosystem stability. Diverse cropping systems reduce soil nutrient depletion, enhance microbial diversity, and promote natural pest control. Instead of monocropping, regenerative agriculture encourages polycultures, intercropping and crop rotations, which improve nutrient cycling and resilience to climate stress (Rhodes, 2014).

RA emphasizes crop diversity through cover cropping, companion planting, and agroforestry systems, which create a balanced farm ecosystem (Khangura *et al*., 2023). Legumes, for example, fix nitrogen in the soil, while deep-rooted crops enhance carbon sequestration and water retention (Jayasinghe *et al*., 2023). These practices reduce dependency on chemical inputs, making farming systems more sustainable, productive, and climate-resilient.

### 3.4. Keeping Living Roots in the Soil Year-Round

Keeping living roots in the soil year-round is a key principle of regenerative agriculture, as roots help stabilize soil, support mycorrhizal fungi and enhance soil carbon storage (Schreefel *et al*., 2020). Continuous root presence prevents soil erosion, improves nutrient availability and fosters beneficial microbial activity (Coccina *et al*., 2019).

Regenerative agriculture promotes the use of cover crops and perennial crops, which maintain soil structure, enhance fertility and improve moisture retention (Newton *et al*., 2020). These crops provide a constant supply of organic matter, support soil microbial communities and reduce the need for synthetic fertilizers. By ensuring that roots remain in the soil throughout the year, regenerative farming builds long-term soil health, increases resilience to drought, and enhances carbon sequestration, contributing to a more sustainable and productive agricultural system (Ryan *et al*., 2012).

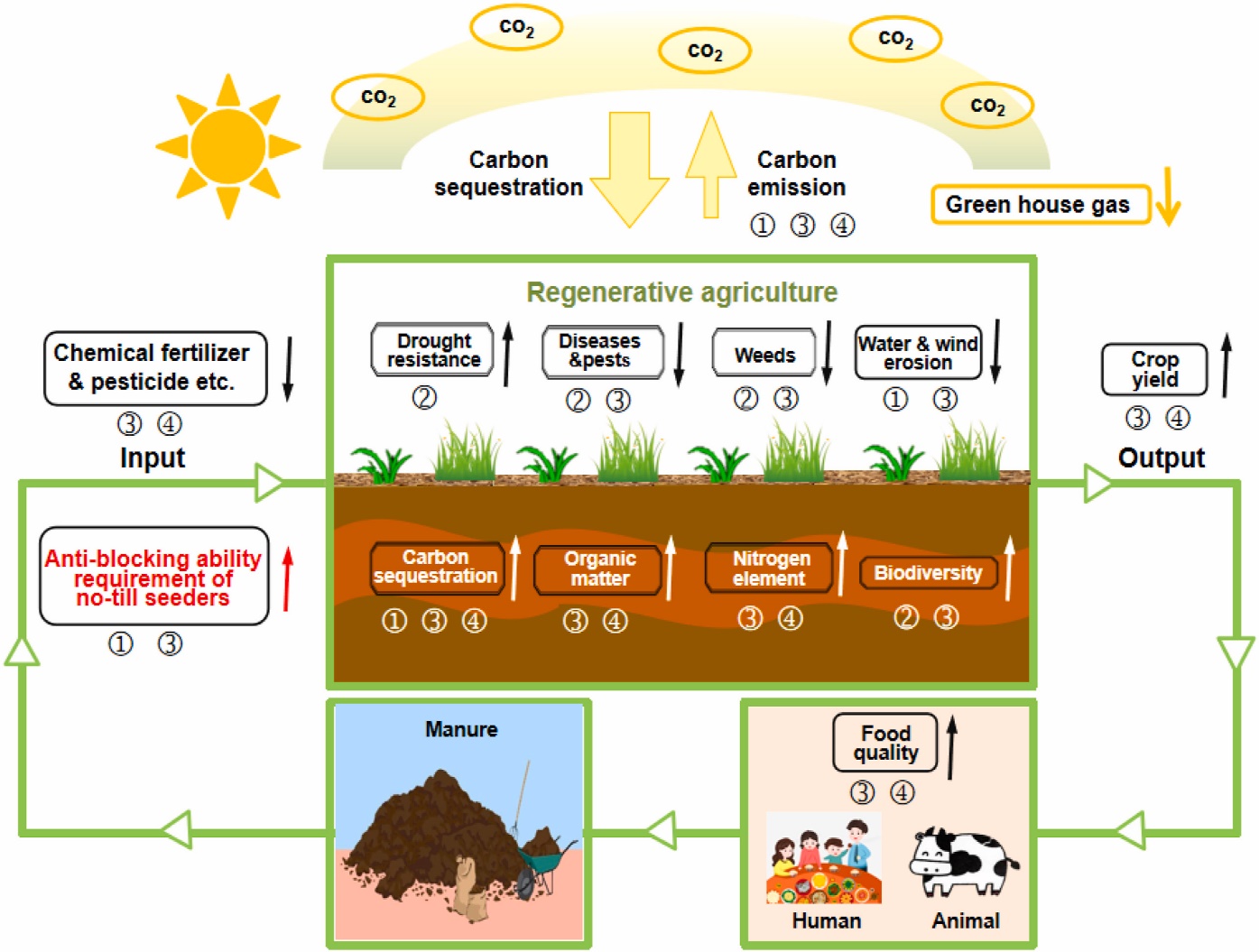
### 3.5. Integrating Livestock for Natural Fertilization

Integrating livestock for natural fertilization is a key regenerative agriculture practice, as well-managed grazing adds organic matter, stimulates plant growth and enhances soil microbial diversity (Rhodes, 2017). Livestock contribute to soil aeration and nutrient cycling by trampling plant residues and returning organic material to the soil (Giller *et al*., 2021). Manure serves as a natural fertilizer, supplying essential nutrients that improve soil fertility and structure, reducing reliance on synthetic fertilizers (LaCanne and Lundgren, 2018). Properly managed rotational grazing prevents overgrazing, allowing pastures to regenerate while enhancing biodiversity and soil health. By integrating livestock into cropping systems, regenerative agriculture improves soil organic matter, boosts microbial activity and enhances ecosystem sustainability, creating a self-sustaining and resilient farming system.

These principles work synergistically to revitalize soil function, making agricultural systems more resilient to climate change and environmental stressors (Giller *et al*., 2021).

## 4. Key Practices in Regenerative Agriculture (RA)

Regenerative agriculture (RA) is a sustainable approach that focuses on restoring soil health, enhancing biodiversity, and increasing ecosystem resilience. By integrating ecological principles with modern farming practices, RA promotes soil conservation, mitigates climate change, and supports long-term agricultural productivity. The conceptual framework of regenerative agriculture is illustrated in Fig. 3.



**Fig. 3** Conceptual framework of regenerative agriculture (RA), adapted from Wang *et al*. (2025). The framework illustrates the influence of four key RA practices: ① – no-till seeding, ② – crop rotation, ③ – ground cover (i.e., cover crops or residue mulching), and ④ – holistic grazing. The arrows indicate the direction of significant effects, where upward arrows (↑) represent positive impacts and downward arrows (↓) represent negative impacts of these practices (①–④) on the agroecosystem indicators shown in the surrounding boxes.

### 4.1. No Tillage / Minimum Tillage

Reducing or eliminating tillage helps preserve soil structure, prevent erosion, and improve soil carbon sequestration. No-till farming enhances soil microbial activity and increases organic matter, leading to improved soil fertility (Dalal *et al*., 1995)​. Research indicates that combining no-till with stubble retention increases soil organic carbon (SOC) by 2-5% over 19 years, compared to only 1.5% in conventional tillage systems (Somasundaram *et al*., 2017; Wang, Fu, Zhang, & Huang, 2021) ​. Long-term studies show that zero-tillage enhances carbon storage in tropical agriculture, providing greater climate change mitigation benefits (Cooper *et al*., 2021)​. The ability of no-till seeders is key to achieving effective no-till seeding technology (NST) for regenerative agriculture (RA) (He *et al*., 2018). To guide seeders and avoid stubble, automatic navigation methods have been developed, including touch-type sensors, machine vision systems, and GNSS-based positioning (Wang *et al*., 2020; Zhang and Guo, 2024). Recent studies have focused on crop stubble detection, target path tracking, path planning, and navigation control (Perez-Ruiz *et al*., 2012). A high-pressure air shooting (HPAS) device was also proposed for no-till seeding (Wang *et al*., 2020). Unlike conventional sowing with furrow openers and seed covering, HPAS enables sowing without seedbed preparation or covering (Wang *et al*., 2021). This integration reduces blockage, saves energy, and improves crop establishment under RA systems.

### 4.2. Stubble Retention

Stubble retention prevents wind erosion, improves soil moisture retention, and enhances nutrient cycling. Retaining crop residues returns nutrients to the soil, reduces water runoff and increases soil organic matter​. In sandy soils, stubble retention can reduce carbon loss by 3% at a 1m depth, significantly improving soil stability​. Studies confirm that combining no-till with stubble retention improves soil aggregate formation and microbial activity (Wakelin *et al*., 2007)​.

### 4.3. Diverse Crop Rotations

Crop rotation disrupts pest and disease cycles, reducing the need for chemical inputs (Blair and Crocker, 2000)​. Legume-based crop rotations enhance nitrogen fixation, increase soil carbon levels, and improve soil structure (Lopez-Bellido *et al*., 2020)​. A global meta-analysis showed that crop rotation, combined with no-till, significantly enhances soil carbon sequestration​ (Zhao *et al*., 2022).

### 4.4. Multispecies Cover Crops

Cover cropping protects soil from erosion, improves water infiltration, and enhances microbial activity. Multi-species cover crops increase soil organic matter, biological nitrogen fixation and beneficial microbial diversity (Kim *et al*., 2020)​. Long-term studies reveal that cover crops combined with reduced tillage can reduce greenhouse gas emissions by 10%​. Cover crops also contribute to carbon sequestration, with fine-textured soils benefiting the most from increased soil carbon storage​.

### 4.5. Intercropping

Intercropping improves nutrient balance and maximizes land use efficiency, leading to higher soil fertility and reduced erosion (Giller *et al*., 2021)​. This practice enhances microbial diversity, reduces pest outbreaks and improves overall crop resilience​. Research shows that intercropping systems contribute to greater carbon sequestration and improved water-use efficiency​.

### 4.6. Rotational Grazing

Properly managed rotational grazing prevents overgrazing, maintains pasture productivity, and increases soil organic carbon levels​.Manure from livestock enhances nutrient cycling, promotes microbial growth and improves soil structure (Rhodes, 2017) ​.Rotational grazing has been shown to increase carbon stocks by 25% compared to conventional grazing systems (Planisich *et al*., 2020)​.

### 4.7. Reducing Synthetic Inputs

Reducing chemical inputs minimizes soil and water contamination, leading to healthier soil microbiomes and improved crop resilience​. A shift from synthetic fertilizers to biological nutrient cycling reduces input costs and enhances long-term soil health​. Studies indicate that reduced pesticide use in RA systems leads to greater beneficial insect populations and pollinator activity​ (Campbell *et al*., 2017).

### 4.8. Composting and Use of Bio stimulants

Composting enriches soil organic matter, improves microbial biodiversity and enhances water retention (Rouphael *et al*., 2020)​.Biochar application boosts soil aeration, retains moisture and supports beneficial microbes (Rhodes, 2017) ​.Biostimulants, including microbial inoculants and organic amendments, improve plant growth and increase soil resilience against environmental stresses​ (Yakhin *et al*., 2017)​.

## 5. Benefits of Regenerative Agriculture for Soil Health

Regenerative agriculture (RA) is a sustainable farming approach that prioritizes soil restoration, biodiversity, and long-term ecosystem resilience. By focusing on soil health, RA delivers substantial environmental, agronomic and socioeconomic benefits (Lal, 2020).

### 5.1. Environmental Benefits

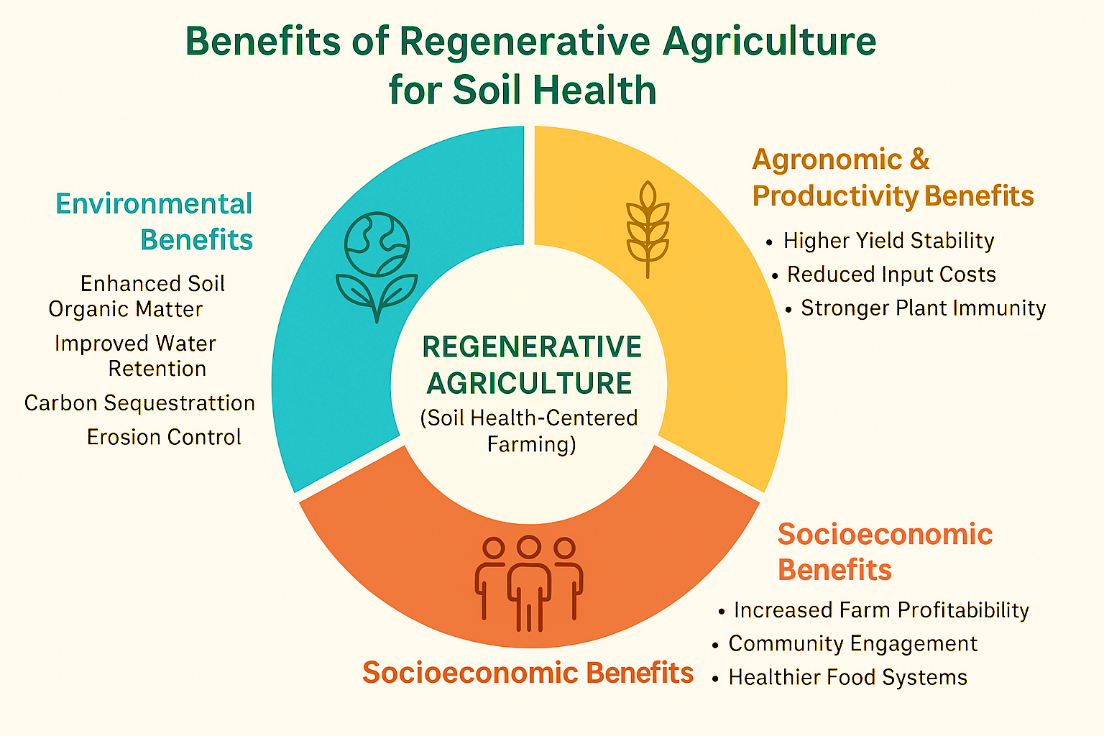
* Enhanced Soil Organic Matter (SOM): RA practices such as composting, biochar application and reduced tillage significantly increase SOM, leading to improved soil fertility, microbial diversity, and nutrient cycling (Khangura *et al*., 2023)
* Improved Water Retention: Organic matter-rich soils enhance water infiltration and retention, reducing surface runoff and increasing drought resilience (Jayasinghe *et al*., 2023). Studies show that regenerative farms exhibit up to 30% higher water infiltration rates than conventionally managed soils (Giller *et al*., 2021)
* Carbon Sequestration: No-till farming, agroforestry, and cover cropping enhance soil carbon sequestration, mitigating climate change impacts by drawing CO₂ from the atmosphere and storing it in the soil (Newton *et al*., 2020). RA systems can sequester up to 2.5 metric tons of CO2 per hectare annually (Lal, 2020)
* Erosion Control: Cover crops and mulching reduce soil erosion by protecting the soil surface from wind and water runoff, thereby preserving topsoil quality and reducing nutrient loss (Rhodes, 2017)

### 5.2. Agronomic and Productivity Benefits

* Higher Yield Stability: RA improves soil structure and moisture availability, ensuring stable crop yields even under extreme weather conditions (Rhodes, 2017). Studies indicate that RA-based systems can outperform conventional farming during droughts by maintaining higher soil moisture levels (Jayasinghe *et al*., 2023)
* Reduced Input Costs: By minimizing reliance on synthetic fertilizers and pesticides, RA lowers production costs while maintaining or even improving yields. A meta-analysis of RA practices found that farms saved up to 30% on input costs while maintaining competitive yields (Newton *et al*., 2020)
* Stronger Plant Immunity: Healthy soils enriched with organic matter support diverse microbial communities that enhance plant immunity and suppress pathogens, reducing the need for chemical disease management (Giller *et al*., 2021)

### 5.3. Socioeconomic Benefits

* Increased Farm Profitability: Farmers practicing RA experience long-term profitability through reduced input costs and enhanced soil productivity. Some studies suggest a 15-20% increase in net farm income due to improved resource efficiency and premium pricing for regeneratively grown produce (Jayasinghe *et al*., 2023)
* Community Engagement and Knowledge Sharing: Regenerative farms promote local food systems, strengthen farmer cooperatives, and facilitate peer-to-peer learning, creating resilient rural communities (Rhodes, 2017)
* Healthier Food Systems: Nutrient-dense crops grown under RA practices provide better food quality while reducing chemical residues in food products, enhancing consumer health (Newton *et al*., 2020)



**Fig. 4 Regenerative agriculture benefits** (Source: Kim *et al*., 2022; modified by K. Akhil, 2025)

## 6. Challenges and Future Directions of Regenerative Agriculture

Regenerative agriculture (RA) holds great potential for restoring soil health, improving biodiversity, and mitigating climate change, yet its widespread adoption faces several challenges. One of the primary barriers is the economic and transition costs, as farmers often experience short-term yield declines before the benefits of improved soil health become evident (Somasundaram *et al*., 2017)​. Additionally, the lack of financial incentives and policy support favors conventional farming, making it difficult for farmers to invest in regenerative practices (Rhodes, 2017)​. Knowledge gaps also hinder adoption, as there is limited long-term empirical research on RA’s scalability, carbon sequestration potential, and economic feasibility (Giller *et al*., 2021)​. Many farmers lack access to site-specific recommendations and technical training, which are necessary to transition from input-dependent conventional systems to biologically driven regenerative practices (Shalloo *et al*., 2004)​. Furthermore, market and policy barriers such as the absence of standardized RA certification systems prevent farmers from accessing premium markets, while corporate greenwashing undermines consumer trust in RA-labeled products (Jayasinghe *et al*., 2023)​. Farmers' dependence on agrochemicals, combined with deeply entrenched industrial farming models, creates additional resistance to change (Schreefel *et al*., 2020)​.

To overcome these barriers, future efforts should focus on strengthening research and development, particularly through long-term field trials that quantify the economic and environmental benefits of RA (Giller *et al*., 2021)​. Additionally, governments should introduce subsidies, tax breaks, and grant programs to support farmers during the transition period (Newton *et al*., 2020)​. Establishing carbon credit markets and incentivizing regenerative agriculture certification programs could further enhance farmer participation and provide additional revenue streams (Jayasinghe *et al*., 2023)​. Policy integration is also crucial, as RA should be incorporated into national sustainability frameworks, climate action plans, and food security strategies (Schreefel *et al*., 2020)​. Moreover, investing in farmer education and knowledge-sharing networks through digital advisory services, peer-to-peer learning, and capacity-building programs will play a key role in ensuring successful RA adoption (Giller *et al*., 2021)​. Addressing these challenges through collaborative efforts between governments, researchers, businesses, and farming communities will be essential in unlocking the full potential of regenerative agriculture and securing its place as a sustainable solution for global food systems.

## Conclusion

Soil degradation is one of the most pressing challenges in global agriculture, but regenerative agriculture provides a viable solution to restoring soil health. By adopting practices such as no-till farming, cover cropping, crop rotations, composting and rotational grazing, RA improves soil fertility, water retention, and carbon sequestration. Despite its benefits, challenges like economic barriers, policy gaps and knowledge limitations hinder widespread adoption. To accelerate RA implementation, financial incentives, research support and farmer training programs are essential. As the demand for sustainable food systems grows, regenerative agriculture stands as a pioneering approach to ensure healthy soils, productive farms, and resilient ecosystems for future generations.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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