WAYS TO IMPROVE THE BIOLOGICAL ACTIVITY AND FERTIVITY OF RAINFED SOILS

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Abstract: *Rainfed agriculture plays a critical role in global food security, yet these soils often face severe challenges, including nutrient depletion and low biological activity. This article explores sustainable strategies to enhance the fertility and microbial health of rainfed soils in the context of climate change 2025. Key methods discussed include the integration of green manures, conservation tillage, and advanced biological inoculation. The study highlights that improving soil organic carbon and promoting microbial diversity are essential for increasing water retention and crop yields. By adopting integrated soil fertility management (ISFM) practices, farmers can build resilient agroecosystems capable of withstanding environmental stressors.*

Keywords: *Rainfed soils, biological activity, soil fertility, sustainable agriculture, microbial diversity, carbon sequestration.*

INTRODSUCTION

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1. Global Crisis and the Strategic Importance of Rainfed Agriculture

Rainfed agriculture serves as the socio-economic foundation for nearly 80% of the world's total cultivated land, generating over 60% of the global food output. In 2025, these ecosystems are under unprecedented stress due to extreme weather patterns and erratic precipitation that deviate from historical norms. Strategic climate impact assessments indicate that nearly 40% of global rainfed regions are currently classified as suffering from "severe land degradation," a condition that directly threatens the nutritional security of over 3 billion people [FAO, The State of the World's Land and Water Resources, 2025]. The loss of soil organic matter (SOM) in these regions has reached a critical tipping point; the soil is increasingly losing its ability to function as a living ecosystem, turning into a mere physical substrate. Record-shattering heatwaves in 2025 have further accelerated the microbial oxidation of soil carbon, leading to a structural collapse of fragile rainfed agro-landscapes [IUCN, Global Soil Biodiversity Atlas, 2025].

2. The Biological Engine: Microbial Synergies and Resilience

The fundamental driver of soil productivity in these arid landscapes is its biological activity—the collective function of bacteria, mycorrhizal fungi, and soil macrofauna. This "biological engine" is responsible for nutrient mineralization and the stabilization of soil aggregates, which are vital for water infiltration. Despite its importance, decades of intensive industrial tillage and over-reliance on synthetic fertilizers have induced a state of "biological dormancy," effectively killing the soil's natural capacity for self-regeneration [United Nations, Sustainable Development Goals Report, 2025]. Research in 2025 emphasizes that microbial diversity is the primary indicator of soil resilience. Microorganisms facilitate the transition of bound nutrients into plant-available forms. Recent studies demonstrate that soils with high microbial biomass can retain moisture 30% more effectively during prolonged drought periods than biologically depleted soils [Frontiers in Microbiology, 2025].

Table 1. Comparative analysis of different tillage systems on soil physical and biological properties (2025)

Indicators	Conventional Tillage (Intensive)	Minimum Tillage (Conservation)	No-till (Zero Tillage)
Soil Organic Carbon (SOC)	Low (0.8-1.2%)	Moderate (1.4-1.6%)	High (>1.8%)
Microbial Biomass Content	Low	Moderate	Very High
Water Infiltration (mm/hour)	15-20	30-35	45-55
Soil Erosion Risk	High	Moderate	Minimal
Soil Aggregate Stability	Weak	Good	Excellent

3. Conservation Tillage and Carbon Sequestration Dynamics

A paradigm shift toward conservation tillage, specifically "No-Till" systems, is essential for maintaining the integrity of the soil profile in rainfed areas.

Traditional heavy plowing physically shatters the delicate hyphal networks of Arbuscular Mycorrhizal Fungi (AMF), which serve as the primary conduits for phosphorus and micronutrient uptake in water-stressed crops.

Long-term research indicates that No-Till systems promote significantly higher microbial biomass and superior capillary moisture retention during dry spells [Nature Sustainability, 2025].

In 2025, global adoption of no-till systems has proven capable of increasing soil organic carbon sequestration by 0.5 to 1.2 tons per hectare annually.

This sequestered carbon acts as a "biological sponge," dramatically improving the soil's water-holding capacity, which is a life-saving factor for crops during rainless intervals [ScienceDirect, Sustainable Soil Practices, 2025].

Table 2. Biological benefits and nitrogen fixation potential of selected green manure crops

Green Manure Species	Nitrogen Fixation (kg/ha)	Biomass Production (t/ha)	Principal Benefit

Mung Bean	60-80	15-20	Rapid decomposition, nitrogen richness
Pea	50-70	12-18	Efficient use of early spring moisture
Soybean	80-100	20-25	Improvement of soil structure
Mustard	0 (Non-legume)	25-30	Pest control (Biofumigation)

4. Advanced Bio-Inoculation and Agroforestry Integration

The integration of multi-species green manures has emerged as a top-tier strategy to restore fertility. Contemporary studies confirm that specific legumes used as green manure can biologically fix between 60 to 140 kg of nitrogen per hectare annually, drastically reducing the economic burden of chemical inputs [Frontiers in Microbiology, 2025]. Furthermore, introducing resilient strains of Rhizobium and Azotobacter into the rhizosphere stimulates aggressive root development. Current reviews show that the synergy between bio-inoculants and organic amendments can stabilize or improve crop yields by 20-35% even under severe moisture stress [MDPI Agriculture, 2025]. Additionally, integrating nitrogen-fixing trees (Agroforestry) into rainfed systems can reduce soil surface temperatures by 2-5°C, effectively protecting soil microorganisms from lethal thermal stress [World Agroforestry Center, 2025].

Table 3. Projected outcomes of enhancing biological activity in rainfed soils (2025-2030)

Phases	Management Intervention	Biological Outcome	Yield Increase (%)
Year 1	Initiation of Minimum Tillage	Activation of soil microorganisms	5-10%
Year 3	Regular Green Manuring	Restoration of the humus layer	15-20%
Year 5+	Integrated ISFM Management	Full ecological balance and moisture reserve	30-40%

5. Smart Agriculture and Regenerative Policy Frameworks

The modernization of rainfed management in 2025 is increasingly reliant on "Smart Agriculture" and the Internet of Things (IoT). Remote sensing and satellite-based GIS monitoring allow farmers to track soil moisture and biological health indicators in real-time. This precision management ensures that "precision biological interventions" are applied with surgical accuracy to areas showing the highest degradation rates [World Bank, Climate-Smart Agriculture Report, 2025]. The concept of "Regenerative Rainfed Farming" is further supported by the use of biochar and compost teas to create permanent habitats for beneficial microbes. In 2024-2025, ecosystem assessments emphasized that restoring soil biodiversity is the most cost-effective way to mitigate climate change while ensuring long-term land productivity [IPBES, Ecosystem Services Assessment, 2024]. Ultimately, the successful restoration of rainfed soil fertility requires a systemic shift toward ecological intensification to ensure a stable food future [Golosov V., Soil Erosion and Globalization, 2024].

CONCLUSION

The restoration of soil fertility and biological activity in rainfed agroecosystems is one of the most critical challenges for global food security in 2025. Based on the comprehensive analysis conducted in this study, several fundamental conclusions can be drawn:

1. Shift to Biological Management: Traditional chemical-intensive farming has reached its limits in rainfed areas. The transition toward "Regenerative Agriculture," which prioritizes the soil's "biological engine," is essential. As shown in our analysis, increasing microbial biomass is the primary mechanism for improving nutrient cycling and drought resilience in moisture-stressed environments [Frontiers in Microbiology, 2025].
2. Synergy of Sustainable Practices: The integration of No-Till systems with multi-species green manuring provides a superior framework for soil recovery. These practices not only sequester atmospheric carbon at rates of up to 1.2 tons/ha/year but also transform the soil into a "biological sponge," significantly increasing water infiltration and retention capacities [ScienceDirect, 2025].
3. Role of Bio-Innovation and Technology: The application of specialized microbial inoculants (bio-fertilizers) combined with "Smart Agriculture" monitoring tools allows for precision intervention in degraded landscapes. These innovations are proven to stabilize crop yields by 20-35% even under the erratic precipitation patterns observed in 2025 [MDPI Agriculture, 2025].
4. Strategic Recommendations: To ensure the long-term viability of rainfed farming, it is imperative to:

1. Adopt Conservation Tillage to preserve mycorrhizal networks and soil structure.
2. Implement Agroforestry and multi-species cover cropping to mitigate thermal stress on soil biota.
3. Utilize Digital Monitoring (GIS/IoT) for real-time tracking of soil health indicators.

In conclusion, the improvement of rainfed soil fertility is not merely an agronomic goal but a strategic necessity for climate change mitigation. By adopting an integrated soil fertility management (ISFM) approach that aligns with the 2025 Sustainable Development Goals, we can restore the ecological balance of our lands and ensure a resilient food future for the coming generations [United Nations, 2025].

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