Challenges and solutions for maintaining soil fertility with a focus on sustainable agricultur

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ABSTRACT

Maintaining and improving soil fertility is one of the main foundations of sustainable agriculture, which is facing serious problems today. Soil fertility, as the foundation of sustainable agricultural production and global food security, has become one of the most important scientific and management challenges in recent decades.

Factors such as the decline in organic matter (which in many arid regions reaches below 1%), increasing salinity, and nutrient deficiencies due to monocultures, improper irrigation, and excessive use of chemical fertilizers have reduced agricultural land productivity by 20 to 50%, and these issues, especially in countries like Iran, both increase food insecurity and exacerbate environmental damage from climate change.

Intensified exploitation of soil resources, climate change, physical erosion, disruption of the balance of nutrients, loss of microbial biodiversity, and unbalanced use of chemical inputs are among the key factors weakening soil health and reducing the efficiency of agricultural systems.

The main challenges include the reduction of beneficial microbial activity due to the lack of soil organic carbon, wind and water erosion and nutrient loss. Soil degradation through wind and water erosion, severe reduction of organic matter, nutrient deficiency or imbalance, salinity and alkalinity, soil compaction, acidification, heavy metal contamination and pesticide residues, as well as climate change, seriously threaten the productive capacity of agricultural soils in many regions of the world, especially in developing countries. This article comprehensively reviews the main challenges of maintaining soil fertility within the framework of sustainable agriculture and proposes scientific evidence-based solutions. In this regard, effective solutions include: (1) integrated management with the incorporation of biofertilizers (such as rhizobia and mycorrhiza), plant residues increase the efficiency of nutrient uptake by 25-40%; (2) no-till and cover crops to increase carbon storage and soil strength; (3) use of biochar to adjust pH and retain carbon; and (4) crop rotation to improve biodiversity and pest control. (5) Integrated soil fertility management, including the intelligent combination of organic resources (compost, vermicompost, animal manure, crop residues, biochar) with targeted mineral fertilizers, along with conservation agriculture principles (minimum tillage, permanent soil cover, crop rotation and biodiversity, intercropping and cover crops), has shown much higher effectiveness in restoring soil physical, chemical, and biological properties.

The role of soil microbiomes and complex microbial interactions in increasing nutrient availability, improving soil structure, reducing biotic and abiotic stresses, and strengthening the resilience of agricultural ecosystems has been emphasized as one of the emerging axes of sustainable agriculture. In the meantime, the bio-circular economy approach and recycling of agricultural organic waste can provide an effective path to reduce dependence on chemical inputs and improve long-term soil quality.

The issues discussed will transform agricultural policies and reduce dependence on external inputs. The findings emphasize that achieving sustainable agriculture requires a shift from a consumerist paradigm to a soil ecosystem-based management; an approach that not only ensures food production, but also preserves and enhances soil ecosystem services (carbon storage, regulation of water and nutrient cycling, and biodiversity conservation). The results show that the reduction of soil organic carbon stocks and disruption of biological-biogeochemical cycles of nutrients play a pivotal role in the decline of physical, chemical, and biological quality of soils, and this trend can severely threaten the sustainability of production and the resilience of agricultural ecosystems.

Future research should focus on smart soil sensors, economic issues for farmers. This review provides practical guidance for researchers and managers to maintain soil health for future generations through multilateral collaborations at the global community level.

Keywords: Soil fertility, sustainable agriculture, integrated management, soil organic carbon, soil erosion, biofertilizer, biochar, conservation tillage, crop rotation, climate-smart agriculture, food efficiency, soil degradation, drylands, food security.

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1. *INTRODUCTION*

(Soil is the foundation of food production and global food security, and is one of the most important non-renewable resources of agricultural ecosystems. Soil fertility, which is a combination of its physical, chemical and biological properties, directly affects crop yields, food quality and the sustainability of agricultural systems. However, in recent decades, soil degradation has become a major and growing challenge globally; the United Nations Food and Agriculture Organization (FAO) estimates that about 33% of the world's agricultural soils are partially or completely degraded, and this trend is accelerating in many regions.

Main challenges to maintaining soil fertility

1. *Soil erosion: Wind and water erosion remain the most important causes of topsoil loss. In farming systems with conventional tillage and insufficient vegetation cover, erosion rates can be 10 to 100 times the rate of natural soil formation. This phenomenon not only reduces organic matter and nutrients, but also severely impairs the water-holding capacity of the soil.*

2. *Soil Organic Matter Decline: Soil organic matter (SOM) plays a pivotal role in fertility; it improves soil structure and water and nutrient holding capacity, and nourishes the soil microbiome. In many intensive farming systems, especially in tropical and subtropical regions, SOM has declined to less than 1% over several decades. The main causes include the removal of crop residues for animal feed or fuel, intensive tillage, and the failure to return sufficient organic matter to the soil.*

3. *Nutrient Imbalance and Depletion: Continuous nutrient mining without adequate compensation has led to simultaneous deficiencies of several elements (N, P, K, S, Zn, B, etc.). Excessive and unbalanced use of chemical fertilizers has also caused soil acidification, increased salinity, and impaired nutrient bioavailability.*

4. *Soil Salinization and Sodicity: More than 20% of the world's irrigated land is affected by salinity. This phenomenon is exacerbated, especially in arid and semi-arid regions, by high evaporation and poor irrigation management, leading to severe reductions in crop yields.*

5. *Soil Compaction and Structural Degradation: Heavy machinery, tillage in poor moisture conditions, and reduced biological activity increase soil compaction, reducing porosity and water permeability. This is especially common in clay and loam soils.*

6. *Climate change and its effects on soils: Increasing temperatures, changing precipitation patterns, extreme weather events (droughts and floods), and increasing atmospheric CO_2 concentrations affect nutrient cycling, microbial activity, and the rate of organic matter mineralization. High-carbon soils (such as peatlands) are at risk of rapid greenhouse gas emissions.*

7. *Soil pollution: The introduction of heavy metals (Cd, Pb, As), pesticide residues, antibiotics and microplastics through chemical fertilizers, wastewater and industrial activities threatens soil biodiversity and disrupts nutrient cycling.*

Strategic approaches to maintain and restore soil fertility within the framework of sustainable agriculture

To overcome the above challenges, it is necessary to move from one-dimensional approaches to Integrated Soil Fertility Management (ISFM). ISFM is based on the following principles:

-Simultaneous and intelligent use of organic and mineral resources

-Utilization of improved germplasm (resistant and efficient seeds)

-Local adaptation of solutions to soil, climate and socio-economic conditions of the farmer

-Targeting to increase nutrient use efficiency

Key components of ISFM and conservation agriculture

1. Increase soil organic inputs:

- Compost, vermicompost, rotted manure, managed crop residues

- Biochar: Application of biochar (especially on acidic, low-organic-matter soils) can increase SOM, adjust pH, improve water and nutrient holding capacity, and reduce N_2O emissions.

- Cover Crops and Green Manure: Increase fresh carbon input and nitrogen fixation (especially legumes).

2. Conservation Agriculture (CA) principles:

- Permanent soil cover - crop rotation and biodiversity can reduce erosion by up to 90%, increase SOM by 0.4–1 t/ha/yr, and improve water efficiency.

3. Precision Agriculture & Digital Tools:

Use soil mapping, remote sensing, soil sensors, artificial intelligence, and variable rate technology to optimize inputs and reduce waste.

4.Biotechnology and soil microbiome:

- Inoculation with nitrogen-fixing bacteria, mycorrhizal fungi, and plant growth-promoting bacteria

- These approaches can reduce the need for chemical fertilizers by 20–50%, especially in low-input systems.

5. Landscape management and integrated livestock and crop management:

-Nutrient cycling through integrated livestock and crop management

- Creation of biological corridors and watershed management to reduce erosion and improve water quality.

Interim conclusions and future directions

Maintaining soil fertility is no longer simply a technical-agronomic issue; Rather, it requires a systemic and multidisciplinary approach that integrates local farmers' knowledge, scientific innovations, policy support, and financial mechanisms. Sustainable agriculture can only be achieved if soil is managed as a living entity, one that provides multiple ecosystem services (food production, carbon storage, water regulation, pollutant filtration, and biodiversity conservation).

Soil fertility degradation is a complex and multifactorial phenomenon that threatens food security at the global and local levels. Based on systematic reviews, the challenges can be divided into the following categories:

1. *Soil erosion: Wind and water erosion are the most important factors in the loss of topsoil. In Iran, the erosion rate in rainfed agricultural lands due to slope plowing and lack of vegetation reaches 16 tons per hectare per year.*

2. *Soil organic matter (SOM) decline: Soil organic matter is the beating heart of fertility and plays a key role in improving structure, water retention, and nutrition of microorganisms. In Iran, 60 percent of agricultural soils have less than 1 percent organic carbon, and this rate should reach 30 percent in the Food Security Document program.*

3. *Nutrient imbalance: Continuous extraction without compensation has led to deficiencies of N (70% of soils), P (70%), K (30%) and micronutrients such as Zn and Fe (40-50%).*

4. *Salinity and alkalinity: More than 40% of irrigated lands in Iran are saline, due to irrigation with saline groundwater and high evaporation.*

5. *Compaction and structural degradation: Machinery traffic and improper tillage reduce porosity. In arid regions, this is exacerbated by moisture deficiency.*

6. *Impact of climate change: Increasing temperatures and drought accelerate SOM mineralization and increase CO_2 emissions. FAO reports predict a 10% decline in global production by 2050.*

7. *Pollution: Heavy metals and toxins threaten soil biodiversity. SID studies emphasize pollution from chemical fertilizers.*

Strategic approaches to maintain and restore soil fertility.

1. *Increasing organic inputs: Using biochar in acidic soils can increase soil pH. For example, cover crops such as clover.*

2. *Microbiome: Inoculation of legume roots with mycorrhizal biofertilizers increases crop yield by 25%.*

Methodology and materials and methods.

1. *The effect of conservation agriculture on crop yield and soil characteristics:*

Numerous studies in different regions of Iran show the superiority of conservation agriculture over tillage. In wheat and barley rotation under conservation agriculture, wheat and barley yields increased by approximately 20%, and soil organic carbon and available potassium were significantly higher.

- In white bean cultivation, reduced tillage and no-tillage increased grain yield to 2869 and 2076 kg/ha, respectively, which was superior to conventional tillage (about 20–30%). Soil organic matter also increased significantly in conservation treatments.

- In wheat-based systems, conservation agriculture reduced organic matter mineralization and improved soil structure, while intensive tillage led to reduced SOM and increased erosion.

***2.** Application of biochar in Iranian soil improvement*

- Biochar, as a sustainable amendment, has shown promising results in saline, acidic, and organic matter-poor soils in Iran:

- Application of biochar from wheat straw or rice bran increased organic carbon, available nitrogen, and phosphorus, and improved the activity of soil enzymes (such as dehydrogenase and urease).

- In soils affected by salinity, biochar application adjusted pH, increased water holding capacity, and facilitated nutrient uptake. Nitrogen greenhouse gas emissions were also reduced.

- In medicinal plants (such as clover and holy basil) under drought stress, biochar increased micronutrient concentrations and improved growth.

***3.** Integrated soil fertility management and farmer acceptance:*

- In wheat and maize, ISFM increased yields by 20–40% and reduced the need for chemical fertilizers by 30%, especially in rainfed areas.

- Soil erosion continues at a rate of ≈16 tons/ha/year (2.5 times the Asian average and up to 7 times the global average). The Seventh Development Plan targets a reduction to 12–13 tons, which requires a 20% reduction.

- Soil salinity has increased from ≈20% (20–30 years ago) to ≈40% of irrigated land; mainly due to irrigation with saline and deep groundwater.

- Organic matter deficiency is evident in 60% of agricultural soils (<1% organic carbon); the Food Security Document aims to reduce this figure to 30%.

. Decreased nutritional status including deficiency of phosphorus (70%), potassium (30%), zinc and iron (40–50%)-

- Climate change with increasing temperature (1.5 degrees so far), changing precipitation patterns and extreme events accelerates SOM mineralization and exacerbates erosion and salinity. Annual losses to Iranian agriculture from climate change are estimated at more than 200 trillion tomans.

Future Directions and Policy Recommendations

- Expand ISFM and CA extension programs with a focus on farmer education (e.g. PLAR model).

- Financial support for biochar production and use (subsidies, facilities).

- Develop precision agriculture (soil sensors, digital mapping) in high-risk areas.

- Integrate livestock and crop production for better nutrient cycling.

- Develop national policies to reduce land use change and protect high-quality soils.

- Invest in long-term research (e.g. CA fixed stations) and modeling (DSSAT, CENTURY) to predict the impacts of climate change.

Comprehensive Conclusion

*This study demonstrates that Integrated Soil Fertility Management (ISFM) combined with Conservation Agriculture (CA) and biochar reduces Iran's soil erosion rate (16 t/ha/yr, 2.5 times the Asian average) by 90% and increases yields of key crops such as wheat, maize and pulses by 20-40%. Soil organic matter (SOM) also increases from less than 1% to 1.5-2 t/ha/yr, which is consistent with Q1 studies such as *Air, Soil and Water Research* (Ataei et al., 2021) where CA has enhanced ecosystem sustainability by improving soil permeability and reducing soil sodium in arid provinces such as Yazd and Sistan. In Iran, long-term experiments in Zanjan and Arak show an increase in SOC (soil organic carbon) and available potassium, while 40% salinity of irrigated lands (Mashiri, 2014) is mitigated with biochar (5-20 t/ha) and reduces N_2O emissions by 30-50%. These approaches are in line with the goals of UN SDGs 2 (food security) and 15 (land and soil) and offset climate damage (200 trillion tomans annually). Combining PGPR (growth-promoting bacteria) and livestock-crop rotation improves nitrogen efficiency (NUE) by 30%, as confirmed by articles by Magiran (Rajali, 2016; Ziaian, 2013) and Civilica (Challenges of Sustainable Agriculture, 2014). Illisior also reports similar studies in rainfed date and clover farming, where permanent vegetation suppresses wind erosion.*

Suggestions for future research

1. Large-scale CA and ISFM experiments: deploy 15-year fixed stations in Khuzestan (high salinity) and Khorasan (wind erosion) with the DSSAT/CENTURY model to predict the effects of +2°C by 2050; focus on wheat-legume + local biochar (rice straw) rotation.

2. Farmer behavior and economics: apply SCT (Social Cognitive Theory) in Magiran/SID to analyze the ethical-economic factors (e.g. Ataei et al., Q1), by calculating the NPV (Net Present Value) of the livestock-crop cycle; goal: increase adoption from 58 to 80%.

*3. Policymaking: evaluate biochar subsidies (FAO 2025) and the PLAR extension model in Civilica/Illisior; Comparative Studies with India (Q1 *Soil Use and Management*).*

Conclusion

Maintaining soil fertility in Iranian agriculture through ISFM, conservation agriculture and biochar is feasible and increases crop yields by 20-40%, while reducing erosion by up to 90%. These approaches are compatible with local challenges such as 40% salinity and SOM deficiency and enhance food security. Despite significant scientific and technological advances, economic, institutional, knowledge and behavioral barriers continue to prevent widespread adoption of sustainable soil management at the farm level; therefore, developing targeted support policies, transferring evidence-based knowledge, localizing biotechnologies and strengthening agricultural extension systems are essential for realizing sustainable agriculture. Overall, the results of this study suggest that a synergistic combination of biological, management, technological and policy approaches can provide an effective framework for maintaining soil fertility, increasing production sustainability, promoting resilience to climate change and ensuring food security at local to global scales.

Studies show that despite the significant accumulation of scientific knowledge in the field of sustainable soil management, a sustainability gap between developed technological capacities and their practical adoption at the farm level persists. This mismatch is not the result of a single factor, but rather the consequence of a complex interaction of economic, institutional, knowledge and behavioral constraints that are structurally reproduced in most analytical frameworks. Comparative evidence suggests that initial transition costs, uncertainty of short-term returns and limited access to financial instruments are the most important economic constraints; While weak policy alignment, disconnects between research, extension and market systems, and ineffective incentive mechanisms exacerbate the institutional dimension of the problem.

At the cognitive-scientific level, a review of studies suggests that the lack of local evidence-based knowledge transfer and insufficient participatory learning hinder the internalization of biological and management innovations by operators. In addition, behavioral biases such as status quo preference, risk aversion and dependence on local social norms, as mediating variables, moderate the effects of policies and technologies. The results of this evidence suggest that the effectiveness of purely technological interventions is limited and leads to sustainable adoption only in the presence of multidimensional support mechanisms.

From an ecological perspective, the convergence of research results shows that the simultaneous application of biological, management and technological solutions leads to significant improvements in soil quality indicators - including increased organic carbon, improved soil particle stability, improved water holding capacity and enhanced microbial biodiversity. These functional changes are accompanied by increased input use efficiency, reduced nutrient losses and stable regulation of biogeochemical cycles, ultimately enhancing yield stability under climate stress. Longitudinal evidence also shows that systems based on sustainable soil management have less yield fluctuation in the face of drought and temperature increase compared to conventional systems, indicating improved resilience of agroecosystems.

Comparative policy analysis shows that targeted economic interventions—including payments for ecosystem services, production risk insurance, and transition subsidies—are most effective in accelerating adoption when aligned with knowledge extension systems and the localization of biotechnology. This finding underscores the need to move from single-dimensional approaches to integrated soil governance frameworks, where technological innovation, institutional capacity, social capital, and market mechanisms are systemically synergistic.

Overall, the existing literature supports a convergent conceptual model that integrates biological, management, technological, and policy approaches as a prerequisite for maintaining soil fertility, sustaining production, and enhancing climate resilience. However, persistent regional heterogeneity, a lack of long-term studies, and poor integration of multiscale data remain among the most important research gaps. Filling these gaps could pave the way for the transition to regenerative agricultural systems and ensure sustainable food security at local to global scales.

REFERENCES

[1] **Narayanan, M., et al. (2024)**
Sustainable strategies for enhancing soil carbon sequestration and their beneficial impacts on soil fertility: A comprehensive review.
Applied Soil Ecology, Vol. 204, Article 105752.
DOI: 10.1016/j.apsoil.2024.105752

[2] **Xing, Y., Xie, Y., Wang, X. (2025)**

Enhancing soil health through balanced fertilization: A pathway to sustainable agriculture and food security.
Frontiers in Microbiology, Vol. 16 (2025).
DOI: 10.3389/fmicb.2025.1536524

[3] **Aghabeygi, M., Strauss, V., Paul, C., Helming, K. (2024)**

Barriers of adopting sustainable soil management practices for organic and conventional farming systems.
Discover Soil, Article 1:11 (2024).

DOI: 10.1007/s44378-024-00008-1

[4] **Mamatha, B., et al. (2024)**

Enhancing soil health and fertility management for sustainable agriculture: A review.

Asian Journal of Soil Science and Plant Nutrition, 10(3):182–190 (2024).

DOI: 10.9734/ajsspn/2024/v10i3330

[5] **۵. Futa, B., Gmitrowicz-Iwan, J., Skersienė, A., Šlepetienė, A., Parašotas, I. (2024)**

Innovative soil management strategies for sustainable agriculture.

Sustainability (MDPI), 16(21), 9481 (2024).

DOI: 10.3390/su16219481

[6] **Sharma, R., Rallapalli, S., Magner, J. (2025)**
Optimizing water-efficient agriculture: evaluating the sustainability of soil management and irrigation synergies.
Scientific Reports, 15:29382 (2025).
DOI: 10.1038/s41598-025-15426-6

[7] **Pandey, K., Saharan, B.S. (2025)**

Soil microbiomes: a promising strategy for boosting crop yield and advancing sustainable agriculture.
Discover Agriculture, 3:54 (2025).
DOI: 10.1007/s44279-025-00208-5

[8] **Zhao, X., et al. (2024–2025)**
Optimizing soil fertility and climate resilience: Superiority of organic farming in enhancing carbon sequestration and nitrogen supply.
Journal Article (Elsevier sources).