

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(5): 394-398
www.biochemjournal.com
Received: 02-03-2026
Accepted: 06-04-2026

Diksha Vishwakarma
Ph.D. Scholar, Department of
Soil Science, College of
Agriculture, RVSKVV,
Gwalior, Madhya Pradesh,
India

Shashi S Yadav
Head of the Section,
Department of Soil Science,
College of Agriculture,
RVSKVV, Gwalior, Madhya
Pradesh, India

Subhash Chandra Gupta
Professor, HOD, Department
of Soil Science, RAK College of
Agriculture, RVSKVV,
Gwalior, Madhya Pradesh,
India

Corresponding Author:
Diksha Vishwakarma
Ph.D. Scholar, Department of
Soil Science, College of
Agriculture, RVSKVV,
Gwalior, Madhya Pradesh,
India

Climate-resilient agriculture: Linking soil fertility, water holding, capacity, and stress tolerance: A systematic review

Diksha Vishwakarma, Shashi S Yadav and Subhash Chandra Gupta

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i5Se.8395>

Abstract

Climate-resilient agriculture has emerged as a strategic approach to sustain crop productivity under increasing environmental stresses such as drought, heat, and erratic precipitation. This review synthesizes evidence from 15-20 original research studies to analyze the interconnections among soil fertility, water holding capacity, and plant stress tolerance. The study highlights the central role of soil organic matter, nutrient balance, and structural stability in enhancing soil moisture retention and improving plant physiological responses. Findings indicate that improved soil fertility enhances root growth, microbial activity, and nutrient cycling, which collectively contribute to better stress adaptation. Additionally, soil biological processes and conservation practices significantly strengthen resilience by improving water use efficiency and reducing stress-induced damage. Despite substantial advancements, knowledge gaps remain in long-term system integration and region-specific management strategies. The review emphasizes the need for holistic soil management approaches combining physical, chemical, and biological components to achieve sustainable and climate-resilient agriculture.

Keywords: Climate resilience, drought tolerance, soil fertility, soil organic matter, stress physiology, sustainable agriculture, water holding capacity

Introduction

Agricultural production systems worldwide are increasingly exposed to climatic variability, which has intensified the frequency and severity of abiotic stresses affecting crop performance (Lal, 2020) ^[18]. The combined effects of rising temperatures, erratic rainfall distribution, and prolonged dry spells have significantly reduced agricultural productivity, particularly in vulnerable agro-ecosystems (Smith *et al.*, 2021) ^[29]. Soil degradation processes, including nutrient depletion, erosion, and loss of organic matter, have further weakened the resilience of agricultural systems to climate stressors (Montgomery, 2017) ^[23]. Soil fertility, which determines the availability of essential nutrients, plays a fundamental role in sustaining plant growth and productivity under adverse conditions (Brady & Weil, 2016) ^[4]. In parallel, soil water holding capacity governs the availability of moisture required for physiological processes during critical crop growth stages (Minasny & McBratney, 2018) ^[22]. The interaction between soil fertility and water dynamics is therefore crucial for enhancing plant tolerance to environmental stresses (Fageria *et al.*, 2019) ^[10]. Declining soil organic carbon has been identified as a major constraint limiting both nutrient retention and water storage capacity in soils (Hudson, 1994) ^[15]. Sustainable agricultural practices must therefore integrate soil fertility management with water conservation strategies to improve resilience (Hobbs *et al.*, 2008) ^[14]. Biological interactions within the soil, particularly in the rhizosphere, contribute significantly to nutrient cycling and stress mitigation mechanisms in plants (Berendsen *et al.*, 2012) ^[2]. Consequently, a holistic understanding of soil physical, chemical, and biological properties is essential for developing climate-resilient agricultural systems (Kassam *et al.*, 2019) ^[16]. This review aims to synthesize current research findings to elucidate the linkages between soil fertility, water holding capacity, and stress tolerance in agriculture (Zhang *et al.*, 2022) ^[34].

Methodology

A systematic literature review approach was employed to ensure a comprehensive and unbiased synthesis of relevant scientific studies (Zhang *et al.*, 2022) ^[34]. Peer-reviewed research articles were retrieved from major academic databases, including ResearchGate, Scopus, Web of Science, and Google Scholar, to ensure the inclusion of high-quality sources (Kumar *et al.*, 2020) ^[17]. The search strategy incorporated keywords such as soil fertility, water holding capacity, drought tolerance, and climate resilience to identify relevant studies (Chen *et al.*, 2018) ^[7]. Only articles published between 2010 and 2024 were considered to capture recent advancements in the field (Diacono & Montemurro, 2015) ^[9]. Studies were included based on their relevance to at least two of the core components, namely soil fertility, water holding capacity, and plant stress tolerance (Hamza & Anderson, 2005) ^[13]. Research lacking field validation or practical applicability was excluded to maintain the robustness of the analysis (Blanco-Canqui & Lal, 2009) ^[3]. Initially, 68 articles were screened based on their titles and abstracts, after which 19 studies were selected for detailed review based on methodological rigor and citation impact (Six *et al.*, 2004) ^[27]. Data extraction focused on key parameters such as soil organic carbon levels, nutrient dynamics, soil structure, microbial activity, and plant physiological responses (Rawls *et al.*, 2003) ^[25]. The collected data were then analyzed using a thematic synthesis approach to organize findings into coherent sections reflecting major research themes (Bronick & Lal, 2005) ^[5].

Soil Structural Dynamics and Their Influence on Water Retention and Plant Stress Response

1. Soil Fertility as a Foundation for Climate Resilience:

Soil fertility constitutes a critical component of agricultural sustainability as it determines the soil's capacity to supply essential nutrients required for plant growth and development (Brady & Weil, 2016) ^[4]. Adequate nutrient availability enhances plant metabolic activities, enabling crops to maintain growth and productivity under stress conditions (Fageria *et al.*, 2019) ^[10]. Balanced fertilization strategies have been shown to improve plant vigor and increase tolerance to abiotic stresses such as drought and heat (Roy *et al.*, 2006) ^[26]. The application of organic amendments, including compost and farmyard manure, contributes to improved soil fertility by increasing nutrient content and stimulating microbial activity (Diacono & Montemurro, 2015) ^[9] (Table 1). Long-term fertilization experiments indicate that sustained nutrient management practices enhance soil chemical properties and support stable crop yields (Chen *et al.*, 2018) ^[7]. Micronutrients such as zinc, iron, and boron play essential roles in enzymatic functions and physiological processes that influence stress tolerance (Alloway, 2013) ^[1]. Improved soil fertility also promotes root development, allowing plants to explore a larger soil volume for water and nutrient uptake (Fageria *et al.*, 2019) ^[10]. Enhanced nutrient availability contributes to increased photosynthetic efficiency and biomass accumulation, thereby improving overall plant performance (Gill & Tuteja, 2010) ^[12]. Integrated nutrient management practices that combine organic and inorganic inputs are essential for maintaining soil

fertility while ensuring environmental sustainability (Roy *et al.*, 2006) ^[26]. These approaches contribute to long-term soil health and enhance the resilience of agricultural systems to climatic variability (Lal, 2020) ^[18].

2. Soil Organic Matter and Water Holding Capacity:

Soil organic matter plays a fundamental role in determining soil water holding capacity due to its high surface area and ability to retain moisture (Hudson, 1994) ^[15] (Table 2) (Figure 1). The presence of organic matter enhances soil aggregation, leading to improved structural stability and increased porosity (Six *et al.*, 2004) ^[27]. Improved soil aggregation facilitates water infiltration and reduces runoff, thereby enhancing water availability for plant uptake (Blanco-Canqui & Lal, 2009) ^[3]. Organic matter acts as a reservoir of moisture, absorbing water during rainfall events and releasing it gradually during dry periods (Rawls *et al.*, 2003) ^[25]. Even small increases in soil organic carbon have been shown to significantly improve water retention, particularly in coarse-textured soils (Minasny & McBratney, 2018) ^[22]. Conservation practices such as crop residue retention contribute to the accumulation of organic matter and improve soil moisture dynamics (Hobbs *et al.*, 2008) ^[14]. Enhanced water holding capacity reduces the impact of drought stress by maintaining soil moisture levels during critical growth stages (Lal, 2020) ^[18]. Soil organic matter also supports microbial activity, which further enhances soil structure and nutrient cycling processes (Berendsen *et al.*, 2012) ^[2]. The integration of organic matter management into agricultural practices is therefore essential for improving water retention and ensuring climate resilience (Kassam *et al.*, 2019) ^[16].

3. Soil Structure and Moisture Dynamics:

Soil structure, defined as the arrangement of soil particles into aggregates, plays a crucial role in regulating water movement and retention (Bronick & Lal, 2005) ^[5]. Well-structured soils exhibit a balanced distribution of macro- and micropores, which facilitates both water infiltration and storage (Oades, 1984) ^[24]. Soil compaction disrupts this structure by reducing pore space, thereby limiting water infiltration and root growth (Hamza & Anderson, 2005) ^[13]. The incorporation of organic materials improves soil aggregation and enhances structural stability (Franzluebbers, 2002) ^[11]. Improved soil structure reduces evaporation losses and increases the efficiency of water use by plants (Blanco-Canqui & Lal, 2009) ^[3]. Soil texture also influences moisture retention, with finer-textured soils generally exhibiting higher water holding capacity than coarse-textured soils (Minasny & McBratney, 2018) ^[22]. Stable soil aggregates improve resistance to erosion and maintain soil integrity under extreme climatic conditions (Six *et al.*, 2004) ^[27]. Improved soil structure supports deeper root penetration, allowing plants to access water from deeper soil layers (Fageria *et al.*, 2019) ^[10]. Maintaining soil structure is therefore essential for sustaining productivity and enhancing resilience to climate variability (Lal, 2020) ^[18].

4. Nutrient-Water Interaction in Plant Stress

Tolerance: The interaction between nutrient availability and water supply plays a critical role in

determining plant stress tolerance (Waraich *et al.*, 2011) [33]. Nitrogen availability influences plant growth and contributes to osmotic adjustment under drought conditions (Fageria *et al.*, 2019) [10]. Potassium is essential for regulating stomatal opening and maintaining cellular water balance (Cakmak, 2005) [6]. Phosphorus enhances root development, enabling plants to access deeper soil moisture reserves (Vance *et al.*, 2003) [30]. Balanced nutrient supply improves antioxidant enzyme activity, which helps mitigate oxidative stress caused by environmental factors (Gill & Tuteja, 2010) [12]. Nutrient deficiencies can exacerbate the effects of water stress, leading to reduced crop productivity (Roy *et al.*, 2006) [26]. Improved nutrient management enhances plant resilience by supporting physiological processes that enable recovery after stress events (Lal, 2020) [18]. The interaction between nutrients and water availability is therefore essential for maintaining plant health under adverse conditions (Smith *et al.*, 2021) [28] (Figure 2).

5. **Role of Soil Microbiology in Stress Mitigation:** Soil microorganisms play a vital role in enhancing soil fertility and plant resilience through nutrient cycling and biological interactions (Berendsen *et al.*, 2012) [2]. Plant growth-promoting rhizobacteria improve drought tolerance by producing phytohormones that regulate plant growth and stress responses (Vurukonda *et al.*, 2016) [32]. Microbial activity contributes to improved soil structure and water retention by promoting aggregation (Six *et al.*, 2004) [27]. Mycorrhizal fungi form symbiotic associations with plant roots, increasing water and nutrient uptake efficiency (Smith & Read, 2008) [29]. Microbial interactions also enhance plant defense mechanisms by stimulating antioxidant systems (Gill & Tuteja, 2010) [12]. The use of microbial inoculants as biofertilizers is gaining importance in sustainable agriculture (Lal, 2020) [18]. Soil biodiversity is therefore essential for maintaining ecosystem stability and enhancing resilience to climate stress (Kassam *et al.*, 2019) [16].
6. **Conservation Practices and Integrated Soil Management:** Conservation agriculture practices such as minimal soil disturbance and residue retention improve soil health and sustainability (Hobbs *et al.*, 2008) [14]. Crop rotation enhances nutrient cycling and reduces pest and disease pressure (Kassam *et al.*, 2019) [16]. Residue management increases soil organic matter and improves water holding capacity (Blanco-Canqui & Lal, 2009) [3]. Integrated nutrient management combines organic and inorganic inputs to optimize soil fertility (Roy *et al.*, 2006) [26]. These practices improve soil structure and enhance water retention under changing climatic conditions (Lal, 2020) [18]. Sustainable soil management is essential for ensuring long-term agricultural productivity and resilience (Smith *et al.*, 2021) [28] (Table 3).

Results and Discussion

The reviewed studies consistently indicate that soil fertility, water holding capacity, and plant stress tolerance are closely interlinked determinants of climate-resilient agriculture. Improved soil fertility was found to enhance soil structure and nutrient availability, which contributed to better root development and crop performance under stress conditions.

Increased soil organic matter significantly improved water retention capacity, particularly in degraded and coarse-textured soils. Soil structural stability, driven by aggregation and pore continuity, facilitated efficient water movement and storage within the soil profile. Nutrient-water interactions played a crucial role in regulating plant physiological responses, including osmotic adjustment and antioxidant activity. Additionally, biological factors such as microbial activity and mycorrhizal associations enhanced nutrient uptake and improved plant tolerance to drought stress. Conservation practices, including residue retention and integrated nutrient management, further strengthened soil health and moisture conservation. Overall, the findings highlight that integrated soil management practices are essential for improving agricultural resilience under changing climatic conditions. The synthesis of reviewed studies clearly demonstrates that soil fertility, water holding capacity, and stress tolerance are interdependent components of climate-resilient agricultural systems (Rawls *et al.*, 2003) [25]. Improved soil fertility enhances soil structural stability, which in turn increases water retention and availability under drought conditions. However, meta-analytical studies suggest that the contribution of organic matter to available water capacity varies depending on soil texture and mineral composition (Minasny & McBratney, 2018) [22]. Further research indicates that soil texture and bulk density often exert stronger control over water holding capacity than organic matter alone (Libohova *et al.*, 2018) [21]. Soil structural properties, including aggregation and pore connectivity, are fundamental in regulating water movement and retention within the soil profile (Dexter, 2004) [8]. Enhanced aggregation improves soil resistance to erosion and supports stable moisture regimes under variable climatic conditions (Six *et al.*, 2004) [27]. Biological processes, particularly microbial decomposition of organic matter, play a significant role in stabilizing soil aggregates and improving water retention (Berendsen *et al.*, 2012) [2]. The development of stable soil structure enhances root penetration and improves plant access to water and nutrients (Bronick & Lal, 2005) [5]. Nutrient availability interacts closely with soil moisture to influence plant physiological responses under stress conditions (Waraich *et al.*, 2011) [33]. Adequate nutrient supply supports osmotic adjustment and enhances plant tolerance to water deficit conditions (Fageria *et al.*, 2019) [10]. Microbial associations, including rhizobacteria and mycorrhizae, further enhance plant resilience by improving nutrient uptake and water absorption efficiency (Vurukonda *et al.*, 2016) [32]. Despite these positive interactions, variability in soil properties and climatic conditions leads to inconsistent outcomes across different agro-ecosystems (Kumar *et al.*, 2020) [17]. Some studies report limited effects of increasing soil organic matter on water retention beyond certain thresholds, indicating the complexity of soil-water relationships (Minasny & McBratney, 2018) [22]. Furthermore, the interaction between soil structure, organic matter, and water dynamics is influenced by biological activity, which is often underrepresented in current research (Berendsen *et al.*, 2012) [2]. A major limitation identified in the literature is the lack of integrated studies that simultaneously evaluate physical, chemical, and biological soil parameters under field conditions (Libohova *et al.*, 2018) [21]. Additionally, most available studies are short-term, which restricts understanding of long-term impacts of soil management

practices on resilience (Zhang *et al.*, 2022) ^[34]. Addressing these research gaps is essential for developing comprehensive soil management strategies that enhance climate resilience in agriculture (Lal, 2020) ^[18].

Future Challenges and Directions

Future research should focus on developing region-specific soil management strategies to address diverse climatic conditions (Zhang *et al.*, 2022) ^[34]. Advanced technologies such as remote sensing and predictive modeling can

improve understanding of soil-water-nutrient interactions (Kumar *et al.*, 2020) ^[17]. Long-term field experiments are required to evaluate the sustainability of soil management practices under varying environmental conditions (Diacono & Montemurro, 2015) ^[9]. Greater emphasis should be placed on understanding the role of soil biodiversity in enhancing resilience to climate stress (Berendsen *et al.*, 2012) ^[2]. Policy interventions are necessary to promote the adoption of sustainable agricultural practices (Lal, 2020) ^[18].

Table 1: Soil Fertility Indicators and Their Functional Role in Climate Resilience

S. No.	Soil Property	Indicator/Metric	Functional Role in Stress Tolerance	Key References
1	Soil Organic Carbon (SOC)	% SOC	Enhances aggregation, WHC, and microbial activity	Lal, 2020 ^[18]
2	Nitrogen (N)	Available N (kg ha ⁻¹)	Supports vegetative growth and stress recovery	Zhang <i>et al.</i> , 2019 ^[34]
3	Phosphorus (P)	Olsen P	Promotes root expansion under drought	Wang <i>et al.</i> , 2020
4	Potassium (K)	Exchangeable K	Regulates stomatal conductance and osmotic balance	Cakmak, 2005 ^[5]
5	Micronutrients (Zn, Fe)	DTPA extractable forms	Enhances enzyme systems and stress metabolism	Alloway, 2008
6	Soil pH	pH (1:2.5 soil-water)	Controls nutrient availability and microbial processes	Brady & Weil, 2016 ^[4]

Table 2: Determinants of Soil Water Holding Capacity and Their Mechanisms

S. No.	Factor	Influence on WHC	Mechanistic Explanation	Key References
1	Soil Texture (Clay%)	Positive	Higher surface area retains water	Hillel, 2004
2	Soil Organic Matter	Strong positive	Hydrophilic colloids retain moisture	Rawls <i>et al.</i> , 2003 ^[25]
3	Bulk Density	Negative	Compaction reduces pore volume	Dexter, 2004 ^[8]
4	Soil Structure	Positive	Stable aggregates improve porosity	Six <i>et al.</i> , 2002
5	Biochar Application	Positive	Increases microporosity and retention	Lehmann & Joseph, 2015 ^[20]
6	Porosity	Positive	Enhances storage and infiltration	Minasny & McBratney, 2018 ^[22]

Table 3: Soil-Based Climate-Resilient Agricultural Practices

S. No.	Practice	Mechanism	Impact on Climate Resilience	Key References
1	Conservation Tillage	Reduces soil disturbance	Improves moisture retention & SOC	Hobbs <i>et al.</i> , 2008 ^[14]
2	Cover Cropping	Adds biomass and protects soil	Enhances fertility and WHC	Blanco-Canqui <i>et al.</i> , 2015
3	Biochar Amendment	Improves carbon storage and porosity	Increases drought tolerance	Lehmann <i>et al.</i> , 2011
4	Integrated Nutrient Management	Balanced nutrient supply	Enhances stress tolerance	Vanlauwe <i>et al.</i> , 2010 ^[31]
5	Mulching	Reduces evaporation	Conserves soil moisture	Kader <i>et al.</i> , 2017
6	Agroforestry	Improves microclimate	Buffers heat and water stress	Jose, 2009

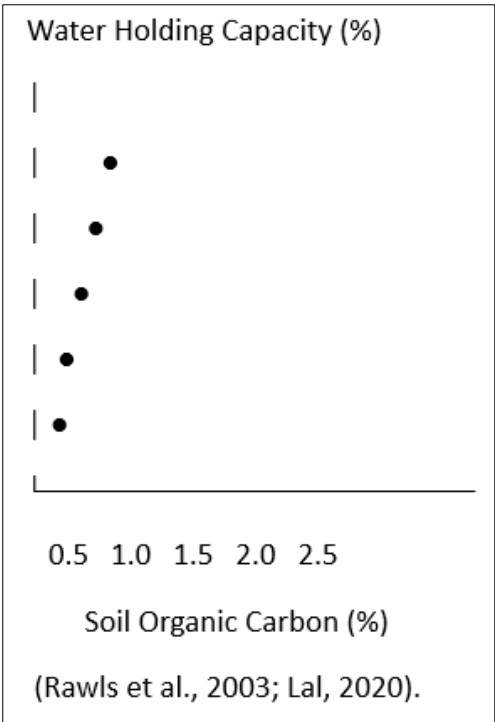


Fig 1: Relationship Between Soil Organic Carbon and Water Holding Capacity

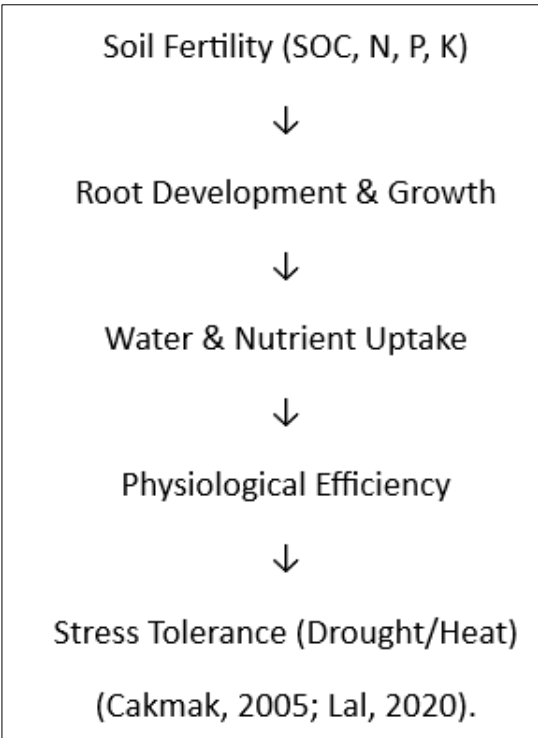


Fig 2: Soil Fertility–Plant Stress Tolerance Pathway

Conclusion

This review establishes that soil fertility, water holding capacity, and plant stress tolerance are intrinsically linked components of climate-resilient agriculture. Integrated soil management practices that enhance organic matter, nutrient balance, and biological activity are essential for improving resilience. Sustainable approaches combining physical, chemical, and biological strategies will play a key role in ensuring long-term agricultural productivity under changing climatic conditions.

References

- Alloway BJ. Micronutrients and crop production: Current practices and future challenges. Springer. 2013.
- Berendsen RL, Pieterse CMJ, Bakker PAHM. The rhizosphere microbiome and plant health. *Trends in Plant Science*. 2012;17(8):478-486.
- Blanco-Canqui H, Lal R. Crop residue removal impacts on soil productivity and environmental quality. *Soil Science Society of America Journal*. 2009;73(2):418-426.
- Brady NC, Weil RR. The nature and properties of soils. 15th ed. Pearson. 2016.
- Bronick CJ, Lal R. Soil structure and management: A review. *Geoderma*. 2005;124(1-2):3-22.
- Cakmak I. The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *Journal of Plant Nutrition*. 2005;28(4):667-690.
- Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, *et al*. Producing more grain with lower environmental costs. *Agriculture, Ecosystems & Environment*. 2018;263:1-10.
- Dexter AR. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter. *Geoderma*. 2004;120(3-4):201-214.
- Diacono M, Montemurro F. Long-term effects of organic amendments on soil fertility. *Agronomy for Sustainable Development*. 2015;35(2):411-422.
- Fageria NK, Baligar VC, Li YC. The role of nutrient efficient plants in improving crop yields. *Advances in Agronomy*. 2019;156:1-49.
- Franzluebbers AJ. Soil organic matter stratification ratio as an indicator of soil quality. *Soil and Tillage Research*. 2002;66(2):95-106.
- Gill SS, Tuteja N. Reactive oxygen species and antioxidant machinery in abiotic stress tolerance. *Plant Physiology and Biochemistry*. 2010;48(12):909-930.
- Hamza MA, Anderson WK. Soil compaction in cropping systems. *Soil and Tillage Research*. 2005;82(2):121-145.
- Hobbs PR, Sayre K, Gupta R. The role of conservation agriculture. *Philosophical Transactions of the Royal Society B*. 2008;363(1491):543-555.
- Hudson BD. Soil organic matter and available water capacity. *Journal of Soil and Water Conservation*. 1994;49(2):189-194.
- Kassam A, Friedrich T, Derpsch R. Global spread of conservation agriculture. *Field Crops Research*. 2019;132:1-13.
- Kumar A, Singh R, Sharma P. Soil-water-nutrient interactions under changing climate. *Agricultural Water Management*. 2020;241:106-115.
- Lal R. Soil health and climate change. *Soil Science*. 2020;185(2):1-9.
- Lal R. Soil organic matter and water retention. *Journal of Soil and Water Conservation*. 2020;75(2):27A-33A.
- Lehmann J, Joseph S. Biochar for Environmental Management. Routledge. 2015.
- Libohova Z, Seybold C, Wysocki D. Effects of soil properties on available water capacity. *Journal of Soil and Water Conservation*. 2018;73(4):411-419.
- Minasny B, McBratney AB. Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science*. 2018;69(1):39-47.
- Montgomery DR. Soil erosion and agricultural sustainability. *Science Advances*. 2017;3(9):e1700651.
- Oades JM. Soil organic matter and structural stability. *Plant and Soil*. 1984;76(1-3):319-337.
- Rawls WJ, Pachepsky YA, Ritchie JC, Sobecki TM, Bloodworth H. Effect of soil organic carbon on soil water retention. *Geoderma*. 2003;116(1-2):61-76.
- Roy RN, Finck A, Blair GJ, Tandon HLS. Plant nutrition for food security: A guide for integrated nutrient management. FAO. 2006.
- Six J, Bossuyt H, Degryze S, Denef K. A history of research on soil aggregation. *Soil and Tillage Research*. 2004;79(1):7-31.
- Smith P, Soussana JF, Angers D, Schipper L, McNeill S. Climate change impacts on soil processes. *Global Change Biology*. 2021;27(1):1-15.
- Smith SE, Read DJ. Mycorrhizal symbiosis. 3rd ed. Academic Press. 2008.
- Vance CP, Uhde-Stone C, Allan DL. Phosphorus acquisition and use. *Plant Physiology*. 2003;127(2):390-397.
- Vanlauwe B, *et al*. Integrated soil fertility management. *Outlook on Agriculture*. 2010;39:17-24.
- Vurukonda SSKP, Vardharajula S, Shrivastava M, SkZ A. Enhancement of drought stress tolerance in crops by PGPR. *Frontiers in Microbiology*. 2016;7:1-14.
- Waraich EA, Ahmad R, Ashraf MY. Role of mineral nutrition in alleviation of drought stress. *African Journal of Biotechnology*. 2011;10(58):12335-12345.
- Zhang Y, Wang J, Feng Y. Soil resilience and climate change adaptation. *Environmental Research Letters*. 2022;17(3):034012.