Review Article

Influence of Soil on Crop Performance and Ecosystem Services: A Review

Abstract

Globally, the soil has a direct or indirect role in effective and sustainable agricultural production. This is due to the soil's multiple benefits to the creation of food, whether it comes from crops or animals. The pH, organic matter content, and nutritional balance of soils all affect how well they perform as vital life supports and nourishment sources. In addition to supporting a variety of living things and aiding in water regulation, these substrates are essential for sequestering carbon, particularly in light of climate change. But because of climate and human influences, soils are under danger, necessitating proactive resource management techniques. Combating degradation of the soil, which is impacted by things like unsustainable agriculture, deforestation, and inadequate irrigation, is essential to stopping desertification. Sustainable practices like nutrient management and integrated soil fertility management, proper tillage operation, etc. aim to increase crop productivity and improve soil fertility. Management techniques and environmental modifications have the potential to boost sustainability and enhance ecosystem serviceand help create agroecosystems that are robust to stress, resource efficiency, and climate change.

Keywords:soil fertility, crop growth and productivity, sustainability, ecosystem service

1. Introduction

Global soil degradation is a significant environmental issue, and there is compelling evidence that the processes leading to soil degradation pose a short-term risk to biomass and economic yields as well as a long-term risk to crop yields in the future. The foundation of our ecosystems is the diverse function that soils play in sustaining plant development, controlling water flow, cycling nutrients, and maintaining a wide variety of species [1,2]. Additionally, soils are important for regulating temperature and reducing greenhouse gas emissions because they function as sinks for carbon (C) [3,4]. But human demands and the effects of climate change have caused an alarming decline in the ecological services that soils offer, jeopardising the health of the world. Nonetheless, more obvious environmental issues sometimes eclipse the intricacy and significance of soils [5,6].

The loss of soil structure is frequently linked to land use and soil/crop management techniques, and it is increasingly recognised as a kind of soil degradation. Due to human activities like pollution, industrial agriculture, deforestation, and urbanisation, soils have to contend with a previously unheard-of range of difficulties. These dangers have impacted the ability of the soil to deliver vital ecosystem services by causing extensive soil degradation, erosion, salinization, and desertification [7]. In addition to negatively impacting the planet's ecosystem services and general climatic conditions, such a scenario increases the dangers of soil erosion, desertification, and biodiversity loss [8]. These difficulties are made worse by the demands of a world population that is predicted to expand by 70% to around 10 billion people by the year 2050 [9]. Soil structure affects externalities including runoff, contamination of surface and ground waters, and emissions of CO_2. Reducing tillage and fertilisation can lower greenhouse gas emissions since they use less fossil fuel for agriculture and production inputs. Management techniques have an impact on species biodiversity; generally speaking, high-input agricultural techniques reduce biodiversity while low-input techniques increase it. Finding ways to boost crop production without sacrificing environmental quality is crucial given the growing population and urbanisation.

Quantifying the alterations to the soil ecosystem is essential for assessing the effects of management strategies on the soil environment. As the cornerstone of flourishing ecosystems and communities, healthy soils are also intimately related to biodiversity, water quality, human health, mitigation and adaptation of climate change, and food and nutritional security [10,11]. It is critical to stop land degradation brought on by nutrient losses, soil erosion, and losses of ecological integrity [12]. This review focuses on a broad spectrum of anthropogenic and environmental elements and their dynamic interactions. In order to increase agricultural production and sustainability, soil factors are examined in connection to the environment, biological components, and management techniques.

Comment [H1]: May add some recent references.

2. Soils in Ecosystem Services and Nutrient Cycling

The foundation of life on Earth, soils enable essential ecological processes that support and maintain life as we know it. With an emphasis on both biogeochemical and ecological viewpoints, this chapter delves deeply into the complex role that soils play in ecosystem services and nutrient cycling [13]. A wide variety of plants and animals, including a vast array of microorganisms that power biogeochemical processes, may be found in soils, which serve as the foundation of terrestrial ecosystems [14]. The supply of ecosystem services—the innumerable advantages that nature offers to humans—is supported by this biodiversity and is frequently influenced by soil characteristics including texture, structure, and organic matter concentration [15,16]. These services fall under the following categories [17].

Providing services: Refers to the material goods made from soils, such as food, fuel, fibre, medicinal plants, and more. Over 2.5 billion people were projected by the World Bank to be directly dependent on agriculture in 2007 [18]. This underscores the critical role that soil health plays in maintaining global food security. This highlights the complicated relationships that are becoming more recognised between crop output, nutritional content, and soil conditions [19]. Nevertheless, unsustainable farming methods such as over cultivation and improper use of chemical fertilisers are steadily reducing soil fertility, endangering food supply in the future, and causing further unanticipated environmental effects [19-21].

Comment [H2]: Provisioning

Controlling services: Includes managing ecological systems and processes. In addition to reducing flood risks and guaranteeing the availability of clean water for use by humans and the environment, soils also play a critical role in water regulation by absorbing, storing, and purifying water through soil-water interactions that are influenced by factors such as soil cation exchange capacity, porosity, and land management [22]. The mitigation of climate change by carbon sequestration is another important regulatory function. By acting as a carbon sink and reducing the impacts of greenhouse gases, soil organic matter has the ability to be strategically manipulated through certain land use practices [23,24].

Supporting services: Uphold biodiversity and facilitate other ecosystem services like nutrient cycling, which is essential to soil fertility, preserving soil structure, and promoting biodiversity. These activities involve intricate interactions between plants, microorganisms, and soil minerals [25].

Cultural services: Include the intangible benefits of ecosystems such as intellectual growth, spiritual enrichment, leisure, and aesthetic enjoyment[26].

Comment [H3]: Add the reference of Bhatt et al, 2024 for the clarity in cultural ecosystem services

Soils play a crucial role in providing these cultural benefits due to their extensive biodiversity (Table 1). They reinforce a feeling of location and cultural identity by sculpting landscapes, influencing regional customs and practices, and igniting creative and spiritual endeavours [27]. But the availability of these ecological services is becoming more and more threatened by human demands and climate change. A major worldwide problem is soil degradation, which is defined by the loss of soil organic matter, the depletion of nutrients, and the disturbance of soil structure. Among the main drivers of soil degradation, disturbance of nutrient cycling, and negative effects on biodiversity and ecosystem services include changes in land-use patterns, deforestation, and inefficient agriculture techniques. Since these processes are intimately related to larger socio-ecological systems, conservation and management must be approached holistically [28].

Table 1: Multifaceted Roles of Soils in Ecosystem Services and Nutrient Cycling

Role of Soil	Description	Ecosystem Service	References
Support for Biodiversity	Supports diverse flora, fauna, and microorganisms driving biogeochemical processes.	Supporting	[29]
Provisioning Services	Includes tangible products derived from soils like food, fiber, fuel, medicinal plants.	Provisioning	[20]
Soil Health & Global Food Security	Link between soil properties, crop yield, and nutritional content. Importance of sustainable practices.	Provisioning	[21]
Water Regulation	Absorbs, stores, and purifies water, influenced by factors like cation exchange capacity, porosity, and land management.	Regulating	[22,30]
Climate Change Mitigation	Acts as a carbon sink through soil organic matter, mitigating greenhouse gases.	Regulating	[23,24]
Nutrient Cycling	Fundamental to soil fertility, maintaining soil structure, and fostering biodiversity.	Supporting	[25]
Cultural Services	Encompasses spiritual enrichment, intellectual development, recreation, and aesthetic enjoyment. Shapes landscapes, traditions, artistic, and spiritual endeavors.	Cultural	[27]
Soil Degradation &	Characterized by nutrient depletion, loss of organic matter, and disruption of structure,	-	[28]

Nutrient Depletion	leading to land degradation.		
Strategic Soil Management	Need to prioritize sustainable soil management, including conservation, reducing degradation, and restoration. Fundamental to continued provision of ecosystem services and nutrient cycling.	-	[28]

Comment [H4]: Please update the table with new references

3. Soils in Plant Growth Mechanism

Soil is a natural resource that gives plants the assistance they need to grow and develop. It does this by facilitating root penetration, maintaining soil pH levels, and offering structural appropriateness and water retention capacity. It performs a variety of tasks that promote plant growth and development in terms of anchoring, nutrient and water supply, as it interfaces with the lithosphere, hydrosphere, atmosphere, and biosphere [31].

Anchorage: For plants to thrive and proliferate on land, the soil serves as a crucial and fundamental substrate or basis. According to Biswas and Mukherjee [32], the ground (soil) or base aids in providing deep anchoring for plant roots to endure high winds and/or lightning.

Nutrient supply: The soil stores nutrients and enables them to change into forms that are useful. The biotic kingdom receives its food supplementation from the soil due to its fertility and productive capacity. The main factor in restoring soil fertility is well-drained soil. According to Sahai [33], soil organic matter enhances soil structure, moisture retention, and root penetration.

Water supply: Soil is the repository of water wealth. Organic matter in the soil contributes to better root penetration, moisture retention, and soil structure. The area of saturated flow in the soil is known as the groundwater and is found there. Water from that region percolates through the soil profile to reach the parts where plant roots may absorb it through the process of infiltration [34].

4. Soil Fertility and Crop Growth

Natural nutrient cycling has taken place throughout Earth's history, with plants and animals receiving nutrients from the soil and returning it to the environment through the breakdown of biomass. The vital nutrients needed for plant development in the soil are preserved in part by this cycle. A variety of physical, chemical, and, most crucially, biological processes are combined in complex nutrient cycles to track the environmental destiny of certain plant nutrients (such as N, P, C, and S) (Fig. 1). Further reference materials are available for a comprehensive investigation of these cycles [35-37].

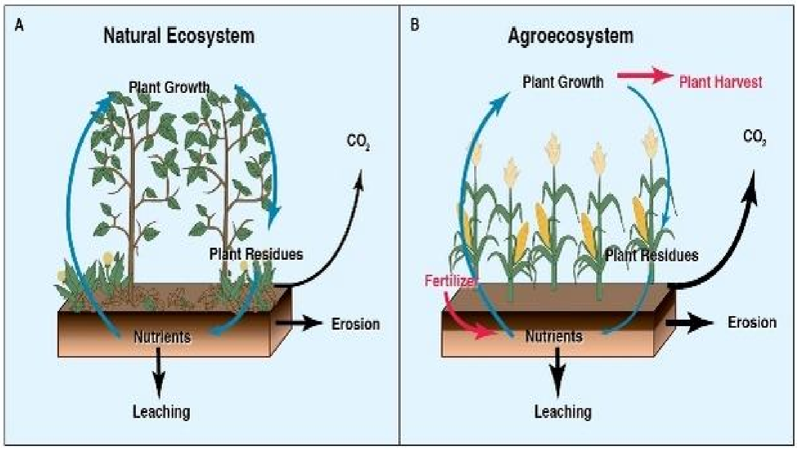

Fig. 1: Nutrient cycling (a) a natural ecosystem and (b) an agroecosystem

(Source: Parikh, [38])

According to Troeh and Thompson [37], there are generally acknowledged to be seventeen key components needed for plant development. The output of crops may be severely limited if any one of these vital nutrients is lacking. The key macronutrients—N, P, and K—are the constituents of minerals that plants require the most from the soil and are most likely to be scarce in agricultural soils. Secondary macronutrients are not usually limiting factors for crop growth since they are required in lesser amounts and are generally present in sufficient amounts in the soil. The micronutrients, also known as trace nutrients, are required in minuscule amounts and can be harmful to plants in excess.

The normal cycle of nutrients in soil is altered by agriculture. Plant nutrients may be efficiently mined from the soil by intensive crop production and harvesting for human or animal use. Soil additives are usually needed to keep the soil fertile enough to provide adequate agricultural yields. Farmers now apply a wide range of soil amendments, such as compost or manure, as well as inorganic chemical fertilisers, to improve soil fertility. This practice frequently results in an excess of primary macronutrients. Crops' application and utilisation of fertilisers is not always efficient, and surplus nutrients—particularly N and P—can contaminate surface and groundwater via leaching from agricultural fields or being carried by surface runoff [39-40]. Choosing the right amount of fertilizers and from organic source have been proven to increase the soil microbial and enzymatic activities. This lead to improve soil fertility resulting in enhanced plant growth and productivity.

5. Soil Health Management, Indicators and Crop Productivity

Confusion surrounds attempts to connect soil health to production since there is disagreement about what defines a "healthy soil" and which frameworks and metrics are most appropriate [41,42]. The lack of a common link between soil health metrics and this fundamental agronomic outcome in assessment frameworks, the infrequency with which yield data are evaluated or reported, and the rarity of studies reporting changes in both soil health indicators and yields with management all contribute to the confusion surrounding the relationship between SH and yields [41,43-45]. Although there is limited direct evidence linking higher soil organic matter (SOM) to higher yields (independent of exogenous organic inputs), soil organic matter (SOM) is widely regarded as the primary soil health indicator due to its positive correlation with numerous biological, chemical, and physical soil health indicators. Additionally, there is still much work to be done to separate regionally specific controls and causative interactions of management, soil type, and climate on the SOM–yield relationship [46,47].

To maximise soil health in relation to improving crop productivity, four guidelines have been proposed: (a) reduce disturbance (no-till); (b) increase plant variety; (c) retain live roots all year round; and (d) increase soil covering [48]. It is well known that different cropping rotations increase yield over continuous monoculture; potential "rotational effects" that increase yield includes reduced insect, weed, and disease pressures as well as increased nutrient availability [49-52]. These ideas are almost exactly the same as those of conservation agriculture (CA), which has been proposed for at least 20 years. The definition of conservation agriculture is (a) no-till or low soil disturbance, (b) permanent soil cover provided by crops, covercrops, or mulch, and (c) varied crop rotations [53]. This vast corpus of work offers a reliable prism through which to examine the possible yield of managing for soil health; it need to be used to formulate and pinpoint the topics that need more investigation as well as to determine which ones have already received sufficient attention.

6. Sustainable Soil Management

6.1 Minimizing Soil Disturbance (No-Till) and Crop Yields

No-till methods can have significant positive effects on the economy and environment by minimising mechanical soil disturbance according to Delgado et al. [54]. These advantages include less field operations, decreased erosion, preservation of nutrient-rich top soil, and enhanced water uptake and retention. A recent worldwide meta-analysis comparing yields under no-till and conventional tillage employing over 5,000 paired yield data across crop types discovered that adopting no-till alone resulted in an overall yield decrease of −9.9% [55], but when no-till was combined with residue retention (−5.2%) or rotation (−6.2%), yield decreases were mitigated. Negative yield impacts were further minimised when all three techniques were used concurrently (−2.5%) [55].

6.2 Cover Crops and Crop Yields

Cover crops offer a variety of ecological advantages, such as decreased erosion and nutrient losses, increased nutrient scavenging and cycling, and N fixation by symbiotic bacteria in legume cover crops [56,57]. Cover crop impacts on marketable cash crop yields are dependent on variables such as crop rotation, climate, growing season length, tillage, soil type, cover crop species, timing and method of termination, and years in cover crop. By absorbing radiation and protecting the soil surface, cover crops regulate soil temperatures. This can have a beneficial effect on yield in warm climates but a negative effect on soil warming and crop establishment in cool climates [56,58]. In the United States and Canada, a recent meta-analysis of corn yield responses under winter conservation systems revealed that grass winter cover crops increase the corn yields with incorporation of legume [59]. According to a review of 17 experiments conducted in temperate U.S. regions, cover crops improved the yields of cash crops in 11 of the trials that followed [56].

7. Soil Sustainable Development and Food Security

Sustainable intensification for food security advocates for increasing food productivity from existing farmland in a manner that reduces environmental impact and enhances resilience to climate change [60-62]. A thorough understanding of the role that soil plays in food production is required, as soil health—which is threatened by salinization, erosion, desertification, and climate change—is exacerbated by unsustainable practices that undermine soil health, endangering our food systems [63] and a range of services essential to agriculture [64]. Mitigating these dangers requires a shift to sustainable agricultural techniques that enhance soil health. Enhancing soil fertility, biodiversity, and overall resilience of agricultural systems may be achieved by the application of techniques such as crop rotation, organic farming, conservation agriculture, and agroforestry [65]. Regenerative agriculture presents a viable path towards sustainable food production by restoring biodiversity and regenerating soils [66].

Farmers must be knowledgeable about effective water and nutrient management, soil health, and sustainable farming techniques. Efforts should be made to make this information accessible and useful. Promoting sustainable farming may be greatly aided by financial incentives. Furthermore, the achievement of sustainable intensification objectives may benefit from advances in agrotech, such as precision agriculture and the use of AI and machine learning to anticipate soil health metrics and crop output [67]. These technologies might assist control the growing unpredictability brought on by climate change, optimise inputs, and reduce their negative effects on the environment [68].

Sustainable soil management and a move towards more sustainable agricultural methods are imperative due to the complex interrelationships among soils, sustainable development, and food production and security [69]. Promising avenues for sustainable food production and soil conservation are provided by cutting-edge agricultural techniques, scientific discoveries, and all-encompassing regulatory frameworks—despite the potential difficulties that may arise. Against the backdrop of growing populations and unpredictable climate change, these diverse strategies that combine policy, technical, and socioeconomic elements can be used to support sustainable development and guarantee global food security. There is a significant role for consumers as well. Demand for more sustainably produced goods may change as a result of growing understanding of the negative environmental effects of food production [70,71].

8. Conclusion

The extensive function that soils play in our lives and their deep influence on the environment, climate change, sustainability, food production, and our eating patterns highlight how intertwined the world's systems are. This review study has examined these intricate relationships and underlined how urgent it is to reconsider and update our strategy for managing soil. Soils are essential to biodiversity and human life because they support nutrient cycling and serve as the basis for ecosystem services. However, a number of issues, including as pollution, deforestation, and unsustainable farming methods, are putting this vital resource in jeopardy. Sustainable soil management is evidently important for our future survival, not merely for environmental reasons. In order to improve agricultural productivity and ecosystem services, we may encourage more resilient, sustainable farming methods by increasing awareness of these linked challenges.

References

1. Wang, X. Managing Land Carrying Capacity: Key to Achieving Sustainable Production Systems for Food Security. Land 2022, 11, 484.
2. Wijerathna-Yapa, A.; Pathirana, R. Sustainable Agro-Food Systems for Addressing Climate Change and Food Security. Agriculture 2022, 12, 1554.
3. Weil, R.R.; Brady, N.C. The Nature and Properties of Soils, 15th ed.; Pearson Prentice Hall: Harlow, UK; London, UK; New York, NY, USA, 2017; ISBN 978-1-29216-223-2.
4. Rahman, S.; Ali, A.; Raihan, A. Soil Carbon Sequestration in Agroforestry Systems as a Mitigation Strategy of Climate Change: A Case Study from Dinajpur, Bangladesh. Adv. Environ. Eng. Res. 2022, 3, 1–13.
5. Mansoor, S.; Farooq, I.; Kachroo, M.M.; Mahmoud, A.E.D.; Fawzy, M.; Popescu, S.M.; Alyemeni, M.N.; Sonne, C.; Rinklebe, J.; Ahmad, P. Elevation in Wildfire Frequencies with Respect to the Climate Change. J. Environ. Manag. 2022, 301, 113769.
6. Ahmad Rather, R.; Bano, H.; Ahmad Padder, S.; Perveen, K.; Al Masoudi, L.M.; Saud Alam, S.; Ho Hong, S. Anthropogenic Impacts on Phytosociological Features and Soil Microbial Health of Colchicum luteum L. an Endangered Medicinal Plant of North Western Himalaya. Saudi J. Biol. Sci. 2022, 29, 2856–2866.
7. Shen, L.; Cheng, G.; Du, X.; Meng, C.; Ren, Y.; Wang, J. Can Urban Agglomeration Bring "1 + 1 > 2Effect"? A Perspective of Land Resource Carrying Capacity. Land. Use Policy 2022, 117, 106094.
8. Francaviglia, R.; Almagro, M.; Vicente-Vicente, J.L. Conservation Agriculture and Soil Organic Carbon: Principles, Processes, Practices and Policy Options. Soil. Syst. 2023, 7, 17.
9. Cherlet, M.; Hutchinson, C.; Reynolds, J.; Hill, J.; Sommer, S.; von Maltitz, G. World Atlas of Desertification Rethinking Land Degradation and Sustainable Land

Management; Publications Office of the European Union: Luxembourg, 2018; ISBN 978-9-27975-350-3.

10. Manter, D. K., Delgado, J. A., Blackburn, H. D., Harmel, D., de León, A. A. P., & Honeycutt, C. W. (2017). Opinion: Why we need a national living soil repository. Proceedings of the National Academy of Sciences of the USA, 114, 13587–13590.
11. National Academies of Sciences, Engineering, and Medicine. (2017). Soils: The foundation of life—Proceedings of a workshop, in brief. Washington, DC: National Academies Press. https://doi.org/10.17226/24866.
12. IPCC. (2019). Summary for policymakers. In: P.R. Shukla et al. (Eds.), Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC.
13. Marín-Sanleandro, P.; Gómez-García, A.M.; Blanco-Bernardeau, A.; Gil-Vázquez, J.M.; Alías-Linares, M.A. Influence of the Type and Use of Soil on the Distribution of Organic Carbon and Other Soil Properties in a Sustainable and Resilient Agropolitan System. Forests 2023, 14, 1085.
14. Ramírez, M.; López-Piñeiro, A.; Peña, D.; Rato Nunes, J.; Albarrán, Á.; Muñoz, A.; Gama, J.; Loures, L. Seasonal and Interannual Fluctuation of the Microbial Soil Community in a Maize Field under Long-Term Conservation Agriculture Management. Sustainability 2017, 9, 778.
15. Kaletová, T.; Loures, L.; Castanho, R.A.; Aydin, E.; da Gama, J.T.; Loures, A.; Truchy, A. Relevance of Intermittent Rivers and Streams in Agricultural Landscape and Their Impact on Provided Ecosystem Services—A Mediterranean Case Study. Int. J. Environ. Res. Public Health 2019, 16, 2693.
16. Telo da Gama, J.; Rato Nunes, J.; Loures, L.; Lopez Piñeiro, A.; Vivas, P. Assessing Spatial and Temporal Variability for Some Edaphic Characteristics of Mediterranean Rainfed and Irrigated Soils. Agronomy 2019, 9, 132.
17. MEA. Ecosystems and Human Well-Being: Wetlands and Water; World Resources Institute: Washington, DC, USA, 2005; ISBN 1-56-973597-2.
18. World Bank. World Development Report 2008: Agriculture for Development; The World Bank: Washington, DC, USA, 2007; ISBN 978-0-82136-807-7.
19. Telo da Gama, J.; Loures, L.; Lopez-Piñeiro, A.; Quintino, D.; Ferreira, P.; Nunes, J.R. Assessing the Long-Term Impact of Traditional Agriculture and the Mid-Term Impact of Intensification in Face of Local Climatic Changes. Agriculture 2021, 11, 814.
20. Kumar, A.; Burdak, B.; Thakur, H.; Harshavardhan, S.; Nalamala, S. A Review on Role of Micro Irrigation for Modern Agriculture. Pharma Innov. J. 2023, 12, 2585–2589.
21. FAO. Status of the World’s Soil Resources: Main Report; FAO: Rome, Italy, 2015; p. 648.

22. Loures, L.; Gama, J.; Nunes, J.; Lopez-Piñeiro, A. Assessing the Sodium Exchange Capacity in Rainfed and Irrigated Soils in the Mediterranean Basin Using GIS. Sustainability 2017, 9, 405.
23. Lal, R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 2004, 304, 1623–1627.
24. Lacerda, N.B.D.; Lustosa Filho, J.F.; Blum, S.C.; Escobar, M.E.O.; Oliveira, T.S.D. Organic Matter Pools in a Fluvisol after 29 Years under Different Land Uses in an Irrigation Region in Northeast Brazil. J. Arid Environ. 2023, 208, 104861.
25. Bennett, E.M.; Peterson, G.D.; Gordon, L.J. Understanding Relationships among Multiple Ecosystem Services. Ecol. Lett. 2009, 12, 1394–1404.
26. Telo da Gama J. The Role of Soils in Sustainability, Climate Change, and Ecosystem Services: Challenges and Opportunities. Ecologies. 2023; 4(3):552-567. https://doi.org/10.3390/ecologies4030036.
27. Daniel, T.C.; Muhar, A.; Arnberger, A.; Aznar, O.; Boyd, J.W.; Chan, K.M.; Costanza, R.; Elmqvist, T.; Flint, C.G.; Gobster, P.H. Contributions of Cultural Services to the Ecosystem Services Agenda. Proc. Natl. Acad. Sci. USA 2012, 109, 8812–8819.
28. Montanarella, L.; Pennock, D.J.; McKenzie, N.; Badraoui, M.; Chude, V.; Baptista, I.; Mamo, T.; Yemefack, M.; Singh Aulakh, M.; Yagi, K. World's Soils Are under Threat. Soil 2016, 2, 79–82.
29. Ramírez, M.; López-Piñeiro, A.; Peña, D.; Rato Nunes, J.; Albarrán, Á.; Muñoz, A.; Gama, J.; Loures, L. Seasonal and Interannual Fluctuation of the Microbial Soil Community in a Maize Field under Long-Term Conservation Agriculture Management. Sustainability 2017, 9, 778.
30. Dominati, E.; Patterson, M.; Mackay, A. A Framework for Classifying and Quantifying the Natural Capital and Ecosystem Services of Soils. Ecol. Econ. 2010, 69, 1858–1868.
31. Francaviglia, R.; Almagro, M.; Vicente-Vicente, J.L. Conservation Agriculture and Soil Organic Carbon: Principles, Processes, Practices and Policy Options. Soil. Syst. 2023, 7, 17.
32. Biswas, T.D. and Mukherjee, S.K. (2013) Textbook of Soil Science (2nd ed.), McGraw Hill Education (India) Private Limited, New Delhi, 86-87.
33. Sahai, V.N. (2011). Fundamental of Soil, Kalayani Publishers, New Delhi, 138-142.
34. Schoonover, J.E. and Crim, J.F. (2015). An Introduction to Soil Concepts and the Role of Soils in Watershed Management. Journal of Contemporary Water Research & Education, Issue 154: 21-47.
35. Bernhard, A. The Nitrogen Cycle: Processes, Players, and Human Impact. Nature Education Knowledge 2, 12 (2010).
36. Brady, N. C. & Weil, R. R. The Nature and Properties of Soil, 14th ed. Prentice Hall, 2008.
37. Troeh, F. R. & Thompson, L. M. Soils and Soil Fertility, 5th ed. Oxford University Press, 1993.

38. Parikh, S. J. & James, B. R. (2012) Soil: The Foundation of Agriculture. Nature Education Knowledge 3(10):2.
39. Moss, B. Water pollution by agriculture. Philosophical Transactions of the Royal Society B-Biological Sciences 363, 659-666, doi:10.1098/rstb.2007.2176 (2008).
40. Sharpley, A. N., Haygarth, P. M. & Jarvis, S. C. Introduction: Agriculture as a potential source of water pollution. Agriculture, hydrology and water quality, 4-5 (2002).
41. Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G.,de Goede, R., . . . Mäder, P. (2018). Soil quality: A critical review.Soil Biology and Biochemistry, 120, 105–125. http://doi.org/10.1016/j.soilbio.2018.01.030.
42. Wander, M. M., Cihacek, L., Coyne, M., Drijber, R., Grossman, J.,Gutknecht, J. L., . . . Snapp, S. (2019). Developments in agriculturalsoil quality and health: Reflections by the Research Committee onSoil Organic Matter Management. Frontiers in Environmental Sci-ence, 7, 109. http://doi.org/10.3389/fenvs.2019.00109.
43. Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D.,Reiter, M. S., & Strickland, M. S. (2018). What we talk about whenwe talk about soil health. Agricultural & Environmental Letters, 3,180033. https://doi.org/10.2134/ael2018.06.0033.
44. Devi OR, Ojha N, Laishram B and Devi OB. Opportunities and Challenges of Soil Fertility Management in Organic Agriculture. Vigyan Varta. 2023; 4(8): 228-232.
45. Kiran Doggali G, Tiwari U, Pandey PK, Devi OR, Gireesha D, Laishram B and Patel A. Discovering new frontiers in plant breeding: The fascinating world of advancements shaping future growth. International Journal of Research in Agronomy. 2024; 7(1):441–445. https://doi.org/10.33545/2618060x.2024.v7.i1f.262.
46. Lal, R. (2020). Soil organic matter content and crop yield. Journal ofSoil and Water Conservation, 75, 27A–32A. http://doi.org/10.2489/jswc.75.2.27A.
47. Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and cropyields. Soil, 5, 15–32. http://doi.org/10.5194/soil-5-15-2019.
48. USDA-NRCS. (2019). Soil health. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.
49. Beal Cohen, A. A., Seifert, C. A., Azzari, G., & Lobell, D. B. (2019).Rotation effects on corn and soybean yield inferred from satelliteand field-level data. Agronomy Journal, 111, 2940–2948. http://doi.org/10.2134/agronj2019.03.0157.
50. Laishram B, Devi OR and Ngairangbam H. Insight into Microbes for Climate Smart Agriculture. Vigyan Varta. 2023; 4(4):53-56.
51. Laishram B, Singh TB, Kalpana A, Wangkheirakpam M, Chongtham SK and Singh W. Effect of Salicylic Acid and Potassium Nitrate on Growth and Yield of Lentil (Lens culinaris L.) under Rainfed Condition. International Journal of Current Microbiology and Applied Sciences. 2020; 9(11):2779–2791. https://doi.org/10.20546/ijcmas.2020.911.337.

52. Seifert, C. A., Roberts, M. J., & Lobell, D. B. (2017). Continuouscorn and soybean yield penalties across hundreds of thousandsof fields. Agronomy Journal, 109, 541–548. http://doi.org/10.2134/agronj2016.03.0134.
53. Hobbs, P. R., Sayre, K., & Gupta, R. (2007). The role of conservationagriculture in sustainable agriculture. Philosophical Transactionsof the Royal Society B: Biological Sciences, 363, 543–555. http://doi.org/10.1098/rstb.2007.2169.
54. Delgado, J., Barrera Mosquera, V., Escudero López, L., CartagenaAyala, Y., Alwang, J., Stehouwer, R., . . . Valverde, F. (2019). Conser-vation agriculture increases profits in an Andean region of SouthAmerica. Agrosystems, Geosciences & Environment 2, 180050.
55. Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee,J., Lundy, M. E., . . . Van Kessel, C. (2015). Productivity limits andpotentials of the principles of conservation agriculture. Nature,517, 365.
56. Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A.,Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Covercrops and ecosystem services: Insights from studies in temperatesoils. Agronomy Journal, 107, 2449–2474. http://doi.org/10.2134/agronj15.0086.
57. Devi KM, Devi OR, Laishram B, Luikham E, Priyanka E, Singh LR and Babasaheb DV. Effect of Planting Geometry and Nutrient Management on Yield, Economics and Quality of Dwarf Rice Bean (*Vigna umbellata*) under Rainfed Condition. International Journal of Plant and Soil Science. 2023; 35(9):1–9. https://doi.org/10.9734/ijpss/2023/v35i92897.
58. Snapp, S., Swinton, S., Labarta, R., Mutch, D., Black, J., Leep, R., . . .O'Neil, K. (2005). Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agronomy Journal,97, 322–332.
59. Marcillo, G., & Miguez, F. (2017). Corn yield response to winter covercrops: An updated meta-analysis. Journal of Soil and Water Con-servation, 72, 226–239. http://doi.org/10.2489/jswc.72.3.226.
60. Cassman, K.G.; Grassini, P. A Global Perspective on Sustainable Intensification Research. *Nat. Sustain.* **2020**, *3*, 262–268.
61. Devi, O.R, Ojha, N, Laishram, B., Dutta, S. and Kalita, P. (2023). Roles of Nano-Fertilizers in Sustainable Agriculture and Biosafety. Environment and Ecology, 41(1B): 457—463.
62. Xie, H.; Huang, Y.; Chen, Q.; Zhang, Y.; Wu, Q. Prospects for Agricultural Sustainable Intensification: A Review of Research. Land 2019, 8, 157.
63. Telo da Gama, J.; Loures, L.; Lopez-Piñeiro, A.; Quintino, D.; Ferreira, P.; Nunes, J.R. Assessing the Long-Term Impact of Traditional Agriculture and the Mid-Term Impact of Intensification in Face of Local Climatic Changes. Agriculture 2021, 11, 814.
64. Bangash, R.F.; Passuello, A.; Sanchez-Canales, M.; Terrado, M.; López, A.; Elorza, F.J.; Ziv, G.; Acuña, V.; Schuhmacher, M. Ecosystem Services in Mediterranean River Basin: Climate Change Impact on Water Provisioning and Erosion Control. *Sci. Total Environ.* **2013**, *458–460*, 246–255.

65. Nielsen, U.N.; Ayres, E.; Wall, D.H.; Bardgett, R.D. Soil Biodiversity and Carbon Cycling: A Review and Synthesis of Studies Examining Diversity-Function Relationships. *Eur. J. Soil. Sci.* **2011**, *62*, 105–116.
66. Newton, P.; Civita, N.; Frankel-Goldwater, L.; Bartel, K.; Johns, C. What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes. *Front. Sustain. Food Syst.* **2020**, *4*, 194.
67. Liakos, K.G.; Busato, P.; Moshou, D.; Pearson, S.; Bochtis, D. Machine Learning in Agriculture: A Review. Sensors 2018, 18, 2674.
68. Zhang, N.; Wang, M.; Wang, N. Precision Agriculture—A Worldwide Overview. Comput. Electron. Agric. 2002, 36, 113–132.
69. Keesstra, S.D.; Bouma, J.; Wallinga, J.; Tittonell, P.; Smith, P.; Cerdà, A.; Montanarella, L.; Quinton, J.; Pachepsky, Y.; Van Der Putten, W.H. Forum Paper: The Significance of Soils and Soil Science towards Realization of the UN Sustainable Development Goals (SDGS). Soil. Discuss. 2016, 2016, 1–28.
70. Laishram B, Singh TB, Devi OR, Khumukcham PS and Ngairangbam H. Yield, Economics, Nutrient uptake and Quality of Lentil (Lens culinaris L.) as Influence by Salicylic Acid and Potassium Nitrate under Rainfed Condition. Environment and Ecology. 2023; 41(3A):1591–1596. https://doi.org/10.60151/envec/hdsa3286.
71. Hartmann, C.; Siegrist, M. Consumer Perception and Behaviour Regarding Sustainable Protein Consumption: A Systematic Review. *Trends Food Sci. Technol.* **2017**, *61*, 11–25.