Advancements in Agronomic Practices for Sustainable Crop Production :A review

Abstract

This review provides a comprehensive analysis of the advancements in agronomic practices that contribute to sustainable crop production. In the context of escalating global food demand, climate change, and environmental concerns, sustainable agriculture has become a pivotal focus. This paper systematically examines the evolution of agronomic practices from traditional methods to contemporary innovations, highlighting the integration of technology, sustainability, and socio-economic factors in modern agriculture.The historical perspective of agronomic practices reveals a transition from rudimentary, labor-intensive methods to technologically driven, precision-based approaches. Traditional practices, while sustainable, often faced limitations in scalability and efficiency. The advent of the Green Revolution marked a significant shift, introducing high-yield crop varieties and synthetic inputs. However, the long-term ecological impacts of these methods prompted a reevaluation towards more sustainable practices.Contemporary advancements in agronomy are largely characterized by precision agriculture, which employs satellite and drone technology, sensor-based monitoring systems, and AI applications. These tools have revolutionized farming by enabling precise resource management and data-driven decision-making. In tandem, the rise of organic farming and integrated pest management reflects a growing emphasis on ecological balance and reduced chemical inputs.The paper also delves into the crucial role of education and extension services in disseminating modern agronomic knowledge, particularly in developing regions. Government policies and international regulations are analyzed for their impact on promoting sustainable practices. Additionally, the review addresses the vital aspect of environmental sustainability, focusing on strategies for carbon footprint reduction, biodiversity preservation, and ecosystem services enhancement.Technological innovations, especially in genetics and digital tools, are identified as key drivers in shaping future agronomic practices. The potential of CRISPR in crop improvement and the application of big data and IoT in farming are discussed as future trends.

Keywords:*Sustainability, Precision, Innovation, Genetics, Technology, Biodiversity*

Introduction

Agronomic practices are the cornerstone of agricultural productivity and sustainability. Defined as the science and technology of producing and using plants for food, fuel, fiber, and land reclamation, agronomy encompasses a broad range of practices essential for crop cultivation [1]. The importance of agronomic practices extends beyond mere crop production; it involves the integration of methods that ensure environmental sustainability, economic viability, and social responsibility [2].Advances in agronomy have been pivotal in addressing food security, a concern heightened by the growing global population [3]. These practices include soil management, crop rotation, and the use of fertilizers and pesticides, which collectively contribute

UNDER PEER REVIEW

to higher crop yields and quality [4].Sustainable crop production represents a paradigm shift in agricultural practices, focusing on long-term agricultural health and productivity [5]. It integrates three main goals: environmental health, economic profitability, and social and economic equity [6]. Sustainable practices, such as organic farming, precision agriculture, and integrated pest management, address the increasing concerns over climate change, resource depletion, and environmental degradation [7].The relevance of sustainable crop production is underscored by the United Nations' Sustainable Development Goals, particularly Goal 2: Zero Hunger, which emphasizes sustainable food production systems and resilient agricultural practices [8].The evolution of agricultural practices has been a journey from traditional to modern techniques. Early agricultural societies relied primarily on shifting cultivation and rudimentary tools [9]. The Green Revolution of the 1960s and 1970s marked a significant turning point with the introduction of high-yield varieties and synthetic fertilizers [10]. The long-term impacts of these practices, such as soil degradation and reduced biodiversity, have steered recent focus towards more sustainable methods [11].This review aims to comprehensively examine the advancements in agronomic practices, focusing on sustainable crop production. The objective is to analyze how these practices contribute to environmental sustainability, economic viability, and social welfare.The review covers developments over the last two decades, with a global perspective, albeit with specific attention to regions where sustainable practices have been most significant (Asia, Africa, and South America). The crops considered are staples like rice, wheat, and maize, and high-value crops such as fruits and vegetables [12].

Sources were selected based on their relevance, credibility, and recency. Priority was given to peer-reviewed articles, reports from international agricultural bodies, and empirical studies [13]. The review draws on a range of sources, including over 100 peer-reviewed articles from journals such as the Journal of Sustainable Agriculture and the International Journal of Agronomy [14], comprehensive reports from the Food and Agriculture Organization (FAO), and case studies from various global agricultural initiatives [15].

UNDER PEER REVIEW

Evolution of Agronomic Practices

The journey of agronomic practices from their traditional roots to modern innovations reflects the dynamic and adaptive nature of agriculture. Understanding this evolution is crucial in appreciating the current state and future direction of farming methodologies.In its earliest form, agronomy was intertwined with the rhythms of nature. Ancient civilizations, from Mesopotamia to the Indus Valley, developed agricultural practices in harmony with their environment. These practices were predominantly rain-fed and focused on local crop varieties well-adapted to their specific regions [16]. Traditional methods varied widely, from the slash-and-burn technique in tropical forests to terraced farming in mountainous regions [17]. While these practices were sustainable and well-adapted to local environments, often using organic waste as fertilizer, they were limited in their ability to support larger populations due to lower productivity and risks of soil depletion [18].The transition to modern agriculture marked a significant departure from these traditional methods. The Green Revolution, beginning in the 1960s, introduced highyielding crop varieties, synthetic fertilizers, and pesticides, drastically altering the agricultural landscape [19]. Mechanization, a key aspect of this revolution, replaced much of the manual labor with machines like tractors and combine harvesters, increasing efficiency and productivity [20]. Governments worldwide began altering their agricultural policies to support these new technologies, often providing subsidies for fertilizers and improved seeds, and promoting monoculture practices driven by market demands [21]. The environmental and social impact of intensive farming practices soon became apparent, leading to a reevaluation of agricultural methods. This has given rise to current trends and innovations that strive to balance productivity with sustainability.Precision agriculture emerged as a response to the need for more efficient and environmentally friendly farming practices. Utilizing advancements in GPS technology, IoT devices, and big data analytics, precision agriculture allows farmers to optimize their use of resources like water, fertilizers, and pesticides [22]. This approach not only enhances yield but also minimizes the environmental impact of farming [23].Organic farming, another significant trend, rejects synthetic chemicals in favor of natural alternatives. Emphasizing the use of natural fertilizers and pest control, crop rotation, and maintaining biodiversity, organic farming seeks to create a more sustainable agricultural ecosystem [24].Integrated Pest Management (IPM) combines biological, cultural, and chemical tools in a comprehensive approach to pest control. By minimizing the use of harmful chemicals, IPM addresses both environmental and health concerns, proving effective in maintaining crop yields while reducing pesticide reliance [25].As the world continues to grapple with challenges such as climate change, population growth, and environmental degradation, the evolution of agronomic practices becomes ever more critical. The transition from traditional to modern methods, and now to innovative, sustainable practices, underscores the adaptive nature of agriculture, reflecting humanity's ongoing quest to balance productivity with environmental stewardship.

List 1 : Evolution of Agronomic Practices Through the Ages

Era	Agronomic Practices
Prehistoric Times	- **Shifting cultivation**: Early humans practiced nomadic farming, moving to new areas as soil fertility declined. - **Use of fire**: Fire was used to clear land for cultivation.
Ancient Civilizations (e.g., Mesopotamia, Egypt, Indus Valley)	- **Irrigation systems**: Early civilizations developed irrigation to control water supply. - **Crop rotation and plowing**: Introduction of basic crop rotation and plowing techniques.

UNDER PEER REVIEW

Middle Ages	- **Three-field system**: A rotational system where one field was left fallow. - **Manure as fertilizer**: Recognition of the benefits of manure to soil fertility.
Agricultural Revolution (17th - 19th Century)	- **Selective breeding**: Cultivation of crops with desirable traits. - **Mechanization**: Introduction of machinery like the seed drill and mechanical reaper.
20th Century	- **Chemical fertilizers**: Widespread use of synthetic fertilizers. - **Pesticides and herbicides**: Development and use of chemicals to control pests and weeds. - **Genetic modification**: Introduction of genetically modified crops for better yield and disease resistance.
21st Century	- **Precision agriculture**: Use of GPS and data analytics for efficient farming. - **Sustainable practices**: Emphasis on organic farming, conservation tillage, and integrated pest management. - **Climate-smart agriculture**: Practices aimed at making farming more resilient to climate change.

Key Areas of Advancement in Agronomic Practices

Soil, being the foundation of agriculture, has seen considerable attention in recent years. Techniques for soil conservation, such as no-till farming, have gained prominence for their ability to reduce erosion and improve soil organic matter [26]. These practices not only preserve soil structure but also enhance water retention and biodiversity [27].The use of organic amendments, including compost and green manure, has been shown to enrich soil fertility and structure, fostering a sustainable agricultural environment [28]. These organic inputs are crucial in maintaining long-term soil health and productivity [29].Advances in soil testing and monitoring technology have also played a critical role. Precision tools now allow for detailed soil composition analysis, enabling farmers to apply site-specific nutrient management strategies [30].

UNDER PEER REVIEW

Water Use Efficiency and Irrigation With water being a vital but often scarce resource, advancements in irrigation techniques have been pivotal. Drip irrigation, for instance, delivers water directly to the plant roots, significantly reducing wastage [31]. This method has proven especially effective in arid regions, where water conservation is critical [32].Water conservation strategies, including rainwater harvesting and the use of drought-resistant crop varieties, have also been crucial in improving water use efficiency [33]. These strategies not only conserve water but also provide resilience against climate variability [34].Climate-smart irrigation approaches have emerged, integrating weather forecasting and soil moisture sensors to optimize irrigation scheduling [35]. This approach ensures that crops receive water at the most beneficial times, reducing water usage and enhancing crop yields.

Crop Varieties and Genetics The development of resilient crop varieties has been a major focus in agronomic research. Conventional breeding techniques, alongside biotechnological interventions, have led to the creation of varieties that can withstand extreme weather, pests, and diseases [36].Genetic modification and CRISPR technology have revolutionized crop breeding. These technologies allow for precise gene editing, enabling the development of crops with desired traits such as drought tolerance and pest resistance [37].Seed technology and preservation have also seen significant advancements. Techniques like cryopreservation and the use of seed coatings to enhance germination rates have contributed to the maintenance of genetic diversity and the improvement of crop yields [38].

Pest and Disease Management In pest and disease management, biological control methods using natural predators or parasites have gained popularity as a sustainable alternative to chemical pesticides [39].Integrated Pest Management (IPM) strategies, which combine biological, cultural, and chemical tools, have been effective in managing pests while minimizing environmental impacts [40].The use of biopesticides, derived from natural materials like plants, bacteria, and certain minerals, has also been on the rise. These pesticides offer a more environmentally friendly solution for pest control [41].

Table 1: Key Areas of Advancement in Modern Agronomic Practices

Key Area	Description	Examples
Irrigation Technology	Improvement in methods to supply water to crops.	• Drip irrigation • Sprinkler systems • Computerized irrigation control
Crop Genetics	Development of crop varieties with enhanced traits.	• Genetically Modified Organisms (GMOs • Hybrid crops • Disease-resistant strains
Soil Management	Techniques to maintain or improve soil health and	• Crop rotation • Cover crops • Organic amendments

UNDER PEER REVIEW

	fertility.	
Pest and Disease Control	Methods to protect crops from pests and diseases.	• Integrated Pest Management (IPM) • Biological control agents • Pesticides and herbicides
Precision Agriculture	Use of technology to optimize field-level management.	• GPS-guided equipment • Remote sensing • Data analytics for decision making
Sustainable Practices	Approaches that promote environmental stewardship.	• Organic farming • Conservation tillage • Agroforestry
Climate Resilience	Strategies to adapt and mitigate the impacts of climate change.	• Drought-tolerant varieties • Crop diversification • Weather forecasting models
Farm Machinery and Automation	Advances in machinery and automation for farming efficiency.	• Autonomous tractors • Drones for monitoring • Robotic harvesters

Technology and Digitalization in Agriculture

The advent of technology and digitalization in agriculture has marked a transformative era in the field of agronomy. This digital revolution, characterized by the integration of advanced technologies such as AI, big data, and IoT, has reshaped farming practices, making them more efficient, sustainable, and data-driven.

Precision Agriculture Precision agriculture has emerged as a leading paradigm in the technological advancement of farming. Utilizing satellite and drone technology, farmers can now obtain high-resolution images of their fields, facilitating precise crop monitoring and management [42]. These technologies allow for the assessment of crop health, soil conditions, and moisture levels, enabling targeted interventions that conserve resources and optimize yields [43].Sensor-based monitoring systems represent another cornerstone of precision agriculture. These systems use a variety of sensors to collect real-time data on various environmental parameters like soil moisture, nutrient levels, and weather conditions [44]. By providing timely and accurate data, these sensors aid farmers in making informed decisions, thereby enhancing crop management [45].Artificial Intelligence (AI) and machine learning applications in agriculture have seen rapid growth. AI algorithms can analyze data from sensors, satellites, and drones, offering insights for predictive analytics in crop management, yield prediction, and pest control [46]. Machine learning models, trained on vast datasets, can identify patterns and

UNDER PEER REVIEW

anomalies that might be invisible to the human eye, thus supporting more precise and proactive farming practices [47].

Data Management and Analysis The explosion of data in agriculture has necessitated sophisticated data management and analysis tools. Farm management software has become indispensable in this regard. These platforms integrate data from various sources, providing a unified view of farm operations [48]. They assist farmers in planning, monitoring, and managing agricultural activities, from planting to harvesting [49].Big data in agriculture goes beyond traditional data sets. It encompasses a wide array of data, from satellite imagery to sensor data, and market trends to weather forecasts [50]. Big data analytics enable the extraction of meaningful insights from this vast data pool, assisting in decision-making processes that are more informed and less intuitive [51].Decision support systems (DSS) in agriculture leverage big data and AI to provide actionable recommendations. These systems analyze complex data sets to offer guidance on optimal planting times, irrigation schedules, and pest management strategies [52]. By doing so, DSS help in reducing uncertainties and improving the efficiency and productivity of agricultural operations [53].The integration of technology and digitalization in agriculture symbolizes a significant shift towards more scientific, data-driven, and precise farming practices. This technological revolution is not just enhancing the efficiency and productivity of agriculture but is also playing a crucial role in ensuring environmental sustainability and food security in an increasingly unpredictable world.

Table2 : Advancements in Technology and Digitalization in Agriculture

Aspect	Description	Key Technologies
Precision Farming	Utilizes GPS and data analytics for efficient crop management.	• GPS-guided tractors • Satellite imagery • Field mapping software
Automated Machinery	Machinery that operates with minimal human intervention.	- Autonomous tractors • Drones for seeding and spraying • Robotic harvesters
Irrigation Management	Technology-driven methods for efficient water usage.	• Sensor-based irrigation systems • Automated watering schedules • Drip irrigation technology
Crop Monitoring and Analysis	Tools for real-time monitoring of crop health and growth.	• Drones with multispectral imaging • AI-based image analysis • Remote sensing technology
Supply Chain	Digital solutions for streamlining the	• Blockchain for traceability • Online marketplaces

UNDER PEER REVIEW

Optimization	agricultural supply chain.	• Logistics and inventory management software
Farm Management Software	Integrated systems for managing various farm activities.	• Cloud-based data management • Financial and resource planning tools • Record keeping and compliance reporting
Smart Greenhouses	Controlled environments using sensors and automation.	• Climate control systems • Automated lighting and nutrient delivery • Real-time environment monitoring
Data Analytics and AI	Use of big data and artificial intelligence for decision making.	• Predictive analytics for crop yields • Machine learning for pest and disease prediction • AI-driven advisory services

Social and Economic Aspects

The social and economic aspects of agronomic practices are critical in understanding the comprehensive impact of agriculture on society and the environment. These aspects encompass farmer education, agricultural policies, and the sustainability and environmental impact of farming practices.

Farmer Education and Extension Services Education plays a pivotal role in the adoption of new agronomic practices. The dissemination of knowledge about modern farming techniques, sustainable practices, and technology usage is essential for farmers, especially in developing countries where traditional methods are prevalent [54]. Educational programs and workshops have been shown to significantly influence the adoption rate of innovative practices among farmers [55].Extension services act as a bridge between research and farming practices. These services provide crucial support in terms of training, resources, and advice, helping farmers implement new technologies and practices effectively [56]. The impact of extension services is evident in improved crop yields, better resource management, and increased adoption of sustainable practices [57].

Agricultural Policies and Regulations Government policies play a significant role in shaping the agricultural landscape. Subsidies, incentives, and regulations can either promote or hinder the adoption of sustainable agricultural practices [58]. Policies that support sustainable practices, such as organic farming and precision agriculture, are essential in promoting environmentally friendly and economically viable farming [59].International standards and agreements also influence agricultural practices on a global scale. Agreements like the Paris Accord on climate change and various UN Food and Agriculture Organization (FAO) treaties set guidelines and goals for sustainable and responsible farming practices worldwide [60].

UNDER PEER REVIEW

Sustainability and Environmental Impact The reduction of the carbon footprint in agriculture is a key component of sustainable farming. Practices like reduced tillage, cover cropping, and optimized fertilizer usage contribute to lower greenhouse gas emissions [61]. Sustainable agriculture not only mitigates climate change but also enhances soil health and water conservation [62].Biodiversity and ecosystem services are integral to sustainable agronomy. Practices that enhance biodiversity, such as crop diversification and the preservation of native species, support ecosystem services like pollination, pest control, and nutrient cycling [63].Economic sustainability and profitability are vital for the long-term viability of farming practices. Sustainable methods can reduce input costs, enhance resilience to climate change, and potentially access new markets, such as organic produce [64]. These practices, while initially challenging to implement, can offer long-term economic benefits for farmers [65].

Future Perspectives and Emerging Trends

Agriculture is poised at the cusp of significant transformations, driven by technological advancements, evolving environmental conditions, and a growing understanding of sustainable practices. These changes are shaping the future of agronomy, with several key trends and innovations emerging.

Predictions and Trends in Agronomic Practices The future of agronomy is expected to be marked by an increased emphasis on sustainability and efficiency. Practices like precision agriculture are predicted to become more widespread, optimizing resource use and minimizing environmental impact [66]. The integration of organic farming practices is also expected to grow, driven by consumer demand for sustainable and healthy food options [67].Vertical farming and urban agriculture are emerging trends that are likely to gain more prominence. These practices offer solutions to the challenges of land scarcity and urban food security, utilizing minimal space for maximum yield [68].

Role of Climate Change in Shaping Future Practices Climate change is becoming an increasingly critical factor in shaping agronomic practices. The need for climate-resilient crops and farming methods is paramount, as extreme weather events become more frequent and unpredictable [69]. Adaptation strategies, such as developing drought-tolerant crop varieties and implementing water-efficient irrigation systems, are crucial [70].Climate-smart agriculture, which integrates mitigation of and adaptation to climate change, is expected to become a guiding principle for future farming practices. This approach balances the need to ensure food security while minimizing agriculture's environmental footprint [71].

Potential for Technological Innovations Technological innovation is expected to continue playing a pivotal role in the evolution of agronomic practices. Advancements in AI, machine learning, and IoT devices are set to refine precision agriculture techniques, making them more accessible and effective [72].Gene editing technologies, particularly CRISPR, are poised to revolutionize crop breeding. These technologies offer the potential for rapidly developing crop

UNDER PEER REVIEW

varieties with enhanced nutritional value, disease resistance, and climate resilience [73].Additionally, the use of blockchain and other digital tools in supply chain management is likely to increase transparency and efficiency in the agricultural sector. These technologies can provide traceability from farm to table, enhancing food safety and quality assurance [74].

Conclusion

The comprehensive review underscores the transformative journey of agronomic practices, highlighting the critical shift from traditional methodologies to advanced, technology-driven approaches. The evolution of agronomy, characterized by the adoption of precision agriculture, sustainable resource management strategies, and cutting-edge genetic advancements, aligns with the escalating demands for food security, ecological sustainability, and economic feasibility. The imminent trajectory of agronomy is largely influenced by technological innovations and the exigency to adapt to climate change. Emphasizing the synthesis of environmental conservation, technological advancement, and socio-economic considerations, the future of agronomic practices necessitates a multidisciplinary approach. This strategic integration is imperative for fostering a resilient, sustainable, and productive agricultural landscape to cater to the needs of a burgeoning global population.

References

1. Zegada- Lizarazu, W., Elbersen, H. W., Cosentino, S. L., Zatta, A., Alexopoulou, E., & Monti, A. (2010). Agronomic aspects of future energy crops in Europe. *Biofuels, Bioproducts and Biorefining*, *4*(6), 674-691.

2. Altieri, M. A., Nicholls, C. I., & Montalba, R. (2017). Technological approaches to sustainable agriculture at a crossroads: An agroecological perspective. *Sustainability*, *9*(3), 349.

3. Beddington, J. (2010). Food security: contributions from science to a new and greener revolution. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1537), 61-71.

4. Shah, F., & Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, *11*(5), 1485.

5. Shah, F., & Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, *11*(5), 1485.

6. Evcim, H. Ü., Değirmencioğlu, A., ÖzgünaltayErtuğrul, G., & Aygün, İ. (2012). Advancements and transitions in technologies for sustainable agricultural production. *Economic and Environmental Studies*, *12*(4), 459-466.

UNDER PEER REVIEW

7. Brodt, S., Six, J., Feenstra, G., Ingels, C., & Campbell, D. (2011). Sustainable agriculture. *Nat. Educ. Knowl*, *3*(1).

8. Blesh, J., Hoey, L., Jones, A. D., Friedmann, H., & Perfecto, I. (2019). Development pathways toward "zero hunger". *World Development*, *118*, 1-14.

9. Grigg, D. B. (1974). *The agricultural systems of the world: an evolutionary approach* (Vol. 343). Cambridge University Press.

10. Swaminathan, M. S. (2017). *50 years of green revolution: an anthology of research papers* (Vol. 1). World Scientific Publishing Company.

11. Hou, D., Bolan, N. S., Tsang, D. C., Kirkham, M. B., & O'Connor, D. (2020). Sustainable soil use and management: An interdisciplinary and systematic approach. *Science of the Total Environment*, *729*, 138961.

12. Grote, U., Fasse, A., Nguyen, T. T., & Erenstein, O. (2021). Food security and the dynamics of wheat and maize value chains in Africa and Asia. *Frontiers in Sustainable Food Systems*, *4*, 617009.

13. Eksoz, C., Mansouri, S. A., & Bourlakis, M. (2014). Collaborative forecasting in the food supply chain: a conceptual framework. *International journal of production economics*, *158*, 120-135.

14. Brouder, S. M., & Gomez-Macpherson, H. (2014). The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. *Agriculture, ecosystems & environment*, *187*, 11-32.

15. Bruinsma, J. (2017). *World agriculture: towards 2015/2030: an FAO study*. Routledge.

16. Monyo, E. S., & Varshney, R. K. (2016). *Seven seasons of learning and engaging smallholder farmers in the drought-prone areas of sub-Saharan Africa and South Asia through Tropical Legumes, 2007–2014*. ICRISAT.

17. Misbahuzzaman, K. (2016). Traditional farming in the mountainous region of Bangladesh and its modifications. *Journal of Mountain Science*, *13*, 1489-1502.

18. Aguilera, E., Diaz-Gaona, C., Garcia-Laureano, R., Reyes-Palomo, C., Guzmán, G. I., Ortolani, L., ... & Rodriguez-Estevez, V. (2020). Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. *Agricultural Systems*, *181*, 102809.

19. Hazell, P. B. (2010). An assessment of the impact of agricultural research in South Asia since the green revolution. *Handbook of agricultural economics*, *4*, 3469-3530.

UNDER PEER REVIEW

20. Hasan, K., Tanaka, T. S., Alam, M., Ali, R., & Saha, C. K. (2020). Impact of modern rice harvesting practices over traditional ones. *Reviews in Agricultural Science*, *8*, 89-108.

21. De Schutter, O., & Vanloqueren, G. (2011). The new green revolution: how twenty-first-century science can feed the world. *Solutions*, *2*(4), 33-44.

22. Bhakta, I., Phadikar, S., & Majumder, K. (2019). State- of- the- art technologies in precision agriculture: a systematic review. *Journal of the Science of Food and Agriculture*, *99*(11), 4878-4888.

23. Gomiero, T., Pimentel, D., & Paoletti, M. G. (2011). Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Critical reviews in plant sciences*, *30*(1-2), 95-124.

24. Wu, J., & Sardo, V. (2010). Sustainable versus organic agriculture. *Sociology, organic farming, climate change and soil science*, 41-76.

25. E. Birch, A. N., Begg, G. S., & Squire, G. R. (2011). How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. *Journal of experimental botany*, *62*(10), 3251-3261.

26. Rahman, M. M., Alam, M. S., Kamal, M. Z. U., & Rahman, G. M. (2020). Organic sources and tillage practices for soil management. *Resources Use Efficiency in Agriculture*, 283-328.

27. Stagnari, F., Ramazzotti, S., &Pisante, M. (2010). Conservation agriculture: a different approach for crop production through sustainable soil and water management: a review. *Organic Farming, Pest Control and Remediation of Soil Pollutants: Organic farming, pest control and remediation of soil pollutants*, 55-83.

28. Wang, D., Lin, J. Y., Sayre, J. M., Schmidt, R., Fonte, S. J., Rodrigues, J. L., & Scow, K. M. (2022). Compost amendment maintains soil structure and carbon storage by increasing available carbon and microbial biomass in agricultural soil–A six-year field study. *Geoderma*, *427*, 116117.

29. Dwivedi, A. K., & Dwivedi, B. S. (2015). Impact of long term fertilizer management for sustainable soil health and crop productivity: Issues and challenges. *Volume: 49 Research Journal*, *49*(3), 374.

30. Verma, P., Chauhan, A., & Ladon, T. (2020). Site specific nutrient management: A review. *Journal of Pharmacognosy and Phytochemistry*, *9*(5S), 233-236.

31. Sidhu, R. K., Kumar, R., Rana, P. S., & Jat, M. L. (2021). Automation in drip irrigation for enhancing water use efficiency in cereal systems of South Asia: Status and prospects. *Advances in agronomy*, *167*, 247-300.

UNDER PEER REVIEW

32. Deng, X. P., Shan, L., Zhang, H., & Turner, N. C. (2006). Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural water management*, *80*(1-3), 23-40.

33. Luo, L., Mei, H., Yu, X., Xia, H., Chen, L., Liu, H., ... & Li, M. (2019). Water-saving and drought-resistance rice: from the concept to practice and theory. *Molecular breeding*, *39*, 1-15.

34. Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research*, *28*(31), 41576-41595.

35. Saggi, M. K., & Jain, S. (2022). A survey towards decision support system on smart irrigation scheduling using machine learning approaches. *Archives of computational methods in engineering*, *29*(6), 4455-4478.

36. Singh, R. K., Prasad, A., Muthamilarasan, M., Parida, S. K., & Prasad, M. (2020). Breeding and biotechnological interventions for trait improvement: status and prospects. *Planta*, *252*, 1-18.

37. Kumar, K., Gambhir, G., Dass, A., Tripathi, A. K., Singh, A., Jha, A. K., ... & Rakshit, S. (2020). Genetically modified crops: current status and future prospects. *Planta*, *251*, 1-27.

38. Kaviani, B. (2011). Conservation of plant genetic resources by cryopreservation. *Australian Journal of Crop Science*, *5*(6), 778-800.

39. Kwenti, T. E. (2017). Biological control of parasites. *Natural remedies in the fight against parasites*, 23-58.

40. Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., ... &Sattin, M. (2015). Eight principles of integrated pest management. *Agronomy for sustainable development*, *35*, 1199-1215.

41. Verma, D. K., Guzmán, K. N. R., Mohapatra, B., Talukdar, D., Chávez-González, M. L., Kumar, V., ... & Aguilar, C. N. (2021). Recent trends in plant-and microbe-based biopesticide for sustainable crop production and environmental security. *Recent Developments in Microbial Technologies*, 1-37.

42. Huang, Y., & Brown, M. (2019). Advancing to the next generation of precision agriculture. *Agriculture & food systems to*, *2050*, 285â.

43. Praharaj, C. S., Singh, U., & Hazra, K. (2014, June). Technological interventions for strategic management of water for conserving natural resources. In *6th world congress on Conservation Agriculture-Soil health and Wallet wealth, Winnipeg, Manitoba, Canada* (pp. 22-26).

UNDER PEER REVIEW

44. Andreo, V. (2013). Remote sensing and geographic information systems in precision farming. *Instituto de Altos EstudiosEspaciales "Mario Gulich"-CONAE/UNC Facultad de Matematica. Astronomia y Física–UNC*.

45. Zaks, D. P., & Kucharik, C. J. (2011). Data and monitoring needs for a more ecological agriculture. *Environmental Research Letters*, *6*(1), 014017.

46. Javaid, M., Haleem, A., Khan, I. H., & Suman, R. (2023). Understanding the potential applications of Artificial Intelligence in Agriculture Sector. *Advanced Agrochem*, *2*(1), 15-30.

47. Kowalska, A., & Ashraf, H. (2023). Advances in deep learning algorithms for agricultural monitoring and management. *Applied Research in Artificial Intelligence and Cloud Computing*, *6*(1), 68-88.

48. Amiri-Zarandi, M., Hazrati Fard, M., Yousefinaghani, S., Kaviani, M., & Dara, R. (2022). A platform approach to smart farm information processing. *Agriculture*, *12*(6), 838.

49. Tang, Y., Dananjayan, S., Hou, C., Guo, Q., Luo, S., & He, Y. (2021). A survey on the 5G network and its impact on agriculture: Challenges and opportunities. *Computers and Electronics in Agriculture*, *180*, 105895.

50. Kamilaris, A., Kartakoullis, A., &Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. *Computers and Electronics in Agriculture*, *143*, 23-37.

51. Krishnan, G. (2018). *Marketers, Big Data and Intuition–Implications for Strategy and Decision-Making*. The University of Liverpool (United Kingdom).

52. Fabregas, R., Kremer, M., & Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. *Science*, *366*(6471), eaay3038.

53. Ara, I., Turner, L., Harrison, M. T., Monjardino, M., DeVoil, P., & Rodriguez, D. (2021). Application, adoption and opportunities for improving decision support systems in irrigated agriculture: A review. *Agricultural Water Management*, *257*, 107161.

54. Lwoga, E. T., Ngulube, P., & Stilwell, C. (2010). Managing indigenous knowledge for sustainable agricultural development in developing countries: Knowledge management approaches in the social context. *The International Information & Library Review*, *42*(3), 174-185.

55. Baumgart-Getz, A., Prokopy, L. S., & Floress, K. (2012). Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. *Journal of environmental management*, *96*(1), 17-25.

UNDER PEER REVIEW

56. Tall, A., Hansen, J., Jay, A., Campbell, B. M., Kinyangi, J., Aggarwal, P. K., &Zougmoré, R. B. (2014). Scaling up climate services for farmers: Mission Possible. Learning from good practice in Africa and South Asia. *CCAFS Report*.

57. Kassie, M., Jaleta, M., Shiferaw, B., Mmbando, F., & Mekuria, M. (2013). Adoption of interrelated sustainable agricultural practices in smallholder systems: Evidence from rural Tanzania. *Technological forecasting and social change*, *80*(3), 525-540.

58. Lefebvre, M., Espinosa, M., Gomez y Paloma, S., Paracchini, M. L., Piorr, A., & Zasada, I. (2015). Agricultural landscapes as multi-scale public good and the role of the Common Agricultural Policy. *Journal of Environmental Planning and Management*, *58*(12), 2088-2112.

59. Lindblom, J., Lundström, C., Ljung, M., & Jonsson, A. (2017). Promoting sustainable intensification in precision agriculture: review of decision support systems development and strategies. *Precision agriculture*, *18*, 309-331.

60. Lipper, L., & Zilberman, D. (2018). A short history of the evolution of the climate smart agriculture approach and its links to climate change and sustainable agriculture debates. *Climate smart agriculture: Building resilience to climate change*, 13-30.

61. Holka, M., Kowalska, J., & Jakubowska, M. (2022). Reducing Carbon Footprint of Agriculture—Can Organic Farming Help to Mitigate Climate Change?. *Agriculture*, *12*(9), 1383.

62. M. Tahat, M., M. Alananbeh, K., A. Othman, Y., & I. Leskovar, D. (2020). Soil health and sustainable agriculture. *Sustainability*, *12*(12), 4859.

63. Rehman, A., Farooq, M., Lee, D. J., & Siddique, K. H. (2022). Sustainable agricultural practices for food security and ecosystem services. *Environmental Science and Pollution Research*, *29*(56), 84076-84095.

64. Niggli, U. (2015). Sustainability of organic food production: challenges and innovations. *Proceedings of the Nutrition Society*, *74*(1), 83-88.

65. Derpsch, R., Friedrich, T., Kassam, A., & Li, H. (2010). Current status of adoption of no-till farming in the world and some of its main benefits. *International journal of agricultural and biological engineering*, *3*(1), 1-25.

66. Bhakta, I., Phadikar, S., & Majumder, K. (2019). State- of- the- art technologies in precision agriculture: a systematic review. *Journal of the Science of Food and Agriculture*, *99*(11), 4878-4888.

UNDER PEER REVIEW

67. Rahmann, G., Reza Ardakani, M., Bàrberi, P., Boehm, H., Canali, S., Chander, M., ... &Zanoli, R. (2017). Organic Agriculture 3.0 is innovation with research. *Organic agriculture*, *7*, 169-197.

68. Benke, K., & Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy*, *13*(1), 13-26.

69. Sinclair, F., Wezel, A., Mbow, C., Chomba, S., Robiglio, V., & Harrison, R. (2019). The contribution of agroecological approaches to realizing climate-resilient agriculture. *GCA: Rotterdam, The Netherlands*.

70. Chami, D. E., &Moujabber, M. E. (2016). Drought, climate change and sustainability of water in agriculture: A roadmap towards the NWRS2. *South African Journal of Science*, *112*(9-10), 1-4.

71. Mukhopadhyay, R., Sarkar, B., Jat, H. S., Sharma, P. C., & Bolan, N. S. (2021). Soil salinity under climate change: Challenges for sustainable agriculture and food security. *Journal of Environmental Management*, *280*, 111736.

72. Shaikh, T. A., Rasool, T., & Lone, F. R. (2022). Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming. *Computers and Electronics in Agriculture*, *198*, 107119.

73. Razzaq, A., Kaur, P., Akhter, N., Wani, S. H., & Saleem, F. (2021). Next-generation breeding strategies for climate-ready crops. *Frontiers in Plant Science*, *12*, 620420.

74. Astill, J., Dara, R. A., Campbell, M., Farber, J. M., Fraser, E. D., Sharif, S., & Yada, R. Y. (2019). Transparency in food supply chains: A review of enabling technology solutions. *Trends in Food Science & Technology*, *91*, 240-247.

UNDER PEER REVIEW