

Review Article

Advancements in Agronomic Practices for Sustainable Crop Production-A review

Comment [Z1]: The title is good (9words)

Abstract

This review provides a comprehensive analysis of the advancements in agronomic practices that contribute to sustainable crop production. Sustainable agriculture has become a pivotal focus in the context of escalating global food demand, climate change, and environmental concerns. 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 face 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 primarily 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.

Comment [Z2]: Abstract is good (282 words). At a maximum abstract of 250 words, it is recommended to simplify it.

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

Comment [Z3]: Keywords are good (6 words). For keywords with a maximum of 5 words, it is recommended that the 5 most important words be selected.

Introduction

Agronomic practices are the cornerstone of agricultural productivity and sustainability. As the science and technology of producing and using plants for food, fuel, fiber, and land reclamation, agronomy encompasses various practices essential for crop cultivation [1]. The importance of agronomic practices extends beyond mere crop production; it involves integrating 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, collectively contributing 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 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].

Evolution of Agronomic Practices

The journey of agronomic practices from their traditional roots to modern innovations reflects agriculture's dynamic and adaptive nature. Understanding this evolution is crucial in appreciating farming methodologies' current state and future direction. In its earliest form, agronomy was intertwined with the rhythms of nature. Ancient civilizations, from Mesopotamia to the Indus Valley, developed agricultural practices harmoniously 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 supporting larger populations due to lower productivity and risks of soil depletion [18].

Comment [Z4]: Introduction is good. It is recommended that an objective be added in the introduction

The transition to modern agriculture marked a significant departure from these traditional methods. The Green Revolution, beginning in the 1960s, introduced high-yielding crop varieties, synthetic fertilizers, and pesticides, drastically altering the agricultural landscape [19]. Mechanization, a vital aspect of this revolution, replaced manual labor with machines like tractors and combined 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]. Intensive farming practices' environmental and social impact soon became apparent, leading to a reevaluation of agricultural methods. This has led to current trends and innovations that 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 using 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 harmful chemicals, IPM addresses 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.

Comment [Z5]: Evolution of Agronomic Practices are good

List 1: Evolution of Agronomic Practices Through the Ages

Era	Agronomic Practices
Prehistoric Times	<ul style="list-style-type: none"> - 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)	<ul style="list-style-type: none"> - Irrigation systems: Early civilizations developed irrigation to control water supply. - Crop rotation and plowing: Introduction of basic crop rotation and plowing techniques.

Middle Ages	<ul style="list-style-type: none"> - 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 (17 th - 19 th Century)	<ul style="list-style-type: none"> - Selective breeding: Cultivation of crops with desirable traits. - Mechanization: Introduction of machinery like the seed drill and mechanical reaper.
20 th Century	<ul style="list-style-type: none"> - 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.
21 st Century	<ul style="list-style-type: none"> - 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 to make farming more resilient to climate change.

Critical Areas of Advancement in Agronomic Practices

As agriculture's foundation, soil has seen considerable attention in recent years. Techniques for soil conservation, such as no-till farming, have gained prominence for reducing erosion and improving soil organic matter [26]. These practices preserve soil structure and enhance water retention and biodiversity [27]. Organic amendments, including compost and green manure, have 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].

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 have improved water use efficiency, including rainwater harvesting and drought-resistant crop varieties [33]. These strategies conserve water and 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 primary focus in agronomic research. Conventional breeding techniques, alongside biotechnological interventions, have created 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 using seed coatings to enhance germination rates have contributed to maintaining genetic diversity and improving crop yields [38].

Pest and Disease Management In pest and disease management, biological control methods using natural predators or parasites have become a sustainable alternative to chemical pesticides [39]. Integrated Pest Management (IPM) strategies, which combine biological, cultural, and chemical tools, have effectively managed pests while minimizing environmental impacts [40]. Biopesticides, derived from natural materials like plants, bacteria, and certain minerals, have 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.	<ul style="list-style-type: none"> • Drip irrigation • Sprinkler systems • Computerized irrigation control
Crop Genetics	Development of crop varieties with enhanced traits.	<ul style="list-style-type: none"> • Genetically Modified Organisms (GMOs) • Hybrid crops • Disease-resistant strains
Soil Management	Techniques to maintain or improve soil health and	<ul style="list-style-type: none"> • Crop rotation • Cover crops • Organic amendments

Comment [Z6]: Critical Areas of Advancement in Agronomic Practices are good

	fertility.	
Pest and Disease Control	Methods to protect crops from pests and diseases.	<ul style="list-style-type: none"> • Integrated Pest Management (IPM) • Biological control agents • Pesticides and herbicides
Precision Agriculture	Use of technology to optimize field-level management.	<ul style="list-style-type: none"> • GPS-guided equipment • Remote sensing • Data analytics for decision making
Sustainable Practices	Approaches that promote environmental stewardship.	<ul style="list-style-type: none"> • Organic farming • Conservation tillage • Agroforestry
Climate Resilience	Strategies to adapt and mitigate the impacts of climate change.	<ul style="list-style-type: none"> • Drought-tolerant varieties • Crop diversification • Weather forecasting models
Farm Machinery and Automation	Advances in machinery and automation for farming efficiency.	<ul style="list-style-type: none"> • 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 agronomy. This digital revolution, characterized by integrating 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. Farmers can now obtain high-resolution images of their fields using satellite and drone technology, facilitating precise crop monitoring and management [42]. These technologies allow for assessing 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, enhancing crop management [45]. Artificial Intelligence (AI) and agriculture machine learning applications have been overgrown. 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 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 helps reduce uncertainties and improve agricultural operations' efficiency and productivity [53]. Integrating 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.

Comment [Z7]: Technology and Digitalization in Agriculture are good

Table 2: Advancements in Technology and Digitalization in Agriculture

Aspect	Description	Key Technologies
Precision Farming	Utilizes GPS and data analytics for efficient crop management.	<ul style="list-style-type: none"> • GPS-guided tractors • Satellite imagery • Field mapping software
Automated Machinery	Machinery that operates with minimal human intervention.	<ul style="list-style-type: none"> - Autonomous tractors • Drones for seeding and spraying • Robotic harvesters
Irrigation Management	Technology-driven methods for efficient water usage.	<ul style="list-style-type: none"> • Sensor-based irrigation systems • Automated watering schedules • Drip irrigation technology
Crop Monitoring and Analysis	Tools for real-time monitoring of crop health and growth.	<ul style="list-style-type: none"> • Drones with multispectral imaging • AI-based image analysis • Remote sensing technology
Supply Chain Optimization	Digital solutions for streamlining the agricultural supply chain.	<ul style="list-style-type: none"> • Blockchain for traceability • Online marketplaces • Logistics and inventory management software
Farm	Integrated systems for	<ul style="list-style-type: none"> • Cloud-based data management

Management Software	managing various farm activities.	<ul style="list-style-type: none"> • Financial and resource planning tools • Record keeping and compliance reporting
Smart Greenhouses	Controlled environments using sensors and automation.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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 farming practices' sustainability and environmental impact.

Farmer Education and Extension Services Education is pivotal in adopting 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 farmers' adoption rate of innovative practices [55]. Extension services act as a bridge between research and farming practices. These services provide crucial support regarding 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].

Sustainability and Environmental Impact Reducing the carbon footprint in agriculture is a critical component of sustainable farming. Practices like reduced tillage, cover cropping, and optimized fertilizer usage contribute to lower greenhouse gas emissions [61]. Sustainable agriculture mitigates climate change and 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]. While initially challenging to implement, these practices can offer long-term economic benefits for farmers [65].

Comment [Z8]: Social and Economic Aspects are good

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 likely to gain 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 increasingly critical in agronomic practices. Climate-resilient crops and farming methods are 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 further, 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 varieties with enhanced nutritional value, disease resistance, and climate resilience [73].Additionally, using blockchain and other digital tools in supply chain management will likely increase transparency and efficiency in the agricultural sector. These technologies can provide traceability from farm to table, enhancing food safety and quality assurance [74].

Comment [Z9]: Future Perspectives and Emerging Trends are good. It is recommended to add a reference to one example of Sustainable Crop Production from a developing country

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 primarily influenced by technological innovations and the necessity 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.

Comment [Z10]: Conclusion is good. It is recommended that recommendations from the review results be added

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Comment [Z11]: References are good. Sufficient and up-to-date references and recommended that reference citations use Mendeley IEEE or APA and a maximum of 20 years of reference.

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