Modern Agronomy in the 21ˢᵗ Century: Advances, Sustainability and Global Applications

Ram Gopal ᵃ⁺⁺, S. S. Yadav ᵇ#*,
Kalyani Pradhan ᶜ†, Dileep Kumar Tiwari ᵈ‡,
Vinod Kumar ᵉ⁺⁺, Sandeep Rout ᶠ^,
Narinder Panotra ᵍ##, Sagar Kashinath Khokale ʰ^,
Anchal Singh ⁱ^ and Virendra Singh ʲ#^

ᵃ Directorate of Extension,ANDUA& T, Kumarganj, Ayodhya - 224229 (U.P), India.
ᵇ P. G. College, Ghazipur, U. P., India.
ᶜ Faculty of Agriculture, Sri Sri University, Cuttack, Disha, Pin-754006, India.
ᵈ RVSKVV, Krishi Vigyan Kendra, Shajapur (MP), India.
ᵉ KVK munger BAU Sabour Bihar, India.
ᶠ Faculty of Agriculture Sri Sri University, Cuttack Odisha, Pin-754006, India.
ᵍ Institute of Biotechnology SKUAST Jammu, Chatha, (J&K)-180009, India.
ʰ Department of Pharmaceutics, Sandip Institute of Pharmaceutical sciences, Nashik, Maharashtra (422213), India.
ⁱ Department of Agricultural Sciences, School of Agricultural Sciences and Engineering, IFTM University, Moradabad 244102, India.
ʲ School of Agricultural Science and Engineering, IFTM University, Moradabad 244102, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

_____

⁺⁺*Subject Matter Specialist (Agronomy);*
#*Assistant professor & Head, Agronomy;*
†*Assistant Professor (Horticulture);*
‡*Technical Officer (Agronomy);*
^ *Assistant Professor;*
##*Associate Professor (Agronomy);*
#^ *Professor;*
*Corresponding author: Email: shivay1304yadav@gmail.com;

Review Article

ABSTRACT

The systematic review examines the key practices that are transforming agronomy, including precision agriculture, biotechnology, conservation agriculture, and integrated pest management. The article will also discuss the role of digital technologies in enabling data-driven and efficient agronomy practices. The field of agronomy has seen significant advancements in the 21st century, with a focus on increasing crop yields, improving sustainability, and addressing global food security challenges. This article aims to provide an in-depth analysis of the advancements and sustainability of modern agronomy practices in the 21st century, with a focus on their application in India. This article explores the latest developments in agronomy practices, including precision agriculture, biotechnology, conservation agriculture, and integrated pest management. The role of digital technologies in enabling data-driven and efficient agronomy practices. It examines how these practices are being implemented in India and other parts of the world to enhance agricultural productivity while minimising environmental impacts. Role of digital technologies, such as remote sensing, data analytics, and robotics, in enabling more efficient and data-driven agronomy. Furthermore, it highlights the importance of sustainable agronomy practices in the face of climate change, soil degradation, and water scarcity. However, the adoption of agroecology in India faces several challenges, such as the dominance of industrial agriculture, the lack of policy support and incentives, and the need for capacity building and social mobilization mobilization. The article concludes by emphasising the need for continued research, innovation, and knowledge sharing to ensure the long-term sustainability and resilience of global agriculture systems. Modern agronomy has the potential to meet the growing demand for food while safeguarding the planet's natural resources for future generations.

1. 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, fibre, and land reclamation, agronomy encompasses a broad range of practices essential for crop cultivation. 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 (Nemade et al., 2023). Agronomy, the science of crop production and soil management, has undergone significant transformations in the 21st century. With the global population projected to reach 9.7 billion by 2050, the demand for food is expected to increase by 70% (FAO, 2017). At the same time,

agriculture faces numerous challenges, including climate change, soil degradation, water scarcity, and the need to reduce environmental impacts. To meet these challenges, agronomists have been developing and implementing innovative practices that aim to increase crop yields, improve resource use efficiency, and promote sustainability.

As the world population continues to grow at an exponential rate, much more effort will be mandatory for sustainable proliferation of agricultural products, thereby improving global food demands, limiting food losses, and ensuring that all people suffering from starvation and malnutrition have access to nutritious food. The global agriculture system must become more prolific and waste-free (Muhie, 2022). In India, agriculture plays a vital role in the economy,

employing over 50% of the workforce and contributing around 18% to the country's GDP (ICAR, 2020). However, Indian agriculture is also facing significant challenges, such as small and fragmented landholdings, dependence on monsoon rains, soil erosion, and declining groundwater levels. To address these challenges, the Indian government and agricultural research institutions have been promoting the adoption of modern agronomy practices, such as precision farming, conservation agriculture, and integrated nutrient management.

Traditional agricultural knowledge, often deeply rooted in local customs, environmental understanding, and community practices, has enabled indigenous and rural communities to cultivate the land in harmony with their ecosystems over generations. Modern agricultural practices, on the other hand, emphasise high efficiency, productivity, and technological advancement, often prioritising rapid yield and scale (Adefila et al., 2024; Rajput et al., 2023). This article aims to provide an in-depth analysis of the advancements and sustainability of modern agronomy practices in the 21st century, with a focus on their application in India. It will examine the key practices that are transforming agronomy, including precision agriculture, biotechnology, conservation agriculture, and integrated pest management. Recently, agriculture has gained much attention regarding automation by artificial intelligence techniques and robotic systems. Particularly, with the advancements in machine learning (ML) concepts, significant improvements have been observed in agricultural tasks. The ability of automatic feature extraction creates an adaptive nature in deep learning (DL), specifically, convolutional neural networks to achieve human-level accuracy in various agricultural applications, prominent among which are plant disease detection and classification, weed/crop discrimination, fruit counting, land cover classification, and crop/plant recognition (Saleem et al., 2021). The article will also discuss the role of digital technologies in enabling data-driven and efficient agronomy practices. Furthermore, it will highlight the importance of sustainable agronomy practices in the face of global challenges such as climate change and resource depletion. By providing a comprehensive overview of modern agronomy, this article aims to contribute to the ongoing efforts to ensure food security and environmental sustainability in India and beyond.

2. PRECISION AGRICULTURE

2.1 Definition and Principles

Precision agriculture, also known as site-specific crop management, is an approach that uses advanced technologies to optimise crop production by taking into account the spatial and temporal variability within a field (Gebbers & Adamchuk, 2010). The main principles of precision agriculture include:

1. **Data collection:** Gathering detailed information about soil properties, crop growth, weather conditions, and other relevant factors using sensors, drones, satellites, and other tools.
2. **Data analysis:** Processing and interpreting the collected data using geographic information systems (GIS), data analytics, and machine learning algorithms to generate insights and recommendations.
3. **Variable Rate Application:** Applying inputs such as seeds, fertilisers, water, and pesticides at variable rates based on the specific needs of each part of the field, rather than using uniform rates across the entire field.
4. **Monitoring and Evaluation:** Continuously monitoring crop growth and health using remote sensing and other technologies, and evaluating the effectiveness of management practices based on yield maps and other performance indicators.

2.2 Technologies and Applications

Precision agriculture relies on a range of advanced technologies, including:

- **Global Positioning System (GPS):** Used for mapping fields, guiding machinery, and geo-referencing data.
- **Remote sensing:** Using satellites, drones, and sensors to collect data on crop health, soil moisture, and other parameters.
- **Variable rate technology (VRT):** Equipment that can apply inputs at variable rates based on prescription maps generated from data analysis.
- **Yield monitors:** Sensors installed on harvesters to measure crop yields in real-time and create yield maps.
- **Soil sampling and mapping:** Collecting soil samples and analysing them for properties such as nutrient content, pH,

and organic matter, and creating soil maps using GIS.

These technologies enable farmers to optimise input use, reduce costs, and improve crop yields and quality. For example, by using VRT to apply fertilisers based on soil nutrient maps, farmers can avoid over-application in some areas and under-application in others, leading to more efficient nutrient use and reduced environmental impacts (Bongiovanni & Lowenberg-DeBoer, 2004).

2.3 Adoption in India

In India, the adoption of precision agriculture is still in its early stages, but there is growing interest and investment in this area. The Indian government has launched several initiatives to promote precision farming, such as the National Mission on Agricultural Extension and Technology (NMAET) and the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) (Mondal & Basu, 2009). These programs aim to provide farmers with access to advanced technologies, training, and financial support for implementing precision agriculture practices.

Several startups and agri-tech companies in India are also developing precision agriculture solutions tailored to the needs of Indian farmers. For example, CropIn Technology Solutions provides a cloud-based platform for crop monitoring, yield estimation, and advisory services using satellite imagery and machine learning (CropIn, 2021). Another startup, SatSure, offers data analytics services for agriculture using remote sensing and AI to help farmers make informed decisions about crop management (SatSure, 2021).

However, the adoption of precision agriculture in India faces several challenges, such as the small size of landholdings, limited access to technology and expertise, and the high cost of equipment and services. To overcome these challenges, there is a need for collaborative efforts between the government, industry, and research institutions to develop affordable and accessible precision agriculture solutions that can benefit small and marginal farmers.

3. BIOTECHNOLOGY

3.1 Genetically Modified Crops

Biotechnology has been a major driver of advancements in agronomy, particularly through the development of genetically modified (GM) crops. GM crops are plants that have had their DNA altered using genetic engineering techniques to introduce new traits, such as resistance to pests, herbicides, or environmental stresses (ISAAA, 2021). Some of the most widely grown GM crops include:

- **Bt cotton:** Cotton modified to express insecticidal proteins from the bacterium *Bacillus thuringiensis* (Bt), which provides resistance to bollworm pests.
- **Herbicide-tolerant soybeans**: Soybeans modified to tolerate the herbicide glyphosate, allowing for more effective weed control.
- **Virus-resistant papaya:** Papaya modified to resist the papaya ringspot virus, which had devastated papaya production in Hawaii.

The adoption of GM crops has been controversial, with concerns raised about their potential impacts on human health, the environment, and socio-economic factors. However, numerous scientific studies have concluded that GM crops are safe for human consumption and have no greater environmental impacts than their non-GM counterparts (National Academies of Sciences, Engineering, and Medicine, 2016). In fact, the use of GM crops has been associated with reduced pesticide use, increased crop yields, and improved farmer incomes in some cases (Qaim, 2009).

3.2 Marker-Assisted Selection

Another application of biotechnology in agronomy is marker-assisted selection (MAS), which uses molecular markers to identify and select plants with desirable traits, such as disease resistance or improved nutritional quality (Collard & Mackill, 2008). MAS involves the following steps:

1. Identifying molecular markers that are linked to the desired trait, such as a gene or a quantitative trait locus (QTL).
2. Screening a population of plants for the presence of the marker using DNA-based techniques such as polymerase chain reaction (PCR) or DNA sequencing.
3. Selecting the plants that possess the marker and breeding them to develop new varieties with the desired trait.

MAS has several advantages over traditional breeding methods, including:

- **Increased efficiency**: MAS can reduce the time and resources required for breeding by allowing breeders to select plants based on their genetic makeup rather than their phenotype.
- **Improved accuracy:** MAS can help identify plants with the desired trait even if the trait is not visually apparent or is influenced by environmental factors.
- **Accelerated breeding**: MAS can be used to pyramid multiple desirable traits into a single plant, accelerating the development of new varieties with improved performance.

3.3 Adoption in India

India has been a major adopter of GM crops, particularly Bt cotton. Since its introduction in 2002, Bt cotton has been widely cultivated in India, covering over 90% of the country's cotton area (ISAAA, 2019). The adoption of Bt cotton has been associated with significant increases in cotton yields, reductions in pesticide use, and improved farmer incomes (Kathage & Qaim, 2012).

However, the adoption of GM crops in India has also faced challenges, including concerns about the concentration of the seed market in the hands of a few multinational companies, the high cost of GM seeds, and the potential impacts on smallholder farmers (Choudhary & Gaur, 2015). To address these challenges, the Indian government has been promoting the development of indigenous GM crops and supporting research on biosafety and socio-economic impacts.

In addition to GM crops, MAS has also been used in India for crop improvement. For example, the Indian Agricultural Research Institute (IARI) has developed several rice varieties with improved resistance to bacterial blight and blast diseases using MAS (Singh et al., 2015). The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has also used MAS to develop pearl millet hybrids with improved resistance to downy mildew disease (Serraj et al., 2005).

4. CONSERVATION AGRICULTURE

4.1 Definition and Principles

Conservation agriculture (CA) is a farming approach that aims to conserve soil and water resources while improving crop productivity and sustainability (FAO, 2021). The three main principles of CA are:

1. **Minimum Soil Disturbance:** Avoiding or minimising tillage to reduce soil erosion and improve soil structure and health.
2. **Permanent Soil Cover:** Maintaining a continuous cover of crops, crop residues, or cover crops to protect the soil from erosion and improve soil organic matter.
3. **Crop Diversification:** Rotating crops or using intercropping to break pest and disease cycles, improve soil fertility, and enhance biodiversity.

CA practices include no-till or reduced tillage, mulching, cover cropping, and crop rotation. These practices can provide several benefits, such as:

- Reduced soil erosion and improved soil health
- Increased water infiltration and moisture retention
- Enhanced soil organic matter and carbon sequestration
- Reduced fuel and labour costs associated with tillage
- Improved crop yields and resilience to climate stresses

4.2 Adoption in India

In India, the adoption of CA has been increasing in recent years, driven by concerns about soil degradation, water scarcity, and the need to improve agricultural sustainability. The Indian government has been promoting CA through various programs and policies, such as the National Mission for Sustainable Agriculture (NMSA) and the Rashtriya Krishi Vikas Yojana (RKVY) (Jat et al., 2016).

Several research institutions and organisations in India have also been working to develop and promote CA practices. For example, the Indian Council of Agricultural Research (ICAR) has established a network of All India Coordinated Research Projects (AICRPs) on CA to conduct research and disseminate CA technologies to

farmers (ICAR, 2021). The International Maize and Wheat Improvement Centre (CIMMYT) and the Borlaug Institute for South Asia (BISA) have also been collaborating with Indian partners to promote CA in the Indo-Gangetic Plains (CIMMYT, 2021).

However, the adoption of CA in India faces several challenges, such as:

- Limited awareness and knowledge about CA among farmers
- Lack of appropriate machinery and equipment for CA
- Concerns about the short-term yield and income impacts of transitioning to CA
- Competing uses for crop residues, such as fodder for livestock or fuel for cooking
- Insufficient policy support and incentives for adopting CA practices

To overcome these challenges, there is a need for increased research, extension, and capacity building efforts to demonstrate the long-term benefits of CA and provide farmers with the knowledge, skills, and resources needed to adopt these practices.

5. INTEGRATED PEST MANAGEMENT

5.1 Definition and Principles

Integrated pest management (IPM) is an ecosystem-based approach to managing pests and diseases in crops (Ehler, 2006). IPM aims to minimise the use of chemical pesticides and promote the use of a combination of biological, cultural, and physical control methods to keep pest populations below economically damaging levels. The main principles of IPM include:

1. **Prevention:** Using cultural practices such as crop rotation, intercropping, and sanitation to prevent pest infestations.
2. **Monitoring:** Regularly scouting fields to identify and monitor pest populations and their natural enemies.
3. **Intervention:** Using a combination of control methods, such as biological control agents, biopesticides, and targeted pesticide applications, when pest populations exceed economic thresholds.
4. **Evaluation:** Assessing the effectiveness of control measures and adjusting management strategies as needed.

IPM can provide several benefits, such as:

- Reduced reliance on chemical pesticides and associated environmental and health risks
- Improved pest control efficacy and crop yields
- Enhanced biodiversity and ecosystem services, such as pollination and natural pest control
- Reduced risk of pesticide resistance development in pest populations
- Increased profitability and sustainability of farming systems

5.2 Adoption in India

In India, the adoption of IPM has been promoted as a way to reduce the overuse and misuse of chemical pesticides, which has led to several problems, such as pesticide resistance, human health impacts, and environmental contamination (Birthal et al., 2000). The Indian government has launched several programs to promote IPM, such as the National Food Security Mission (NFSM) and the National Horticulture Mission (NHM) (Ragunathan & Divakar, 2020).

Several research institutions and organisations in India have also been working to develop and promote IPM practices. For example, the National Centre for Integrated Pest Management (NCIPM) has been conducting research on IPM technologies and providing training and advisory services to farmers (NCIPM, 2021). The ICAR has also established a network of All India Coordinated Research Projects (AICRPs) on IPM to develop and disseminate IPM technologies for different crops and regions (ICAR, 2021).

However, the adoption of IPM in India faces several challenges, such as:

- Limited awareness and knowledge about IPM among farmers and extension workers
- Insufficient availability and quality of biological control agents and biopesticides
- Lack of incentives and policy support for adopting IPM practices
- Pressure from pesticide companies and dealers to use chemical pesticides
- Inadequate infrastructure and resources for IPM research and extension

To overcome these challenges, there is a need for increased investment in IPM research, capacity building, and policy support to create an

enabling environment for the widespread adoption of IPM practices in India.

6. DIGITAL TECHNOLOGIES

6.1 Remote Sensing

Remote sensing is the acquisition of information about an object or area from a distance, typically using satellites or aerial vehicles equipped with sensors (NASA, 2021). In agronomy, remote sensing is used for various applications, such as:

- Crop mapping and acreage estimation
- Crop health and stress monitoring
- Yield prediction and estimation
- Soil moisture and nutrient mapping
- Irrigation scheduling and management

Remote sensing data can be obtained from various sources, such as multispectral and hyperspectral sensors, radar, and LiDAR. These data can be processed and analysed using GIS software and machine learning algorithms to generate insights and recommendations for crop management.

In India, remote sensing has been used for various agricultural applications, such as crop inventory, drought monitoring, and crop insurance (Ray et al., 2014). The Indian Space Research Organisation (ISRO) has been providing remote sensing data and services to the agricultural sector through its satellites, such as Resourcesat, Cartosat, and RISAT (ISRO, 2021).

6.2 Data Analytics and Machine Learning

Data analytics and machine learning are powerful tools for extracting insights and making predictions from large and complex datasets. In agronomy, these technologies are used for various applications, such as:

- Precision agriculture: Analysing sensor data to optimise input use and improve crop yields
- Crop modelling: Simulating crop growth and development under different environmental and management scenarios
- Pest and disease detection: Identifying and predicting pest and disease outbreaks using image recognition and predictive modelling

- Supply chain optimisation: Analysing market trends and logistics data to improve the efficiency and sustainability of agricultural value chains

Several startups and agri-tech companies in India are developing data analytics and machine learning solutions for agriculture. For example, AgNext Technologies provides AI-based solutions for crop quality assessment and traceability (AgNext, 2021). Fasal offers IoT-based sensors and data analytics for precision agriculture and irrigation management (Fasal, 2021).

6.3 Robotics and Automation

Robotics and automation are emerging technologies that have the potential to transform various aspects of agriculture, from planting and harvesting to processing and distribution. Some examples of robotic and automation applications in agronomy include:

- **Autonomous tractors and sprayers:** Driverless machinery that can perform tasks such as tilling, planting, and spraying with high precision and efficiency
- **Robotic harvesters:** Machines that can automatically identify and pick ripe fruits and vegetables, reducing labour costs and improving product quality
- **Drones and UAVs**: Aerial vehicles equipped with sensors and cameras that can be used for crop monitoring, spraying, and other tasks
- **Robotic milking systems:** Automated systems that can milk cows without human intervention, improving animal welfare and productivity
- **Automated food processing and packaging:** Robotic systems that can sort, grade, and package agricultural products with high speed and accuracy

In India, the adoption of robotics and automation in agriculture is still in its early stages, but there is growing interest and investment in this area. For example, the Indian Institute of Technology (IIT) Kharagpur has developed a solar-powered autonomous tractor that can perform various farm operations (IIT Kharagpur, 2020). The startup TartanSense has developed a robotic weeder that uses computer vision and AI to identify and remove weeds from crop rows (TartanSense, 2021).

However, the adoption of robotics and automation in Indian agriculture faces several challenges, such as the high cost of technology, the lack of skilled labour, and the need for infrastructure and support services. To overcome these challenges, there is a need for collaborative efforts between the government, industry, and academia to develop affordable and accessible robotic and automation solutions that can benefit small and marginal farmers.

7. SUSTAINABLE AGRONOMY PRACTICES

7.1 Climate-Smart Agriculture

Climate-smart agriculture (CSA) is an approach that aims to sustainably increase agricultural productivity, adapt and build resilience to climate change, and reduce greenhouse gas emissions where possible (FAO, 2021)].

CSA practices include:

- **Conservation agriculture:** Minimising soil disturbance, maintaining soil cover, and diversifying crops to improve soil health and carbon sequestration
- **Agroforestry:** Integrating trees and shrubs with crops and livestock to improve soil fertility, water retention, and biodiversity
- **Precision agriculture:** Using data-driven technologies to optimise input use and reduce environmental impacts
- **Crop diversification**: Growing a variety of crops to spread risk and improve resilience to climate stresses
- **Water management:** Using efficient irrigation systems and water conservation practices to reduce water use and improve water productivity

In India, the adoption of CSA practices has been promoted as a way to address the challenges of climate change, which is expected to have significant impacts on agriculture, such as increased temperatures, changes in rainfall patterns, and more frequent extreme weather events (Rao et al., 2024). The Indian government has launched several initiatives to promote CSA, such as the National Innovations in Climate Resilient Agriculture (NICRA) program and the National Mission for Sustainable Agriculture (NMSA) (NICRA, 2021).

7.2 Organic Farming

Organic farming is a production system that relies on ecological processes, biodiversity, and natural cycles to support plant and animal health, without the use of synthetic inputs such as fertilisers and pesticides (IFOAM, 2021). Organic farming practices include:

- **Crop rotation:** Alternating crops to break pest and disease cycles and improve soil fertility
- **Composting:** Using organic waste to produce nutrient-rich soil amendments
- **Biological pest control**: Using natural enemies such as predators and parasites to control pests
- **Cover cropping:** Growing plants between cash crops to suppress weeds, improve soil health, and provide habitat for beneficial insects
- **Integrating livestock:** Using animals to recycle nutrients, control weeds, and provide manure for soil fertility

In India, the adoption of organic farming has been increasing in recent years, driven by concerns about food safety, environmental sustainability, and consumer demand for organic products. The Indian government has launched several programs to promote organic farming, such as the Paramparagat Krishi Vikas Yojana (PKVY) and the Mission Organic Value Chain Development for North Eastern Region (MOVCDNER) (APEDA, 2021).

However, the adoption of organic farming in India faces several challenges, such as the lack of access to organic inputs and markets, the high cost of certification, and the need for technical knowledge and skills (Panneerselvam et al., 2012). To overcome these challenges, there is a need for increased research, extension, and policy support to create an enabling environment for the growth of the organic farming sector in India.

7.3 Agroecology

Agroecology is a holistic approach to agriculture that applies ecological principles to the design and management of sustainable food systems (Gliessman, 2018). Agroecology emphasises the importance of biodiversity, soil health, and social equity in agriculture, and seeks to optimise the interactions between plants, animals, humans, and the environment. Agroecological practices include:

- **Intercropping:** Growing two or more crops together to enhance nutrient cycling, pest control, and yield stability
- **Agroforestry:** Integrating trees and shrubs with crops and livestock to improve soil fertility, water retention, and biodiversity
- **Participatory breeding:** Involving farmers in the selection and improvement of locally adapted crop varieties
- **Farmer-to-farmer knowledge sharing:** Facilitating the exchange of knowledge and experiences among farmers to promote innovation and adaptation
- **Strengthening local food systems:** Developing short supply chains and direct marketing channels to connect farmers and consumers

In India, the adoption of agroecology has been promoted as a way to address the social and ecological challenges facing agriculture, such as rural poverty, food insecurity, and environmental degradation (Khadse & Rosset, 2019). Several civil society organisations and farmer groups in India have been working to promote agroecology, such as the Alliance for Sustainable and Holistic Agriculture (ASHA) and the Deccan Development Society (DDS) (ASHA, 2021).

However, the adoption of agroecology in India faces several challenges, such as the dominance of industrial agriculture, the lack of policy support and incentives, and the need for capacity building and social mobilisation (Altieri & Nicholls, 2017). To overcome these challenges, there is a need for a paradigm shift in agricultural research, education, and extension to recognise and promote the value of agroecology as a pathway to sustainable and equitable food systems.

Fig. 1. Overview of precision agriculture technologies, including GPS guidance, variable rate application, and remote sensing
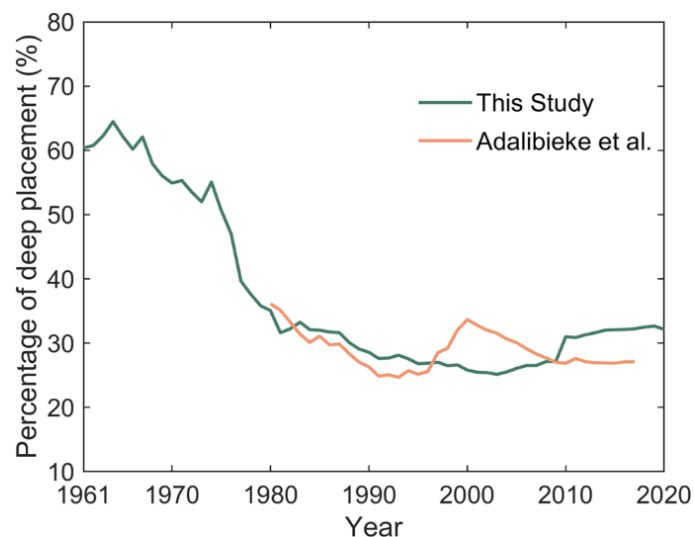

Fig. 2. Trends in global fertilizer consumption from 1961 to 2020

Table 1. Comparison of crop yields between conventional and precision agriculture practices

Crop	Conventional Yield (tons/ha)	Precision Agriculture Yield (tons/ha)	Yield Increase (%)
Corn	10.5	12.3	17.1
Soybeans	3.2	3.8	18.8
Wheat	4.7	5.5	17.0

Table 2. Trends in global population growth and arable land per capita

Year	Global Population (billions)	Arable Land per Capita (ha)
1960	3.0	0.37
1980	4.4	0.28
2000	6.1	0.21
2020	7.8	0.18
2040	9.2 (projected)	0.15 (projected)

Table 3. Common fertilizers used in modern agriculture and their application rates

Fertilizer Type	Nutrient Content (%)	Application Rate (kg/ha)
Urea	46% N	150-300
Ammonium Nitrate	34% N	100-200
Diammonium Phosphate	18% N, 46% P_2O_5	50-150
Potassium Chloride	60% K_2O	50-150

Table 4. Comparison of irrigation methods and their water use efficiency

Irrigation Method	Water Use Efficiency (%)	Suitable Crops
Surface Irrigation	50-60	Rice, alfalfa, pasture
Sprinkler Irrigation	70-80	Corn, soybeans, vegetables
Drip Irrigation	90-95	Fruits, vegetables, row crops

Table 5. Examples of common crop rotation systems in modern agriculture

Crop Rotation	Years	Crops Included
2-year	2	Corn, soybeans
3-year	3	Corn, soybeans, wheat
4-year	4	Corn, soybeans, wheat, alfalfa

Table 6. Comparison of tillage methods used in modern agriculture

Tillage Method	Advantages	Disadvantages
Conventional	Weed control, soil warming	Soil erosion, compaction, moisture loss
Conservation	Reduced erosion, improved soil structure	Increased herbicide use, slower soil warming
No-till	Minimal erosion, improved water retention	Specialized equipment, higher herbicide use

Table 7. Common cover crops and their benefits in modern agriculture

Cover Crop	Benefits
Cereal Rye	Erosion control, nitrogen scavenging
Crimson Clover	Nitrogen fixation, erosion control
Hairy Vetch	Nitrogen fixation, weed suppression
Radish	Soil compaction reduction, nutrient scavenging

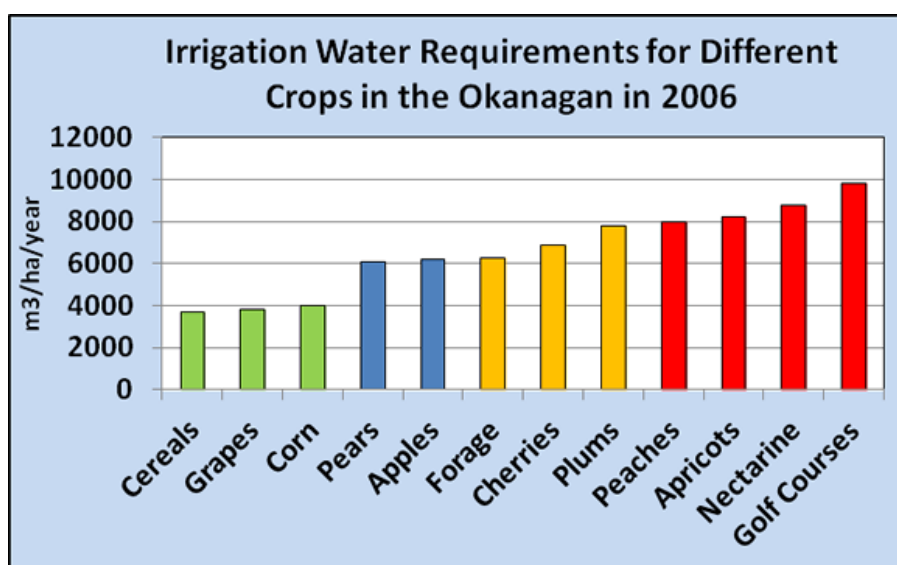**Fig. 3. Comparison of soil erosion rates under different tillage practices**

Fig. 4. Water requirements for major crops at different growth stages

Fig. 5. Components of an integrated pest management (IPM) program, including monitoring, cultural controls, and targeted pesticide use
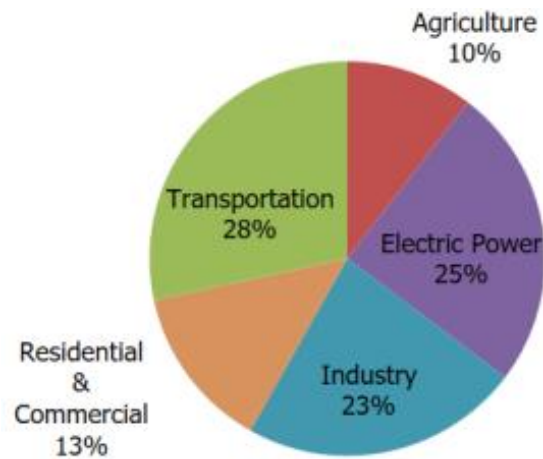
Fig. 6. Sources and trends of greenhouse gas emissions from agricultural activities

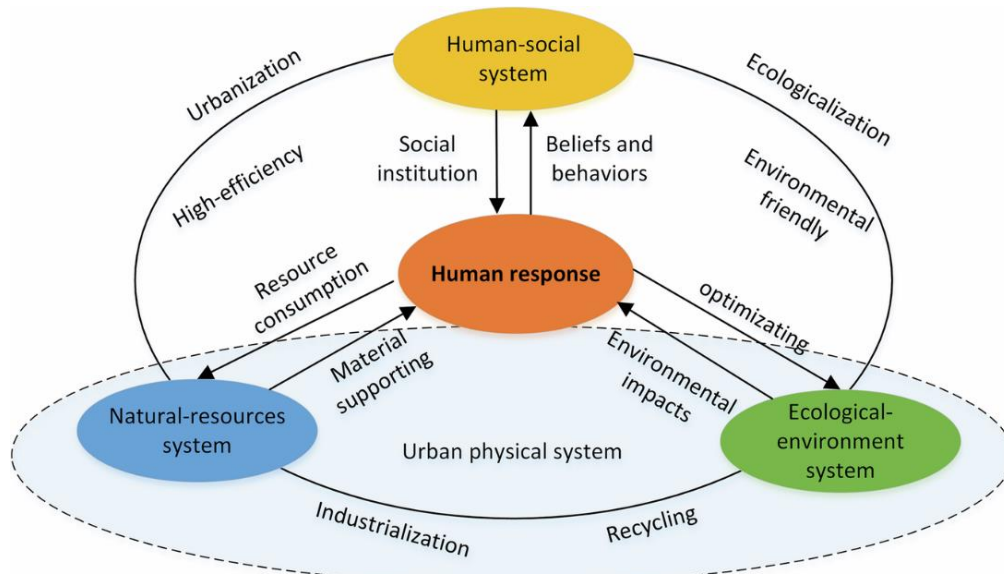**Fig. 7. Projected changes in crop yields due to climate change under different scenarios**

Fig. 8. Conceptual diagram of sustainable intensification, balancing increased productivity with environmental stewardship

8. CONCLUSION

The field of agronomy has seen significant advancements in the 21st century, driven by the need to increase agricultural productivity, improve sustainability, and address global challenges such as climate change and food security. Modern agronomy practices, such as precision agriculture, biotechnology, conservation agriculture, and integrated pest management, have the potential to transform agriculture by optimising resource use, reducing environmental impacts, and enhancing crop yields and quality.

In India, the adoption of modern agronomy practices has been increasing, supported by government programs, research institutions, and private sector initiatives. However, the adoption of these practices faces several challenges, such as the lack of awareness and knowledge among farmers, the high cost of technology and inputs, and the need for policy support and incentives.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Adefila, A. O., Ajayi, O. O., Toromade, A. S., & Sam-Bulya, N. J. (2024). Integrating traditional knowledge with modern agricultural practices: A sociocultural framework for sustainable development. *World Journal of Biology Pharmacy and Health Sciences, 20*(02), 125–135.

AgNext. (2021). About us. Retrieved from https://www.agnext.com/about-us/

Altieri, M. A., & Nicholls, C. I. (2017). Agroecology: A brief account of its origins and currents of thought in Latin America. *Agroecology and Sustainable Food Systems, 41*(3–4), 231–237.

APEDA. (2021). Organic products export. Retrieved from https://apeda.gov.in/apedawebsite/organic/Organic_Products.htm

ASHA. (2021). About ASHA. Retrieved from https://ashanet.org/about-asha/

Birthal, P. S., Sharma, O. P., Kumar, S., & Dhandapani, A. (2000). Pesticide use in rainfed cotton: Frequency, intensity and determinants. *Agricultural Economics Research Review, 13*(2), 107–122.

Bongiovanni, R., & Lowenberg-DeBoer, J. (2004). Precision agriculture and sustainability. *Precision Agriculture, 5*(4), 359–387.

Choudhary, B., & Gaur, K. (2015). *Biotech cotton in India, 2002 to 2014: Adoption, impact, progress & future*. ISAAA Series of Biotech Crop Profiles. Ithaca, NY: ISAAA.

CIMMYT. (2021). Conservation agriculture in the Indo-Gangetic Plains. Retrieved from https://www.cimmyt.org/projects/conservation-agriculture-in-the-indo-gangetic-plains/

Collard, B. C., & Mackill, D. J. (2008). Marker-assisted selection: An approach for precision plant breeding in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1491), 557–572.

CropIn. (2021). About us. Retrieved from https://www.cropin.com/about-us/

Ehler, L. E. (2006). Integrated pest management (IPM): Definition, historical development and implementation, and the other IPM. *Pest Management Science, 62*(9), 787–789.

FAO. (2017). *The future of food and agriculture – Trends and challenges*. Rome: FAO.

FAO. (2021). Climate-smart agriculture. Retrieved from http://www.fao.org/climate-smart-agriculture/en/

FAO. (2021). Conservation agriculture. Retrieved from http://www.fao.org/conservation-agriculture/en/

Fasal. (2021). About us. Retrieved from https://fasal.co/about-us/

Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science, 327*(5967), 828–831.

Gliessman, S. R. (2018). Defining agroecology. *Agroecology and Sustainable Food Systems, 42*(6), 599–600.

ICAR. (2020). *Agricultural statistics at a glance 2020*. New Delhi: ICAR.

ICAR. (2021). All India coordinated research project on biological control of crop pests. Retrieved from https://icar.org.in/content/all-india-

coordinated-research-project-biological-control-crop-pests

ICAR. (2021). All India coordinated research projects on conservation agriculture. Retrieved from https://icar.org.in/content/all-india-coordinated-research-projects-conservation-agriculture

IFOAM. (2021). What is organic agriculture? Retrieved from https://www.ifoam.bio/about-us/what-organic-agriculture

IIT Kharagpur. (2020). IIT Kharagpur develops solar-powered autonomous tractor. Retrieved from http://www.iitkgp.ac.in/news/iit-kharagpur-develops-solar-powered-autonomous-tractor

ISAAA. (2019). *Global status of commercialized biotech/GM crops in 2019: Biotech crops drive socio-economic development and sustainable environment in the new frontier* (ISAAA Brief No. 55). Ithaca, NY: ISAAA.

ISAAA. (2021). GM approval database. Retrieved from https://www.isaaa.org/gmapprovaldatabase/

ISRO. (2021). Earth observation satellites. Retrieved from https://www.isro.gov.in/earth-observation-satellites

Jat, M. L., Dagar, J. C., Sapkota, T. B., Singh, Y., Govaerts, B., Ridaura, S. L., ... & Stirling, C. (2016). Climate change and agriculture: Adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. In *Advances in agronomy* (Vol. 137, pp. 127–235). Academic Press.

Kathage, J., & Qaim, M. (2012). Economic impacts and impact dynamics of Bt (*Bacillus thuringiensis*) cotton in India. *Proceedings of the National Academy of Sciences, 109*(29), 11652–11656.

Khadse, A., & Rosset, P. M. (2019). Zero Budget Natural Farming in India – From inception to institutionalization. *Agroecology and Sustainable Food Systems, 43*(7–8), 848–871.

Mondal, P., & Basu, M. (2009). Adoption of precision agriculture technologies in India and in some developing countries: Scope, present status and strategies. *Progress in Natural Science, 19*(6), 659–666.

Muhie, S. H. (2022). Novel approaches and practices to sustainable agriculture. *Journal of Agriculture and Food Research, 10*, 100446.

NASA. (2021). What is remote sensing? Retrieved from https://earthdata.nasa.gov/learn/backgrounders/remote-sensing

National Academies of Sciences, Engineering, and Medicine. (2016). *Genetically engineered crops: Experiences and prospects*. Washington, DC: The National Academies Press.

NCIPM. (2021). About us. Retrieved from https://icar.org.in/node/10870

Nemade, S., Ninama, J., Kumar, S., Pandarinathan, S., Azam, K., Singh, B., & Ratnam, K. M. (2023). Advancements in agronomic practices for sustainable crop production: A review. *International Journal of Plant & Soil Science, 35*(22), 679–689.

NICRA. (2021). About NICRA. Retrieved from http://www.nicra-icar.in/nicrarevised/index.php/about-us

Panneerselvam, P., Halberg, N., Vaarst, M., & Hermansen, J. E. (2012). Indian farmers' experience with and perceptions of organic farming. *Renewable Agriculture and Food Systems, 27*(2), 157–169.

Qaim, M. (2009). The economics of genetically modified crops. *Annual Review of Resource Economics, 1*(1), 665–694.

Ragunathan, V., & Divakar, B. J. (2020). Integrated pest management strategies. In *Molecular biology of the biological control of pests and diseases of plants* (pp. 173–196). CRC Press.

Rajput, A., Roy, S., Waghmare, M. N., Singh, S., Shukla, V. K., Singh, V., & Singh, P. (2023). Exploring sustainable practices in modern agronomy and their environmental impact: A review. *International Journal of Environment and Climate Change, 13*(11), 3146–3161.

Rao, C. S., Baral, K., Chanadana, V. M., Jagadesh, M., & Karthik, R. (2024). Climate change adaptation and mitigation in Indian agriculture. *Journal of Agrometeorology, 26*(2), 137–148.

Ray, S. S., Mamatha, N. S., & Gupta, S. (2014). Use of remote sensing in crop forecasting and assessment of impact of natural disasters: Operational approaches in India. In *Crop monitoring for improved food security* (pp. 111–121). FAO/ADB.

Saleem, M. H., Potgieter, J., & Arif, K. M. (2021). Automation in agriculture by machine and deep learning techniques: A review of

recent developments. *Precision Agriculture, 22*(6), 2053–2091.

SatSure. (2021). About us. Retrieved from https://www.satsure.co/about-us/

Serraj, R., Hash, C. T., Buhariwalla, H. K., Bidinger, F. R., Folkertsma, R. T., Chandra, S., ... & Crouch, J. H. (2005). Marker-assisted breeding for crop improvement in the semi-arid tropics. In *Proceedings of the international conference on sustainable crop production in stress environments: Management and genetic options* (pp. 67–84). Jodhpur, India.

Singh, A. K., Singh, S. S., Prakash, V., Kumar, S., & Dwivedi, S. K. (2015). Pulses production in India: Present status, bottleneck and way forward. *Journal of AgriSearch, 2*(2), 75–83.

TartanSense. (2021). About us. Retrieved from https://www.tartansense.com/about-us/

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/141119