BKAP697
[1-7]

REVIEW ARTICLE **Bhartiya Krishi Anusandhan Patrika**

Growing Green: Sustainable Agriculture Meets Precision Farming: A Review

S. Kayastha[1], A. Behera[1], J.P. Sahoo[1], M. Mahapatra[1]

10.18805/BKAP697

ABSTRACT

Precision farming involves the use of advanced technologies such as the global positioning system (GPS), sensors and data analytics to make informed decisions on crop management. The integration of sustainable agriculture principles with precision farming techniques offers a holistic approach to address the challenges faced by modern agriculture. This review explores the convergence of sustainable agriculture and precision farming practices, aiming to enhance the efficiency, productivity and environmental sustainability of modern farming systems. The review delves into the principles of precision farming, which involves the use of advanced technologies such as GPS, sensors and data analytics to optimize resource use and improve crop yields. The integration of sustainable practices within precision farming frameworks is a central focus, emphasizing the importance of environmental supervision, soil health and biodiversity conservation. This review also highlights the collaboration between cutting-edge agricultural technologies and environment friendly farming practices, illustrating a path forward for the agriculture industry towards a sustainable and resilient nutritional security.

Key words: Environmental impact, GPS, Precision farming, Sensors, Sustainable agriculture.

Water and soil are vital resources needed for food production and sustaining life and the effects of climate change and urbanisation are tightening these resources (Hatfield *et al*., 2017). It is anticipated that 9 billion people will need to be fed by 2050 under limited conditions of available arable land, as well as natural resources (Lal *et al*., 2017). However, the world economy is expected to face increasing demand for food due to the rising population and standards of living and precision agriculture evolves as a new technology, which will heavily influence the ability to increase global agricultural productivity (FAO, 2009). Meanwhile, traditional farming methods often lead to environmental degradation, soil depletion and resource inefficiency and in response to these challenges, sustainable agriculture practices combined with precision farming are emerging as a promising solution to ensure food and nutritional security (Singh, 2022). This is a strategy that involves using tools such as farm management information systems, remote sensing, geographical information systems global navigation satellite systems and spatial statistics in crop production (Mani *et al*., 2021). This leads to increased agricultural productivity and profitability, in precision agriculture with a potential to meet the global demand for fuel, fiber and food (Liu and Khosla, 2010).

Moreover, it is essential to note that precision farming fosters proper utilization of available resources at the plot level, promotes high output efficiency in fields, maintains food security and ensures environmental integrity (Gebbers and Adamchuk, 2010). Although the power of onboard computers is reducing rapidly due to the reduction in prices with technology becoming better by the day and such include recent robotics, sensors, geo information systems, global navigation satellite system (GNSS) and geomapping, as well as new data processing tools (Picchio *et al*., 2019). Meanwhile, scientists and modern farmers have been assessing crop health and performance with various sensing devices such as *in-situ* sensors, spectrum radiometer, multi-spectral and hyper-spectral remote sensing and satellite photograph (Gebbbers and Adamchuk, 2010). The use of these technologies seek the increase of agriculture production for the improvement of the farm's productivity, profitability and the general sustainability of their farming activities. Such sensing instruments are very important in site specific management and also help to evaluate crops biomass, weed competition, nutritional status and soil characteristics (Velten *et al*., 2015).

However, newly designed advanced modern field equipment is capable of collecting enhanced data of high resolution leading to improved and accurate crop management and development (Lowenberg-DeBoer *et al*., 2021). Meanwhile, sustainable development goals in

---

[1]Faculty of Agriculture and Allied Sciences, C.V. Raman Global University, Bhubaneswar-752 054, Odisha, India.

Corresponding Author: J.P. Sahoo, Faculty of Agriculture and Allied Sciences, C.V. Raman Global University, Bhubaneswar-752 054, Odisha, India. Email: jyotiprakashsahoo2010@gmail.com

How to cite this article: Kayastha, S., Behera, A., Sahoo, J.P. and Mahapatra, M. (2024). Growing Green: Sustainable Agriculture Meets Precision Farming: A Review. Bhartiya Krishi Anusandhan Patrika. DOI: 10.18805/BKAP697.

Submitted: 03-12-2023 **Accepted:** 16-01-2024 **Online:** 18-01-2024

agriculture are indexed in Fig 1. This illustration provides a schematic sketch for the overview of precision agriculture technology. Sustainable soil and crop management enhances the long-term sustainability of Agriculture, so it is a must (Shaheb *et al*., 2022). There are many factors that result in variabilities, such as field topography, soil properties, nutrients, crop characteristics, water contents, meteorologies, pests, *etc*. (Lee *et al*., 2021). For instance, some scholars advocate for the use of climate-smart farming, integrated soil management, sustainable intensification, precision farming, among other methodologies, in achieving sustainable agricultural production (Garibaldi *et al*., 2019). However, these goals can be accomplished if all the best management practices for agroecosystems are used consecutively which makes use of resources, preserves soil and gives both current and future social and environmental benefits without violating anyone of those (Shaheb *et al*., 2022).

Climate-smart agriculture (CSA) is an approach to ensuring food security by directing entire agricultural systems towards resilient practices, sustainable development and climate change adaptable strategies (Lipper and Zilberman, 2018). A key element of CSA is climate-smart pest management (CSPM), which provides advantages for preserving agricultural systems by lowering chemical use (Challinor *et al*., 2022). This analysis focuses on CSPM and phytosanitary issues related to climate change, examining areas that require more effective interventions (Alexander, 2019). It investigates how to modify pest management in response to weather events to support the long-term viability of agricultural systems and discusses the challenges related to the implementation and use of CSPM (Heeb *et al*., 2019). Precision agriculture (PA) emerges as a crucial strategy for sustainable agriculture in the twenty-first century (Lipper and Zilberman, 2018). It involves in sophisticated information, communication and data analysis techniques, aiming to minimize environmental effects, reduce water and fertilizer losses and enhance agricultural yields (Heeb *et al*., 2019).

However, the fourth agricultural revolution, driven by advancements in information and communication technology, emphasizes the role of technologies like artificial intelligence (*AI*), big data analysis, remote sensing, *GPS*, *GIS* and the Internet of Things (*IoT*) (Velásquez *et al*., 2018). These technologies are instrumental in optimizing agricultural operations, reducing losses and increasing productivity (Ristaino *et al*., 2021). IoT technology systems, such as cloud computing and wireless sensor networks, are integral to smart farming operations, enabling disease and pest monitoring and automated irrigation systems (Li *et al*., 2021). AI techniques, including machine learning, facilitate precise and automated application of pesticides, fertilizers, water and herbicides by predicting crop yield and monitoring soil moisture (Velásquez *et al*., 2018). However, remote sensing instruments generate big amounts of data used in precision agriculture, processed through big data analysis, machine learning and intelligent automation (Roßmann *et al*., 2018). Moreover, cloud computing platforms play a crucial role in processing, distributing and utilizing large datasets for various applications in precision agriculture (Choudhary *et al*., 2016). This review explores the transformative synergy between sustainable agriculture and precision farming, envisioning a paradigm that addresses global challenges of environmental degradation, resource scarcity and increasing food demand. Moreover, by integrating eco-friendly farming practices with advanced precision technologies, this review highlights the potential for creating a resilient and efficient agricultural system.

Precision agriculture

One of the modern farming approaches is precision agriculture that uses measurement of crop growth combined with modern technologies (Shafi *et al*., 2019). Researchers have also adopted different names for it, *i.e*., “Site-specific farming”, “Spatially variable crop production”, “Grid Farming”

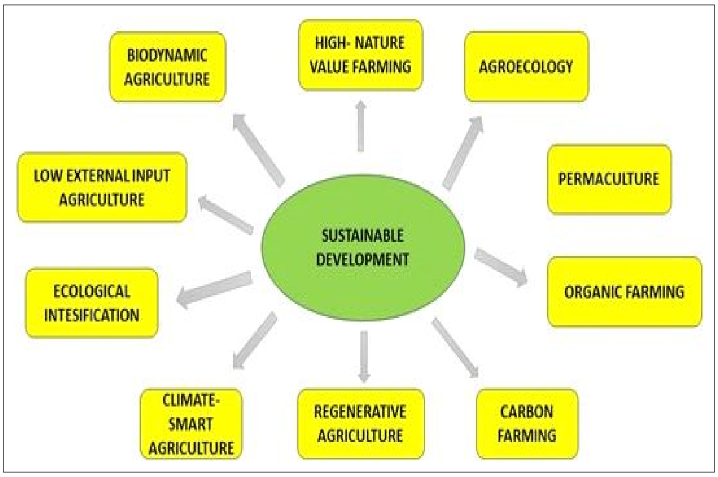

Fig 1: Sustainable development goals in agriculture.

and "Technology-based agriculture" (Sishodia *et al*., 2020). However, some scientist gives an all-inclusive explanation that defines precision agriculture simply as "making use of IT information to enhance decisions relating to agricultural production and marketing, financing as well as people" (Karunathilake *et al*., 2023). Essentially, precision agriculture maps out in-field variability using *GIS* in order to maximize crop yield through efficient resource utilization (Su *et al*., 2023). However, the sensor-IT based technologies which include wireless *GPS* technology, provides a framework for precision agriculture to manage unforeseen uncertainty, which in turn results into informed decision making that is aimed at ensuring maximal productivity within the agricultural system (Saranya *et al*., 2023). For the precision agriculture to occur, accurate data must be collected timely. Nevertheless, it should be analysed appropriately, translated correctly and managed correctly, at the right scales and frequencies (Gokool *et al*., 2023). Moreover, a timeline of precision agriculture is indexed in Table 1.

Importance of precision agriculture

Precision Agriculture is an information technology-based farming method that enhances agricultural output, profitability and efficiency by optimizing resource use and crop management (Andersen *et al*., 2023). Continuous technological advancements, including autonomous tractors, agricultural drones, *GIS* and sensors empower farmers to operate with unprecedented efficiency (Abdullah *et al*., 2024). However, according to researchers, precision agriculture represents an information revolution driven by new technologies, resulting in a more accurate farm management system (Huo *et al*., 2024). Farmers must consider within-field variability, as conventional farming practices often involve uniform application of inputs across the entire field without accounting for spatial changes in soil characteristics such as types, electrical conductivity (EC), moisture content (MC), pH and nutrient availability and factors like land topography, soil texture and historical management practices can contribute to spatial variability in soil (Ghadirnezhad Shiade *et al*., 2024). In fact, in England, crop yields showed considerable spatial variation even at managed fields reflecting the influence of soil variability, rainfall and field operations (Godwin *et al.,* 2003). However, farm productivity and profitability is maximized through accurate crop input management (Bramley, 2009).

Climate smart agriculture

In 2009, Climate-Smart Agriculture (CSA) was introduced to promote sustainable agricultural systems by integrating efforts to mitigate climate change and ensure food security (Lipper and Zilberman, 2018). The Food and Agriculture Organization (FAO) officially introduced the CSA concept in 2010 (Scherr *et al*., 2012). However, CSA aims to establish globally relevant agricultural management principles addressing climate change, with strategic goals including reducing greenhouse gas emissions, adapting to climate change, enhancing household resilience and increasing agricultural output sustainably (Lipper *et al*., 2014). CSA incorporates various sustainable practices to help farming communities and mitigate the effects of climate change (Azadi *et al*., 2021). While international organizations like the World Bank and FAO embraced CSA, disputes arose in policy discussions on sustainability and climate change (Taylor, 2018). International initiatives now focus on improving CSA adoption, considering varying country contexts and addressing the dual challenges of climate

Table 1: Timeline of precision agriculture.

Periods	Developments in precision agriculture
Before the 1980s	20th century - Field heterogeneity, Spatial variability, Site-specific Agriculture is mainly on crop nutrient management. 1930s - Mechanization of agriculture, including tractors and fertilizer application. 1961 - Fertilizer application using soil sampling. 1950s-1960s - Green revolution (High yielding cereals, Fertilizers, Agro-chemicals Application *etc*.). 1970s - First satellite based radio - navigation system, GPS. 1993 - GPS introduced in agriculture.
1980-1990	1980s - PA farming practices. Late 1980s - Development of yield monitors, grid soil sampling, soil sensors, VRT *etc*.
1990-2000	Early 1990s - VRTs and yield monitors are commercially available. 1992 - First International precision agriculture conference was held in Minnesota. 1993 - Invention of the on-the-go-crop yield monitor. 1996 - John Deere developed their first GPS receiver integrating satellite. 1997 - Asian conferences on PA. 1999 - Journal launched called "Precision agriculture".
2000-2010	Use of tablet computers, cell phones and smart phones helped in the implementation of precision farming activities. Publication of books like - Handbook of precision farming, The precision farming guide for agriculturist.
2010-2020	Emerging tools like satellite imagery, unmanned aerial vehicles (UAV) *etc*. are used for the crop production system.
2020-2021	Transition of PA to decision agriculture. Integration of PA program and decision support system (DSS).
2021-2023	Integration of PA technologies like artificial intelligence (AI), IoT and cloud computing.

change and poverty (Huo *et al*., 2024). Current efforts in least developed nations primarily target food, energy and water, though plant protection remains crucial for sustainability (Taylor, 2018).

The FAO has been covering CSA to a large extent, but a few works have referred to "Climate-Smart Pest Management" (CSPM), which is referred to as integrated pest management is the approach employed in CSA (Heeb *et al*., 2019). Integrated Pest Management (IPM) is an approach that considers all pest management options and combines them with measures that discourage pests so they don't develop (Sekabira *et al*., 2022). The latest information provided in the study of CSPM has resulted in optimum response dynamics controlling pests during growing seasons hence reducing losses due to pea aphids' (Du *et al*., 2022). This approach integrates ecological, sustainable and adaptive measures to mitigate the risks associated with pests in agriculture and other ecosystems (Murage *et al*., 2015). Climate-smart pest management focuses on utilizing environmentally friendly and low-impact interventions, such as integrated pest management (IPM) practices, biological control methods and precision agriculture technologies (Bouri *et al*., 2023). By incorporating climate data and predictive modeling, farmers can anticipate pest outbreaks, optimize resource use and enhance resilience to climate-related challenges, ultimately contributing to more sustainable and resilient agricultural systems in the face of a changing climate (Roy, 2022). However, the climate smart pest management is indexed in Fig 2.

Application of precision agriculture

Recent agricultural practices, notably precision agriculture is mostly based on three concepts of efficiency, economy and environment (Sekabira *et al*., 2022). The use of a best management practices method in agricultural field crop is the basis for this (Huo *et al*., 2024). However, precision agriculture technologies are embedded with technical skills and knowledge that facilitate the uptake of safe and eco-friendly soil and crop management approaches.

Geospatial applications

"Geospatial technologies" encompass a variety of instruments utilized for geographical mapping and Earth's surface analysis, including Remote Sensing, geographic information systems, global navigation satellite systems (GNSS) and internet mapping technologies (Scherr *et al*., 2012). Automated field machinery in modern agriculture relies on positional data, *GIS* and *GNSS* guidance for accurate field operations (Andersen *et al*., 2023). Remote sensing technology, with a resolution of just over one meter, collects detailed imagery of Earth's surface, transforming how geographic data is visualized and shared (Picchio *et al*., 2019). Remote sensing, combined with *GIS* and *GNSS*, is essential for precision agriculture, helping segment cropland into small management zones based on factors like soil types, *pH*, *EC*, *MC* and crop characteristics (Velten *et al*., 2015). However, GIS databases store geo-referenced observations from remote sensing, forming the foundation of PA technologies (Azadi *et al*., 2021). For instance, remote sensing imaging links chlorophyll content to crop growth and productivity (Abdullah *et al*., 2024).

Remote sensing

Remote sensing technology makes use of image data derived from airborne cameras and sensor platforms (Shaheb *et al*., 2022). Lately, there has been an observed increase in airborne remote sensing platforms such as remote sensors on aeroplanes and satellite (Challinor *et al*., 2022). These technologies are fundamental in determining soil properties based on combined sensors' spectral data as well as integrated geo-referenced soil/crop fields data (Alexander, 2019). Compared to other techniques in this way is more accurate, requires less investment and takes shorter duration (Heeb *et al*., 2019). Drones of airborne and ground nature have utility for agricultural planting, pesticides, monitoring crop growth, irrigation, soil and field studies and

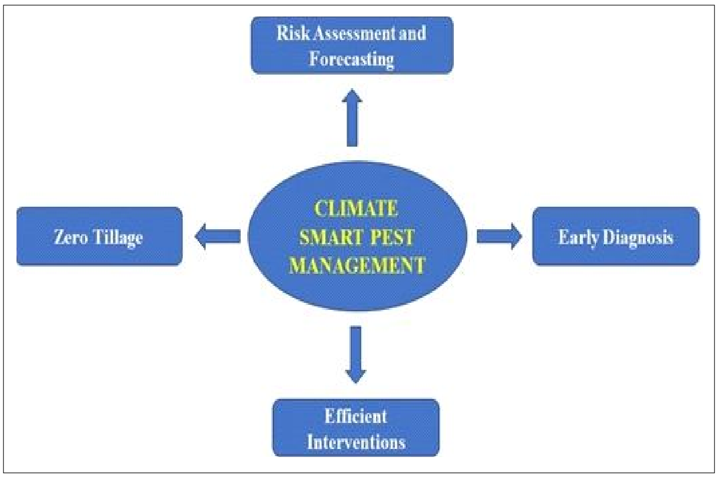

Fig 2: Climate smart pest management.

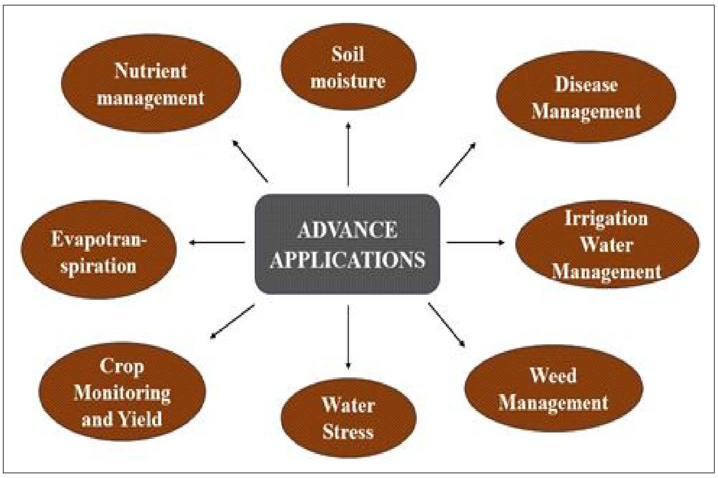

Fig 3: Advance application in precision agriculture.

health assessment (Roßmann *et al*., 2018). The sensors of these platforms are able to provide data associated with crop parameters like growth rate, leaf area index, leaf temperature, infestation of the pests or diseases as well as soil moisture content, nutrient status (fertility), compaction and temperature (Choudhary *et al*., 2016).

Site-specific soil and crop management

Site-specific soil and crop management is a strategy that adjusts farming procedures based on data collected from an appropriate source so as to compensate for the variable soil conditions in each site (Kumar *et al*., 2024). Deep tillage is a precision technique that has got a lot of promise as well as reduced tire pressure and control traffic farming (De Caires *et al*., 2024). Some of the precision agriculture technology such as remote sensing helps manage soil compaction (Xiao *et al*., 2024).

Yield monitoring and mapping

In the contemporary agricultural landscape, modern combine harvesters come equipped with integrated yield monitors, serving as invaluable tools for grain production (Hatfield *et al*., 2017). These monitors empower farmers to evaluate and delineate the impact of weather, soil properties and management practices on grain production (Lal *et al*., 2017). However, the accuracy of these devices relies on proper installation, calibration and operation (Singh, 2022). To gain detailed insights into soil health, farmers often employ soil sampling followed by laboratory analyses, complemented by the use of yield monitors to comprehend spatial variability in crop yield (Mani *et al*., 2021). The yield monitoring system facilitates the collection of geo-referenced yield data, enabling the creation of yield maps that visualize crop performance variability (Liu and Khosla, 2010).

Agricultural robots

The landscape of agriculture has been radically transformed by the integration of robotics and applications of robotics in agriculture, forestry and horticulture are constantly evolving (Wang *et al*., 2024). To achieve precision in crop production management at the individual plant level, the adoption of autonomous and robotic technologies is becoming increasingly crucial (Paul *et al*., 2024). However, emerging technologies such as autonomous tractors, drones, crop harvesting robots, seeding machines and robotic weeding are revolutionizing precision agriculture (Kappagantula, 2024). These autonomous platforms can handle tasks from field preparation to crop harvesting, offering advantages that surpass traditional machinery (Bale *et al*., 2024). Recently, there is growing confidence in the potential of robotic weeding, scouting and the application of crop production inputs through *UAV/drone* technology, particularly in the Midwest United States (Balyan *et al*., 2024). However, advance application in precision agriculture are indexed in Fig 3.

CONCLUSION

The fusion of sustainable agriculture and precision farming encapsulates a promising approach to address the challenges of feeding a growing global population while mitigating environmental impacts. By incorporating advanced technologies and data-driven practices, this integrated model seeks to optimize resource use, reduce ecological footprints and enhance overall farm productivity. Emphasizing a holistic perspective that prioritizes economic viability and social equity, the convergence of sustainable and precision farming holds the potential to revolutionize the agricultural landscape, fostering resilient and environment friendly food systems for future generations.

REFERENCES

Abdullah, H.M., Islam, M.N., Saikat, M.H. and Bhuiyan, M.A. (2024). Precision agriculture practices from planting to postharvest: Scopes, opportunities and challenges of innovation in developing countries. Remote Sensing in Precision Agriculture. 3-26. https://doi.org/10.1016/B978-0-323-91068-2.00014-X.

Alexander, S. (2019). What climate-smart agriculture means to members of the Global Alliance for climate-smart agriculture. Future of Food: Journal on Food, Agriculture and Society. 7: 21-30.

Andersen, B.C., Bandura, K., Bhardwaj, M., Boyle, P.J., Brar, C., Cassanelli, T. and Chime/Frb Collaboration. (2023). CHIME/FRB discovery of 25 repeating fast radio burst sources. The Astrophysical Journal. 947: 83. https://doi.org/10.3847/1538-4357/acc65f.

Azadi, H., Moghaddam, S.M., Burkart, S., Mahmoudi, H., Van Passel, S., Kurban, A. and Lopez-Carr, D. (2021). Rethinking resilient agriculture: From climate-smart agriculture to vulnerable-smart agriculture. Journal of Cleaner Production. 319: 128602. https://doi.org/10.1016/j.jclepro.2021.128602.

Bale, A.S., Varsha, S.N., Naidu, A.S., Vinay, N. and Tiwari, S. (2024). Autonomous Aerial Robots Application for Crop Survey and Mapping. In Precision Agriculture for Sustainability Apple Academic Press. (pp. 123-145).

Balyan, S., Jangir, H., Tripathi, S.N., Tripathi, A., Jhang, T. and Pandey, P. (2024). Seeding a sustainable future: Navigating the digital horizon of smart agriculture. Sustainability. 16: 475. https://doi.org/10.3390/su16020475.

Bouri, M., Arslan, K.S. and ªahin, F. (2023). Climate-smart pest management in sustainable agriculture: Promises and challenges. Sustainability. 15: 4592. https://doi.org/10.3390/su15054592.

Bramley, R.G. (2009). Lessons from nearly 20 years of precision agriculture research, development and adoption as a guide to its appropriate application. Crop and Pasture Science. 60: 197-217.

Challinor, A.J., Arenas-Calles, L.N. and Whitfield, S. (2022). Measuring the effectiveness of climate-smart practices in the context of food systems: Progress and challenges. Frontiers in Sustainable Food Systems. 6: 853630. https://doi.org/10.3389/fsufs.2022.853630.

Choudhary, S.K., Jadoun, R.S. and Mandoriya, H.L. (2016). Role of cloud computing technology in agriculture fields. Computing. 7: 1-7.

De Caires, S.A., Keshavarzi, A., Bottega, E.L. and Kaya, F. (2024). Towards site-specific management of soil organic carbon: Comparing support vector machine and ordinary kriging approaches based on pedo-geomorphometric factors. Computers and Electronics in Agriculture. 216: 108545. https://doi.org/10.1016/j.compag.2023.108545.

Du, X., Elbakidze, L., Lu, L. and Taylor, R.G. (2022). Climate smart pest management. Sustainability. 14: 9832. https://doi.org/10.3390/su14169832.

FAO, (2009). Global agriculture towards 2050. Available at: https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf. Accessed on: 11th January 2023.

Garibaldi, L.A. and Pérez-Méndez, N. (2019). Positive outcomes between crop diversity and agricultural employment worldwide. Ecological Economics. 164: 106358. https://doi.org/10.1016/j.ecolecon.2019.106358.

Gebbers, R. and Adamchuk, V.I. (2010). Precision agriculture and food security. Science. 327: 828-831.

Ghadirnezhad Shiade, S.R., Fathi, A., Kardoni, F., Pandey, R. and Pessarakli, M. (2024). Nitrogen contribution in plants: Recent agronomic approaches to improve nitrogen use efficiency. Journal of Plant Nutrition. 47: 314-331.

Godwin, R.J., Richards, T.E., Wood, G.A., Welsh, J.P. and Knight, S.M. (2003). An economic analysis of the potential for precision farming in UK cereal production. Biosystems Engineering. 84: 533-545.

Gokool, S., Mahomed, M., Kunz, R., Clulow, A., Sibanda, M., Naiken, V. and Mabhaudhi, T. (2023). Crop monitoring in smallholder farms using unmanned aerial vehicles to facilitate precision agriculture practices: A scoping review and bibliometric analysis. Sustainability. 15: 3557. https://doi.org/10.3390/su15043557.

Hatfield, J.L., Sauer, T.J. and Cruse, R.M. (2017). Soil: The forgotten piece of the water, food, energy nexus. Advances in Agronomy. 143: 1-46.

Heeb, L., Jenner, E. and Cock, M.J. (2019). Climate-smart pest management: Building resilience of farms and landscapes to changing pest threats. Journal of Pest Science. 92: 951-969.

Huo, D., Malik, A.W., Ravana, S.D., Rahman, A.U. and Ahmedy, I. (2024). Mapping smart farming: Addressing agricultural challenges in data-driven era. Renewable and Sustainable Energy Reviews. 189: 113858. https://doi.org/10.1016/j.rser.2023.113858.

Kappagantula, S. (2024). Design and Development of a Quadruped Robot for Precision Agriculture Applications. In Precision Agriculture for Sustainability. Apple Academic Press. (pp. 195-219).

Karunathilake, E.M.B.M., Le, A.T., Heo, S., Chung, Y.S. and Mansoor, S. (2023). The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture. 13: 1593. https://doi.org/10.3390/agriculture13081593.

Kumar, S., Yadav, A., Taria, S., Alam, B., Singh, P., Dwivedi, R.P. and Arunachalam, A. (2024). Scope, Importance and Limitations of Precision-agriculture-based Practices for Crop Management: Indian Perspective. In Remote Sensing in Precision Agriculture. Academic Press. (pp. 27-40).

Lal, R., Mohtar, R.H., Assi, A.T., Ray, R., Baybil, H. and Jahn, M. (2017). Soil as a basic nexus tool: soils at the center of the food-energy-water nexus. Current Sustainable/Renewable Energy Reports. 4: 117-129.

Lee, S.K., Lur, H.S. and Liu, C.T. (2021). From lab to farm: Elucidating the beneficial roles of photosynthetic bacteria in sustainable agriculture. Microorganisms. 9: 2453. https://doi.org/10.3390/microorganisms9122453.

Li, Z., Liu, Y., Hossain, O., Paul, R., Yao, S., Wu, S. and Wei, Q. (2021). Real-time monitoring of plant stresses *via* chemiresistive profiling of leaf volatiles by a wearable sensor. Matter. 4: 2553-2570.

Lipper, L. and 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. https://doi.org/10.1007/978-3-319-61194-5_2.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M. and Torquebiau, E.F. (2014). Climate-smart agriculture for food security. Nature Climate Change. 4: 1068-1072.

Liu, T. and Khosla, C. (2010). Genetic engineering of *Escherichia coli* for biofuel production. Annual Review of Genetics. 44: 53-69.

Lowenberg-DeBoer, J., Franklin, K., Behrendt, K. and Godwin, R. (2021). Economics of autonomous equipment for arable farms. Precision Agriculture. 22: 1992-2006.

Mani, P.K., Mandal, A., Biswas, S., Sarkar, B., Mitran, T. and Meena, R.S. (2021). Remote Sensing and Geographic Information System: A Tool for Precision Farming. In: Geospatial Technologies for Crops and Soils. [Mitran, T., Meena, R.S., Chakraborty, A. (eds)] Springer, Singapore. https://doi.org/10.1007/978-981-15-6864-0_2.

Murage, A.W., Midega, C.A.O., Pittchar, J.O., Pickett, J.A. and Khan, Z.R. (2015). Determinants of adoption of climate-smart push-pull technology for enhanced food security through integrated pest management in eastern Africa. Food Security. 7: 709-724. https://doi.org/10.1007/s12571-015-0454-9.

Paul, S. and Chang, J. (2024). Consequent pole flux modulated linear actuator under winding chang and field oriented control driving conditions for long track and multi-track agricultural robot. Computers and Electronics in Agriculture. 217: 108582. https://doi.org/10.1016/j.compag.2023.108582.

Picchio, R., Proto, A.R., Civitarese, V., Di Marzio, N. and Latterini, F. (2019). Recent contributions of some fields of the electronics in development of forest operations technologies. Electronics. 8: 1465. https://doi.org/10.3390/electronics8121465.

Ristaino, J.B. anderson, P.K., Bebber, D.P., Brauman, K.A., Cunniffe, N.J., Fedoroff, N.V. and Wei, Q. (2021). The persistent threat of emerging plant disease pandemics to global food security. Proceedings of the National Academy of Sciences. 118: e2022239118. https://doi.org/10.1073/pnas.2022239118.

Roßmann, B., Canzaniello, A., von der Gracht, H. and Hartmann, E. (2018). The future and social impact of big data analytics in supply chain management: Results from a delphi study. Technological Forecasting and Social Change. 130: 135-149.

Roy, N. (2022). Population ecology and economic thresholds-based time series for climate smart pest management of *Spilosoma obliqua* walker (Lepidoptera: Arctiidae) on three sesame cultivars. The Journal of Basic and Applied Zoology. 83: 19. https://doi.org/10.1186/s41936-022-00283-w.

Saranya, T., Deisy, C., Sridevi, S. and Anbananthen, K.S.M. (2023). A comparative study of deep learning and Internet of things for precision agriculture. Engineering Applications of Artificial Intelligence. 122: 106034. https://doi.org/10.1016/j.engappai.2023.106034.

Scherr, S.J., Shames, S. and Friedman, R. (2012). From climate-smart agriculture to climate-smart landscapes. Agriculture and Food Security. 1: 12. https://doi.org/10.1186/2048-7010-1-12.

Sekabira, H., Tepa-Yotto, G.T., Djouaka, R., Clottey, V., Gaitu, C., Tamò, M. and Ddungu, S. P. (2022). Determinants for deployment of climate-smart integrated pest management practices: A meta-analysis approach. Agriculture. 12: 1052. https://doi.org/10.3390/agriculture12071052.

Shafi, U., Mumtaz, R., García-Nieto, J., Hassan, S.A., Zaidi, S.A.R. and Iqbal, N. (2019). Precision agriculture techniques and practices: From considerations to applications. Sensors. 19: 3796. https://doi.org/10.3390/s19173796.

Shaheb, M.R., Sarker, A. and Shearer, S.A. (2022). Precision Agriculture for Sustainable Soil and Crop Management. In Soil Science-Emerging Technologies, Global Perspectives and Applications. IntechOpen. https://doi.org/10.5772/intechopen.101759.

Singh, A.K. (2022). Precision agriculture in India-opportunities and challenges. Indian Journal of Fertilisers. 18: 308-331.

Sishodia, R.P., Ray, R.L. and Singh, S.K. (2020). Applications of remote sensing in precision agriculture: A review. Remote Sensing. 12: 3136. https://doi.org/10.3390/rs12193136.

Su, J., Zhu, X., Li, S. and Chen, W.H. (2023). AI meets UAVs: A survey on AI empowered UAV perception systems for precision agriculture. Neurocomputing. 518: 242-270.

Taylor, M. (2018). Climate-smart agriculture: what is it good for? The Journal of Peasant Studies. 45(1): 89-107.

Velásquez, A.C., Castroverde, C.D.M. and He, S.Y. (2018). Plant-pathogen warfare under changing climate conditions. Current Biology. 28: R619-R634.

Velten, S., Leventon, J., Jager, N. and Newig, J. (2015). What is sustainable agriculture? A systematic review. Sustainability. 7: 7833-7865.

Wang, J., Zheng, H., Yu, Y., He, Y., and Liu, Y. (2024). Robust multiple obstacle tracking method based on depth aware OCSORT for agricultural robots. Computers and Electronics in Agriculture. 217: 108580. https://doi.org/10.1016/j.compag.2023.108580.

Xiao, L., Wang, G., Wang, E., Liu, S., Chang, J., Zhang, P. and Luo, Z. (2024). Spatiotemporal co-optimization of agricultural management practices towards climate-smart crop production. Nature Food. https://doi.org/10.1038/s43016-023-00891-x.