Biological Forum – An International Journal 16(4): 234-242(2024)

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

Comprehensive Analysis of Precision Farming Technologies and their Impact on Sustainable Crop Management

Rakhi R.[1] and Geetha Radhakrishnan[2*]
[1]Assistant Professor (Horticulture), Department of Fruit Science,
College of Agriculture, Vellayani, Kerala Agricultural University (Kerala), India.
[2]Assistant Professor (Computer Science),
Regional Agricultural Research Station (Southern Zone), Vellayani, Kerala Agricultural University (Kerala), India.

(Corresponding author: Geetha Radhakrishnan)*
(Received: 15 February 2024; Revised: 07 March 2024; Accepted: 26 March 2024; Published: 15 April 2024)
(Published by Research Trend)

ABSTRACT: India, an agricultural nation, confronts severe food scarcity amidst rapid population growth and labour migration from rural agriculture to more profitable jobs. This paper explores advanced agricultural technologies as a solution, highlighting smart farming tools such as sensors, drones, robots, IoT, UAVs, GPS and GIS. These innovations facilitate real-time monitoring of crops, soil and the environment. They enhance the efficiency through aerial surveys and AI-powered robotics for precision planting, automated data exchange and farm management. GPS and GIS contribute to accurate land mapping and informed crop planning. Although these technologies offer the potential for increased productivity and sustainable practices, their field implementation poses significant challenges. The paper reviews these obstacles and suggests solutions.

Keywords: Artificial Intelligence, Smart Agriculture, Hi-Tech Farming, Internet of Things (IoT), Sensors.

INTRODUCTION

Agriculture plays a key role in India, where it occupies 52.3% of arable land, contributes 18.3% to GDP and accounts for nearly 40% of the rural Net Domestic Product (Arth NITI, 2020). It supports the livelihoods of two-thirds of its rural population and plays a vital role in feeding the majority of the population (Anilkumar *et al*., 2017)**.** Despite a record production of 316 million metric tons in 2021-22, the agricultural sector in India confronts challenges like rising population, resource competition and the need for improved food quality. Besides its struggle with high costs, low productivity and climate issues, agriculture in India also faces a scarcity of farming labor and land. Acknowledging the necessity for modernization and embracing new technologies is crucial for boosting food production per unit of arable land (Matson *et al*., 1997).

In response to these challenges, the concept of smart farming has emerged as a revolutionary approach, aiming to overcome the limitations of conventional farming and unlock the full potential of the Indian agricultural sector. Smart farming, defined as the integration of modern technologies and advanced techniques to optimize farming operations, resource utilization and overall efficiency (Balafoutis *et al*., 2017).

The smart farming approach has the potential to improve work safety, enhance consumer acceptance and transform the operations and management of farms (Kamilaris *et al*., 2017). By using spatially varying techniques, smart farming can adapt to different conditions, providing precise and resource-efficient solutions for increased agricultural production and sustainability (Jayne *et al*., 2019). Smart farming employs a range of technologies, including sensors, drones, artificial intelligence and the Internet of Things (IoT), to collect real-time data and provide insights into crop health, soil quality and other key indicators (Sharma *et al*., 2022). Smart farming integrates advanced technologies like IoT, robotics and automation seamlessly into traditional farming practices (Morchid *et al.*, 2024). According to Vishnoi (2019) now a days, automation implementation is viewed as more of a necessity rather than a core-competence.

1. Sensor Technology. A sensor is an electrotechnical device that measures environmental physical quantities and converts data into electrical signals readable by instruments (Pivoto *et al*., 2018). Sensors used in agriculture provide data for farmers to monitor and optimize crops in varying conditions. Research suggest that sensors will be implemented in approximately 525 million global farms by 2050 (Triantafyllou *et al.*, 2019). The choice of the sensor depends on the change to be detected, with applications in weather stations, harvesters, weeders, drones and robots. Sensor readings encompass temperature, humidity, light, pressure, noise levels, mechanical stress, soil patterns, air flow, location, CO_2, water stress and more (Rajak *et al.*, 2023; Chaudhary *et al*., 2023). Sensors use photoelectricity, electromagnetics, conductivity and ultrasound to estimate soil properties, nutrient levels, vegetation, humidity, vapor, air and temperature.

Sensor Characteristics. Prominent sensor features include accuracy, reliability, precision, sensitivity, memory, portability, durability, coverage and computational efficiency (Farooq *et al*., 2020). Sensors are of different types like analog and digital, scalar and vector, and static and dynamic. Static characteristics include accuracy, range, resolution, precision, sensitivity, linearity, drift and repeatability. Dynamic characteristics are of Zero-Order, First-Order and Second-Order Systems characteristics (Dhanaraju *et al*., 2022). Sensors find application in various areas based on their types.

Utilizing Sensor Technology in Agricultural Practises. E –sensing. E-sensing involves replicating human senses through sensor arrays and pattern recognition (Patel *et al*., 2020). An electronic tongue was utilized to discern taste differences in grafted and non-grafted watermelon fruits. Alpha Astree II electronic tongue was used for the measurement of watermelon juices (Fraden, 2016). Metal-oxide gas sensors were employed for early detection of potato storage disease (Rutolo *et al*., 2016).

2. Geographic Information System. GIS can be used for mapping potential growth areas (Rutolo *et al*., 2016), soil analysis and improve farm record keeping (Mennecke and Crossland 1996), to provide information on field soil types, nutrient status, topography, irrigation, drainage, chemical applications and crop production (Dorji *et al*., 2017), precision farming, digital mapping, crop health analysis, agro-climatic conditions, yield estimation, site suitability analysis for crop production (Fekete *et al*., 2018) *etc.* It is also used for the analysis of potential soil degradation on agricultural land (Herdiansyah *et al.,* 2024). Hence, a Geographic Information System (GIS) is a computer-assisted information system that collects, integrates, manages, analyzes and displays spatially referenced data (Gill *et al*., 2023). Commercial GIS software includes ArcGIS, MapInfo, GeoMedia and ArcView, while open-source options are QGIS and Grass GIS.

3. Global Positioning System (GPS). GPS records latitude, longitude and elevation, aiding precise field input application (Falasca *et al*., 2014). It is a network of satellites that accurately pinpoints Earth locations by measuring distances from the satellites (Ojo and Ilunga 2018). *Pieris brassicae* were monitored using GPS and GIS in India, generating georeferenced maps for damage quantification and cabbage butterfly forecasting (Fuentes *et al*., 2018). This approach helps to contribute to future pest management strategies. GPS applications in smart farming include equipment auto-steering, variable-rate seeding, fertilizer and pesticide application, yield monitoring on harvesters and remote sensing for field health assessment and management strategy response data collection. A low-cost Global Navigation Satellite System Positioning Accuracy Assessment Method was proposed for agricultural machinery by Radocaj *et al*. (2022).

4. Unmanned Aerial Vehicles (UAV's)/drones. An Unmanned Aerial Vehicle (UAV), operating without an onboard human pilot, significantly enhances agricultural practices through intelligent aerial mapping. Equipped with autonomous flight controls and advanced hyperspectral snapshot cameras, high-resolution images processed from UAVs are valuable in the study of plant diseases and can be used to monitor various aspects of crop health, including leaf thickness, contaminants, chlorophyll levels and temperature (Walter *et al*., 2017). UAVs are capable of calculating biomass, assessing crop fertilization and distinguishing plant diseases (Hussain *et al.*, 2018). These UAVs utilize sensors and microprocessors for operation, allowing them to assess growth vigor, nutrient status, presence of pathogens, weeds and drought stress. Additionally, UAVs equipped with sensors can map field water, schedule irrigation, detect water shortages and identify water impurities (Pungavi and Praveenkumar 2024).

Drones, outfitted with GPS and onboard sensors, deliver detailed images and data essential for evaluating crop health across temporal, spatial and spectral resolutions. These lightweight and cost-effective devices have revolutionized decision-making and risk management in agriculture (Walter, 2017; Mohsan *et al*., 2022). Agricultural drones, equipped with multispectral sensors, capture electromagnetic radiation to calculate indices such as Leaf area index (LAI), Photochemical reflectance index (PRI) and Normalized difference vegetation index (NDVI) (Nourmohammadi, 2018). In the realm of vegetable production, they facilitate monitoring, pest control and precision agriculture practices (Niu *et al*., 2019). Furthermore, drones play a critical role in collecting thermal and multispectral data, vital for irrigation decisions in crops like onions and potatoes (Oksana *et al*., 2021). According to Soman *et al*. (2024), the main applications of drones in agriculture include crop spraying, crop monitoring, mapping and soil analysis, livestock monitoring and seed planting. Also, unmanned ground vehicle (UGV) systems designed for plant protection can dynamically adjust spray volumes based on vegetation distribution, utilizing decision-making processes informed by machine vision algorithms (Dong *et al*., 2024).

5. The Unmanned Ground Vehicle (UGV)/Robots. The unmanned ground vehicle (UGV) is a comprehensive intelligent system that integrates environmental perception, location, navigation, path planning, decision-making and motion control (Bishop, 2000). The global market for mobile robots is expected to increase at a compound annual growth rate of over 15% from 2017 to 2025 (Gonzalez-De-Santos *et al*., 2020). Amid the growing need for sustainable farming, the integration of robotics in vegetable production, as highlighted by Lowenberg-DeBoer *et al*. (2020), has emerged as a transformative force. Yuan *et al.* (2016) introduced a pollination robot designed for hormone treatment of tomato flowers in inclined-wire cultivation.

6. Variable-Rate Technology (VRT) and Grid Soil Sampling. In agriculture, grid soil sampling collects soil data to create parameter maps, which guide Variable-Rate Technology (VRT) applicators through GPS-directed changes in input delivery (O'Grady and O'Hare 2017). VRT utilizes GIS-derived maps to predict input delivery rates, ensuring precise input placement at varying amounts to optimize efficiency and yield (Lowenberg-DeBoer *et al.,* 2020). Variable rate technology in precision agriculture enables data collection using diverse technological platforms such as sensors, global positioning systems, hyperspectral imaging, drones, satellites and artificial intelligence. Applications of this technology include variable rate seeding (VRS), variable rate fertilization (VRF), variable rate irrigation (VRI) and variable rate crop protection chemical (VRC) deployment (Angelopoulou *et al*., 2019).

7. Internet of Things. The Internet of Things (IoT), is defined by the International Telecommunications Union (2020), as a foundational global infrastructure for the information society, bridging physical and virtual elements. IoT-based solutions, such as smart fertilizer management systems, are rapidly being developed and implemented to advance smart farming practices. One early implementation includes an IoT-based wireless imaging platform for monitoring the growth status of orchids (Kamilaris *et al*., 2016). Additionally, a framework for decision-making and event detection using agri-IoT for medium-to-large farms (Yang *et al*., 2018) and IoT-based sensors enable monitoring of entire farming cycles from seed to sale (Doshi *et al*., 2019) has been proposed.

Recently, Morchid *et al.* (2024) outlined the significant applications of IoT in agriculture, including irrigation systems, fertilizer administration, crop disease detection, monitoring, forecasting, harvesting, climate condition monitoring and fire detection. Also, Internet-based technology now allows for the monitoring of crop conditions, soil and weather, which can be managed *via* smartphones. According to emerging research by Jafarpanah and Karshenas (2024), the Internet of Things (IoT) remains the most critical technological domain in the agricultural sector.

8. Information Communication Technology (ICT). Smart Farming aims to transform traditional techniques into innovative solutions based on Information Communication Technologies (Foughali *et al*., 2018). Information communication technology (ICT) enables individuals to create, collect, process and manage information in different ways (voice, text or image). ICT supports farmers by facilitating access to the market through real-time data on market prices, weather forecasting, information on pests, seed varieties and planting techniques (Moysiadis *et al*., 2021). ICT applications include automated farming, early identification of pests and diseases, crop quality management, monitoring environmental factors and the use of machine vision systems for adjustments (Roztocki *et al.,* 2019). ICT also integrates soil fertility maps, quasi-real-time crop growth data and weather data using global navigation satellite systems (GNSS), various sensors including machine vision, robotic technology, artificial intelligence, internet of things and cloud computers (Madakam *et al.*, 2022).

9. Artificial Intelligence/Machine Learning/Deep Learning. Artificial intelligence (AI), machine learning (ML) and deep learning are collections of technologies that autonomously address challenges and accomplish objectives without human guidance (Toriyama, 2020). These technologies have been effectively applied in agriculture for various purposes. Ashwin Kumar *et al*. (2022) proposed an optimal mobile network-based convolutional neural network model (OMNCNN), which is useful in detecting and classifying plant leaf diseases. The rapid advancements in AI are crucial due to their problem-solving capabilities in these areas (Sharma *et al*., 2022). Data-driven technologies built over AI or ML algorithms can assist farmers with critical decision-making (Balkrishna *et al*., 2023), showcasing the ongoing evolution and utility of these technologies in modern agriculture.

10. Big Data. The vast amount of data generated in smart farming from diverse sources requires efficient management and analysis (Hashem *et al*., 2015). Big data refers to the significant increase in data volume that traditional database technologies struggle to store, process and analyze (Capizzi *et al*., 2016). Big data analytics tools are capable of processing and analyzing this data to identify meaningful patterns, trends and correlations. These insights allow farmers to better understand crop performance, resource utilization and environmental conditions, aiding in the optimization of farming practices, resource conservation, cost reduction and increased profitability (Madhuri and Indramma 2019). Furthermore, Big Data analytical platforms accommodate the growing volume, velocity, variety and veracity of data in agriculture, supporting significant advancements (Arvanitis *et al*., 2020). Data analytics significantly enhances the accuracy and predictability of smart agricultural systems (Aliar *et al*., 2022), providing crucial support to the evolving needs of modern agriculture.

APPLICATIONS OF SMART FARMING TECHNOLOGIES IN AGRICULTURE

Precision Farming. GPS controllers, sensor technology and wireless communication are crucial in precision farming, enhancing the monitoring of soil, climate and irrigation parameters (Tarun *et al*., 2020). IoT-based methods such as CWSI-based irrigation management have been developed to transform traditional irrigation practices and improve water productivity in agriculture (Zhang *et al*., 2018). Advanced precision farming systems that integrate smart irrigation, fertilizer guidance, disease detection and crop damage forecasting through IoT, machine learning and deep learning technologies have also been introduced (Garg *et al*., 2021). Furthermore, utilizing machine learning, Reddy *et al.* (2024) introduced a system for recommending crops and fertilizers based on soil classification, aiding farmers in determining the appropriate ratios of NPK fertilizers.

Greenhouse Farming and Protected Cultivation. Experiments were conducted to study the IoT-based environment change monitoring and control in a greenhouse using WSN (Shinde and Siddiqui 2018). The greenhouse approach stands out as the most effective method for achieving the objectives of protected cultivation. Greenhouse cultivation effectively controls the micro-climate for optimal plant growth (Sidharth *et al.*, 2023).

Hydroponics. Hydroponics can be defined as the cultivation in a solution or cultivation using substrates like sand, gravel, liquid, and any other except soil (Jan *et al*., 2020). IoT-based hydroponics in combination with Deep Neural Network technology (Aires, 2018) and an IoT-based automated indoor vertical hydroponics farming system, ensuring autonomous adjustment and maintenance of critical parameters like pH, electrical conductivity, temperature and water level, have shown the feasibility of sensors in hydroponics (Chowdhury *et al*., 2020).

Vertical Farming. Vertical farming (VF) offers an opportunity to keep the plants in a precisely controlled environment, significantly reducing resource consumption and at the same time, increasing production at varied times (Kalantari *et al*., 2017). VF is also extremely effective in higher yields and reducing water consumption compared to traditional farming. The carbon dioxide measurement is the most critical parameter; hence, non dispersive infrared (NDIR) CO_2 sensors play a vital part in tracking and controlling the conditions in vertical farms (Dhanaraju *et al*., 2022).

Aeroponics. Aeroponics is a novel and efficient soilless farming technique that combines the aspects of hydroponics and vertical farming innovative agricultural practices (Lucero *et al.*, 2020). An Arduino-based system utilizing microcontrollers and electronic devices has been developed to regulate and monitor temperature, humidity and irrigation in lettuce cultivation (Calzita *et al*., 2023). Besides this, Sadek and Shehata (2024), have designed and implemented a smart greenhouse system, employing hydroponic and aeroponic methods powered by Internet of Things (IoT) technology.

Soil Sampling and Mapping. Soil composition results from the interaction of various abiotic and biotic elements and is unique based on its geographic location, hence it plays an important role in determining the source for food traceability and biosecurity (Ananthi *et al*., 2017). loT system consisting of various sensors such as a pH sensor, temperature sensor, humidity sensor, a microcontroller, a microprocessor and a web camera can be set up in a field to automate irrigation and to collect data about the items mentioned (Lad *et al.*, 2022). Additionally, Pham and Nguyen (2024) developed an innovative tool for soil sampling using deep learning which integrates traditional and modern soil sampling methods.

Crop Monitoring, Yield Monitoring, Forecasting and Harvesting. In horticulture, tracking fruit growth is key component for assessing crop progress and yield. A yield monitor, mounted on a harvester and linked to a mobile app, shows live harvest data and syncs with a web platform (Dhanaraju *et al*., 2022). Additionally, a small IoT camera has shown success in monitoring and forecasting tomato harvest times, highlighting IoT's role in improving crop monitoring and yield prediction, essential for better harvesting (Lee *et al*., 2022). A smart crop monitoring system was reported by Kumar Pradhan *et al*. (2024) using technologies like the Internet of Things (IoT) and artificial intelligence (AI) to cater different farming operations such as soil quality, meteorological conditions and crop requirements. Application of remote sensing technology for monitoring mangroves was reported by Masood *et al.* (2015)

Crop Pest and Disease Management. Recent IoT-based intelligent devices such as wireless sensors, robots, and drones are allowing growers to slash pesticide use significantly by precisely spotting crop enemies (Ayaz *et al*., 2017). Smart farming has helped to monitor infections in crops at a much faster detection rate and also reduced the time of diagnosis. Modern IoT-based pest management provides real-time monitoring, modeling and disease forecasting, proving more effective compared to the traditional calendar or prescription-based pest control procedures (Ayaz *et al.*, 2019). IoT-enabled pest identification and classification with Meta-Heuristic-Based Deep Learning Framework was proposed by Kathole *et al*. (2024).

DISCUSSIONS

The article reviews smart farming technologies and their varied applications in agriculture. It highlights technologies like sensors, GIS, GPS, UAVs, UGVs, robots, VRT, IoT, ICT, AI, machine learning, deep learning and big data. The focus is on their use in vegetable farming for tasks such as precision farming, greenhouse and vertical farming, hydroponics, aeroponics, soil sampling, crop and yield monitoring, forecasting, harvesting and managing pests and diseases.

Referring to Table 1, between 1999-2010, precision farming technologies, GPS and sensors were slowly adopted, with initial explorations into integrating IoT and AI. Limited mentions of drones and UAVs are noted in this era. The focus on sustainability and resource efficiency was limited, with basic sensors like soil moisture, temperature and humidity sensors being common. From 2010-2023, there was an accelerated adoption of advanced technologies such as IoT, AI and drones. This shift led to smarter, more connected and data-driven agricultural practices. The period also saw a growing emphasis on sustainability and efficient resource management, with a global spread of research and applications. Sensor technology advanced, becoming more miniaturized and integrated, facilitating precision and expanded functionalities through AI and IoT.

Table 1: Use of Items in Precision Agriculture.

Sr. No.	Particulars	1999-2010	2010-2023
1.	Adoption of Technology	The adoption of precision farming technologies, GPS and sensors started gaining attention, albeit at a slower pace.	There is an accelerated adoption of advanced technologies, including IoT, AI and drones, indicating a shift towards more connected and data-driven agriculture.
2.	Integration of IoT and AI	Initial stages of exploring the potential of IoT and AI in agriculture.	The growing integration of IoT and AI, leading to smart farming practices. This is reflected in references discussing IoT-based smart agriculture, AI applications and data analytics
3.	Drones and UAVs	Limited mentions of UAVs and drones in agriculture.	Increased utilization of drones and UAVs for crop monitoring, mapping and other precision agriculture tasks.
4.	Focus on sustainability	Limited emphasis on sustainability and resource efficiency.	References indicate a growing awareness of sustainability, with technologies being applied for efficient resource management.
5.	Global Perspectives	Initial studies and applications are primarily in specific regions.	The references show a broader global perspective, with applications and research in different continents.
6.	Sensor types	Basic sensors were prevalent, including simple soil moisture sensors, temperature sensors and humidity sensors.	Sensors became increasingly miniaturized, efficient and integrated into various devices. Advancements during this time allowed for improved precision, expanded functionalities and the incorporation of emerging technologies like AI and IoT.

The graph in Fig. 1 illustrates the projected growth of the global smart technology industry from 2016 to 2032. The values given are in trillions of U.S. dollars and represent the global compound annual growth rate (CAGR). Starting at approximately $0.65 trillion in 2016, the industry sees a steady increase. By 2022, the value is more than double and has reached to around $9.3 trillion, and it continues to rise to about $10.49 trillion by 2024 (DataIntelo, 2024), (Statista, 2024). There's a notable jump in growth projected by 2032, where the value reaches over $27.47 trillion. This trend indicates robust growth in the smart technology sector, suggesting increasing investment and expansion across the industry globally. The steep growth curve between 2030 and 2032 could imply a significant technological breakthrough or increased market adoption rates, leading to a surge in the industry's value.

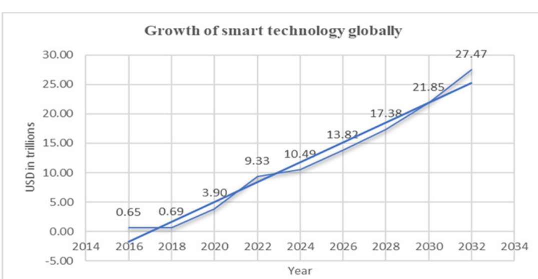

Fig. 1. Growth of the Smart Technology industry globally.

The graph in Fig. 2 illustrates the adoption rates of various smart technologies in agriculture. Sensors/IoT lead with the highest usage, around 50%. GPS/GIS follows as the second most used technology at approximately 30%. UAVs (drones) show a lower adoption rate, just above 10%. Unmanned ground vehicles (UGVs) and ICT are the least utilized technologies, both falling under 10%. Big Data usage is slightly higher than UGVs and ICT, indicating its emerging role in the agricultural sector. The graph underscores a significant reliance on sensor technology and location mapping in smart farming.

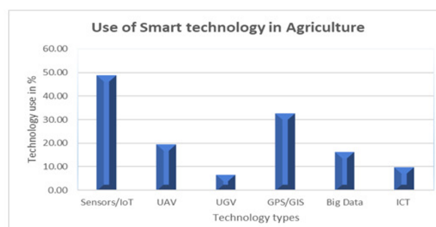

Fig. 2. Use of Smart Technology in Agriculture.

Despite the numerous advantages of IoT sensors in agriculture, several challenges persist. Some of these include the high initial implementation cost, the need for reliable internet connectivity in remote areas and data privacy concerns. Overcoming these challenges will be crucial for widespread adoption and maximizing the potential benefits of IoT sensors in agriculture (Prakash *et al*., 2023).

Challenges in the agriculture sector, include population growth, competition for resources, climate change and the scarcity of labour. These challenges underscore the need for innovative solutions. The advent of Smart Farming in agriculture offers exciting developments. Smart farming practices in vegetable cultivation will boost production by dealing with every inch of land using technologies. It is essential to promote good practices for smart farming of the future (Rajak *et al*., 2023).

Future developments in IoT sensors for agriculture may involve advancements in sensor technology, such as integrating multispectral imaging for advanced crop monitoring and combining sensor data with AI algorithms to enable predictive analytics for optimized crop management.

CONCLUSIONS

IoT sensors have emerged as a game-changer in modern agriculture, empowering farmers with real-time data and insights for more efficient and sustainable practices. This review paper highlighted the advancements, applications and challenges associated with IoT sensors in agriculture. As technology continues to evolve, the integration of IoT sensors will become increasingly vital in shaping the future of connected and smart agriculture. Addressing the challenges and embracing innovative developments will drive the agricultural sector towards greater productivity and environmental stewardship.

FUTURE SCOPE

The future scope of smart agriculture in India is pivotal in addressing challenges posed by climate change, increasing food demands and resource scarcity. As the country faces these pressures, high-tech agricultural practices become not just beneficial but essential. Smart farming technologies such as IoT sensors, precision farming and AI-driven analytics can optimize resource use, enhance crop yields and minimize environmental impact.

Training programs are crucial to equip farmers with the skills necessary to implement these technologies. Reducing hesitancy towards new methods will be key, necessitating widespread educational initiatives to demonstrate the benefits and ease of use of advanced tools. Innovations in low-cost sensors and sustainable technologies will further enable adoption, making advanced farming accessible to a broader range of farmers. Urban farming presents a unique opportunity to utilize educated yet unemployed youth, turning urban spaces into productive agricultural hubs. Managed *via* smartphones, these micro-farms can contribute significantly to local food production, reducing dependency on supermarkets and enhancing nutritional self-sufficiency, a vital consideration in scenarios like the COVID-19 pandemic.

By integrating smart agriculture into the mainstream, India can address malnutrition and ensure a resilient food system capable of withstanding global disruptions and climate-related challenges, paving the way for a sustainable agricultural future.

REFERENCES

Aires, A. (2018). Hydroponic Production Systems: Impact on Nutritional Status and Bioactive Compounds of Fresh Vegetables. *Vegetables - Importance of Quality Vegetables to Human Health,* 56-66.

Aliar, A.A.S., Yesudhasan, J., Alagarsamy, M., Anbalagan, K., Sakkarai, J. and Suriyan, K. (2022). A comprehensive analysis on IoT-based smart farming solutions using machine learning algorithms. *Bulletin of Electrical Engineering and Informatics 11*(3), 1550-1557.

Ananthi, N., Divya, J., Divya, M., and Janani, V. (2017). IoT based smart soil monitoring system for agricultural production. In: *IEEE Technological Innovations in ICT for Agriculture and Rural Development (TIAR);* 07-08, Chennai Institute of Electrical and Electronics Engineers, Chennai, 209-214.

Angelopoulou, T., Tziolas, N., Balafoutis, A., Zalidis, G. and Bochtis, D. (2019). Remote Sensing Techniques for Soil Organic Carbon Estimation: A Review. *Remote Sensing*, *11*(6),676-684.

Anilkumar, T. G. and Ganesh, T. D. (2017). Enable smart farm in Digital India with artificial intelligence and IoT. *Imp. J. Interdiscip. Res*., *3*(3), 1669-1672.

Arth NITI ANNIVERSARY EDITION, (2020). *Special Feature. Indian Agriculture* Vol. 5. Arthnitinewslettersep30_0.pdf

Arvanitis, K. G. and Symeonaki, E. G. (2020). Agriculture 4.0: The role of innovative smart technologies towards sustainable farm management. *The Open Agriculture Journal, 14*(1), 130-135.

Ashwinkumar, S., Rajagopal, S., Manimaran, V. and Jegajothi, B. (2022). Automated plant leaf disease detection and classification using optimal MobileNet based convolutional neural networks. *Materials Today: Proceedings*, *51*, 480-487.

Ayaz, M. Uddin, M. A., Sharif, Z., Mansour, A., and Aggoune, E. H. M. (2019). Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE Access 7*, 129551-129583.

Ayaz, M., Ammad-Uddin, M. and Baig, I. (2017). Wireless sensor’s civil applications, prototypes, and future integration possibilities: A review. *IEEE Sens. J.*, *18*(1), 4-30.

Balafoutis, A.T., Beck, B., Fountas, S., Tsiropoulos, Z., Vangeyte, J., van der Wal, T., Soto-Embodas, I., Gómez-Barbero, M. and Pedersen, S.M. (2017). Smart farming technologies–description, taxonomy, and economic impact. In: Pedersen, M., Lind, K.M. (eds), *Precision agriculture: Technology and economic perspectives*, Springer International Publishing, 21-77.

Balkrishna, A., Pathak, R., Kumar, S., Arya, V. and Singh, S. K. (2023). A comprehensive analysis of the advances in Indian Digital Agricultural architecture. *Smart Agricultural Technology*, *5*, 100318.

Bishop, R. (2000). A survey of intelligent vehicle applications worldwide. In: *Proceedings of the IEEE Intelligent Vehicles Symposium, U.S.A*., 25-30.

Calzita, C. R., Jubilo, K. A., Permejo, G., Reas, R., Baun, J. J., Concepcion, R., De Leon, J. A., Bandala, A., Mayol, A.P., Vicerra, R. R. and Dadios, E. (2023). Intelligent Aeroponic System for Real-Time Control and Monitoring of*Lactuca sativa* Production. In: *17th International Conference on Ubiquitous Information Management and Communication (IMCOM)*, 1-7.

Capizzi, G., Lo Sciuto, G.R.A.Z.I.A., Napoli, C., Tramontana, E. and Woźniak, M.A.R.C.I.N. (2016). A Novel Neural Networks-Based Texture Image Processing Algorithm for Orange Defects Classification. *International Journal of Computer Science and Applications*, *13*(2), 45-60

Chaudhary, V., Khanna, V., Awan, H.T.A., Singh, K., Khalid, M., Mishra, Y.K., Bhansali, S., Li, C.Z. and Kaushik, A. (2023). Towards hospital-on-chip supported by 2D MXenes-based 5th generation intelligent biosensors. *Biosensors and Bioelectronics*, *220,* 114847.

Chowdhury, M. E. Khandakar, A., Ahmed, S., Khuzaei, F. A, Hamdalla, J., Haque, F. Reaz, M. B., Al Shafei, A.,

and Emadi, N. A. (2020). Design, construction and testing of loT-based automated indoor vertical hydroponics farming test- bed in Qatar. *Sensors, 20*(19), 5637.
Dataintelo.com, https://dataintelo.com/report/technology-market.Technology Market Size, Growth, Industry & Revenue | 2032
Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S., and Kaliaperumal, R. (2022). Smart Farming: Internet of Things (IoT)-Based Sustainable Agriculture. *Agriculture*, *12*(10), 1745.
Dong, H., Shen, J., Yu, Z., Lu, X., Liu, F. and Kong, W. (2024). Low-Cost Plant-Protection Unmanned Ground Vehicle System for Variable Weeding Using Machine Vision. *Sensors, 24*(4), 1287.
Dorji, U., Pobkrut, T. and Kerdcharoen, T. (2017). Electronic nose based wireless sensor network for soil monitoring in precision farming system. In: *9th International Conference on Knowledge and Smart Technology (KST)*, 182-186.
Doshi, J., Patel, T. and Kumar Bharti, S. (2019). Smart Farming using IoT, a solution for optimally monitoring farming conditions. *Procedia Computer Science*, *160*, 746-751.
Falasca, S. L., Pitta Alvarez, S. I. and Bernabé, M. A. (2014). Agroclimatic Zoning for Amaranth (*Amaranthus caudatus*) Using a Geographical Information System in Argentina. *Journal of Geography, Environment and Earth Science International, 1*(12), 9-23.
Farooq, M. S., Riaz, S., Abid, A., Umer, T. and Zikria, Y. B. (2020). Role of IoT technology in agriculture: A systematic literature review. *Electronics*, *9*(2), 319.
Fekete, D., Balázs, G., Bőhm, V., Várvölgyi, E. and Kappel, N. (2018). Sensory evaluation and electronic tongue for sensing grafted and non-grafted watermelon taste attributes. *Acta Aliment., 47*(4), 487-494.
Foughali, K., Fathallah, K. and Frihida, A. (2018). Using Cloud IOT for disease prevention in precision agriculture. *Procedia computer science*,130,575-582.
Fraden, J. (2016). Humidity and Moisture Sensors. *In: Handbook of Modern Sensors. Springer, Cham.* 5th Ed, 507-523.
Fuentes, R. M., Fuentes, E. T., Quintana, S. E. and García–Zapateiro, L. A. (2018). Application of geographic information systems for characterization of preharvest and postharvest factors of squash (*Cucurbita* sp.) in Bolívar Department, Colombia. *Indian J. Sci. Technol., 11*(9), 1-10.
Garg, S, Pundir, P., Jindal, H., Saini, H, and Garg, S. (2021). Towards a multimodal system for precision agriculture using IoT and machine learning In: *Conference Proceedings of 12th International Computing Communication and Networking Technologies (ICCCNT);* IIT, Kharagpur, 1-7.
Gill, E., Morton, J., Axelrad, P., Akos, D.M., Centrella, M. and Speretta, S. (2023). Overview of space-capable global navigation satellite systems receivers: heritage, status and the trend towards miniaturization. *Sensors, 23*(17),7648.
Gonzalez-De-Santos, P., Fernández, R., Sepúlveda, D., Navas, E., and Armada, M. (2020). Unmanned Ground Vehicles for Smart Farms, *Agron. Clim. Chang. Food Secur*, *6*, 73.
Hashem, I. A. T., Yaqoob, I., Anuar, N. B., Mokhtar, S., Gani, A. and Khan, S. U. (2015). The rise of "big data" on cloud computing: Review and open research issues. *Inf. Syst*., *47,* 98-115.
Herdiansyah, G., Herawati, A., Safira, R., Hardian, T., Istiqomah, N.M., Hasanah, K. and Romadhon, M. R. (2024). Analysis of potential soil degradation on agricultural land based on geographic information systems in Slogohimo District, Wonogiri Regency. In *IOP Conference Series: Earth and Environmental Science, 1314*(1), 012108.
Hussain, B., War, A. R. and Pfeiffer, D. G. (2018). Mapping foliage damage index and monitoring of *Pieris brassicae* by using GIS-GPS technology in cole crops. *J. Entomol. Zool. Stud., 6*(2), 933-938.
ITU (International Telecommunication Union). (2022). ITU homepage [online]. http://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx.
Jafarpanah, I. and Karshenas, A. (2024). Technological trends in smart agriculture. *Journal of Entreneurship and Agriculture, 10*(20), 94-108.
Jan, S., Rashid, Z., Ahngar, T. A., Iqbal, S., Naikoo, M.A., Majeed, S., Bhat, T. A., Gul, R. and Nazir, I. (2020). Hydroponics–A review. *International Journal of Current Microbiology and Applied Sciences*, *9*(8), 1779-1787.
Jayne, T.S., Snapp, S., Place, F. and Sitko, N. (2019). Sustainable agricultural intensification in an era of rural transformation in Africa, *Glob. Food Sec., 20,* 105-113.
Kalantari, F., Mohd Tahir, O., Mahmoudi Lahijani, A. and Kalantari, S. (2017). A Review of Vertical Farming Technology: A Guide for Implementation of Building Integrated Agriculture in Cities, *Advanced Engineering Forum* ,24,76–91.
Kamilaris, A., Gao, F., Prenafeta-Boldu, F. X. and Ali, M. I. (2016). Agri-IoT: A semantic framework for Internet of Things-enabled smart farming applications, *In: Proceedings of the IEEE 3rd World Forum on Internet of Things (WF-IoT), USA*, 442-447.
Kamilaris, A., Kartakoullis, A. and Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture, *Comput Electron Agric*., *143,* 23-37.
Kathole, A. B., Vhatkar, K. N. and Patil, S. D. (2024). IoT-Enabled Pest Identification and Classification with New Meta-Heuristic-Based Deep Learning Framework. *Cybernetics and Systems, 55*(2), 380-408.
Kumar Pradhan, A., Kumar, D., Chaurasia, H., Murmu, S., Samal, I., Kumar Bhoi, T., Kumar, G.A.K. and Mondal, B. (2024). Crop Monitoring System Integrating with Internet of Things and Artificial Intelligence. *In: Pandey, K., Kushwaha, N.L., Pande, C.B., Singh, K.G. (eds) Artificial Intelligence and Smart Agriculture. Advances in Geographical and Environmental Sciences, Springer, Singapore*, 193-208.
Lad, A., Nandre, S., Raichurkar, K., Zarkhande, S. and Charles, P. (2022). A Literature Survey on Smart Agriculture Monitoring and Control System Using IOT. *International Journal for Research in Applied Science and Engineering Technology*, *10*(2), 2321-9653.
Lee, U., Islam, M. P., Kochi, N., Tokuda, K., Nakano, Y., Naito, H., Kawasaki, Y., Ota, T., Sugiyama, T., and Ahn, D. H. (2022). An Automated, Clip-Type, Small Internet of Things Camera-Based Tomato Flower and Fruit Monitoring and Harvest Prediction System, *Sensors, 22*(7), 2456.
Lowenberg-DeBoer, J., Huang, I. Y., Grigoriadis, V. and Blackmore, S. (2020). Economics of robots and automation in field crop production. *Precision Agriculture*, *21*(2), 278-299.
Lucero, L., Lucero, D., Mejia, E.O., and Collaguazo, G. (2020). Automated aeroponics vegetable growing system. Case study Lettuce. In: *2020 IEEE ANDESCON*, Quito, Ecuador, 1-6.

Madakam, S., Uchiya, T., Mark, S. and Lurie, Y. (2022). Artificial Intelligence, Machine Learning and Deep Learning (Literature: Review and Metrics). *Asia-Pacific Journal of Management Research and Innovation*, *18*(1-2), 7-23.

Madhuri, J. and Indiramma, M. (2019). Role of big data in agriculture. *International Journal of Innovative Technology and Exploring Engineering (IJITEE), 9*(2), 3811-3821.

Masood, H., Afsar, S., Zamir, U. B. and Kazmi, J. H. (2015). Application of comparative remote sensing techniques for monitoring mangroves in Indus Delta, Sindh, Pakistan. *Biological Forum*, 7(1),783

Matson, P. A., Parton, W. J., Power, A. G. and Swift, M. J. (1997). Agricultural intensification and ecosystem properties. *Science*, *277*(5325), 504-509.

Mennecke, B.E. and Crossland, M.D. (1996). Geographic information systems: Applications and research opportunities for information systems researchers. In: *Proceedings of HICSS-29: 29th Hawaii International Conference on System Sciences*, *Hawaii, 3,* 537-546.

Mohsan, S.A.H., Khan, M.A., Noor, F., Ullah, I. and Alsharif, M.H. (2022). Towards the unmanned aerial vehicles (UAVs): A comprehensive review. *Drones, 6*(6), 147.

Morchid, A., El Alami, R., Raezah, A. A. and Sabbar, Y. (2024). Applications of internet of things (IoT) and sensor technology to increase food security and agricultural Sustainability: Benefits and challenges. *Ain Shams Engineering Journal*, *15*(3), 102509.

Moysiadis, V., Sarigiannidis, P., Vitsas, V. and Khelifi, A. (2021). Smart farming in Europe. *Computer science review*, *39*, 100345-100367.

Niu, H., Zhao, T., Wang, D. and Chen, Y. (2019). A UAV resolution and waveband aware path planning for onion irrigation treatments inference. In: *International Conference on Unmanned Aircraft Systems (ICUAS), Atlanta* pp. 808-812.

Nourmohammadi, A., Jafari, M. and Zander, T.O. (2018). A Survey on Unmanned Aerial Vehicle Remote Control Using Brain–Computer Interface, *IEEE Transactions on Human-Machine Systems*, *48*(4), 337-348.

O'Grady, M. and O'Hare, G. (2017). Modeling the smart farm, *Information Processing in Agriculture, 4*(3), 179–187.

Ojo, O. I. and Ilunga, F. (2018). Geospatial analysis for irrigated land assessment, modeling and mapping. In: Rustamov, R. B., Hasanova, S. and Zeynalova, M.H. (eds), *Multi-Purposeful Application of Geospatial Data*, IntechOpen, London, *9,* 65-84.

Oksana, D.; Volodymyr, M. and Oleg, S. (2021). Accounting Automation in Agroindustrial Enterprises Using Drones (UAVs), *In: 11th International Conference on Advanced Computer Information Technologies (ACIT)*, Deggendorf, Germany, 337-341.

Patel, B. C., Sinha, G. R. and Goel, N. (2020). Introduction to sensors. In: IOP Publishing: *Advances in Modern Sensors: Physics, design, simulation and applications*, 1-21.

Pham, T. H. and Nguyen, K. D. (2024). Soil Sampling Map Optimization with a Dual Deep Learning Framework. *Machine Learning and Knowledge Extraction*, *6*(2), 751-769.

Pivoto, D., Waquil, P. D., Talamini, E., Finocchio, C .P. S., Dalla Corte, V. F. and de Vargas Mores, G. (2018). Scientific development of smart farming technologies and their application in Brazil. *Inf. Process. Agric.*, *5*(1), 21-32.

Prakash, C., Singh, L. P., Gupta, A., and Lohan, S. K. (2023). Advancements in smart farming: A comprehensive review of IoT, wireless communication, sensors and hardware for agricultural automation. *Sensors and Actuators A: Physical.*, *362,* 114605.

Pungavi, R. and Praveenkumar, C. (2024). Unmanned Aerial Vehicles (UAV) for Smart Agriculture. *In Springer Nature Singapore:Artificial Intelligence and Smart Agriculture: Technology and Applications*, 251-269.

Radocaj, D., Plaščak, I., Heffer, G. and Jurisic, M. (2022). A low-cost global navigation satellite system positioning accuracy assessment method for agricultural machinery. *Applied Sciences*, *12*(2), 693.

Rajak, P., Ganguly, A., Adhikary, S. and Bhattacharya, S. (2023). Internet of Things and smart sensors in agriculture: Scopes and challenges. *Journal of Agriculture and Food Research*, *14*, 100776.

Reddy, G. V., Reddy, M. V. K., Spandana, K., Subbarayudu, Y., Albawi, A., Chandrashekar, R., Singla, A. and Praveen, P. (2024). Precision farming practices with data-driven analysis and machine learning-based crop and fertiliser recommendation system. In: *E3S Web of Conferences*, *507,* 01078 -01087.

Roztocki, N., Soja, P. and Weistroffer, H. R. (2019). The role of information and communication technologies in socioeconomic development: towards a multi-dimensional framework. *Information Technology for Development*, *25*(2), 171-183.

Rutolo, M. F., Iliescu, D., Clarkson, J. P. and Covington, J. A. (2016). Early identification of potato storage disease using an array of metal-oxide based gas sensors. *Postharvest Biol. Technol., 116,* 50-58.

Sadek, N. and Shehata, D. (2024). Internet of Things based smart automated indoor hydroponics and aeroponics greenhouse in Egypt. *Ain Shams Engineering Journal*, *15*(2), 102341.

Sharma, A., Georgi, M., Tregubenko, M., Tselykh, A. and Tselykh, A. (2022). Enabling smart agriculture by implementing artificial intelligence and embedded sensing. *Comput. Ind. Eng*., *165*(3), 107936-107947.

Shinde, D. and Siddiqui, N. (2018). IoT-based environment change monitoring and controlling in greenhouse using WSN. In: *International Conference on Information, Communication, Engineering and Technology (ICICET)*, Pune, India, 1-5.

Sidharth Patil, Munshi, M. M. and Prashantha, C. (2023). Greenhouses (Protected) cultivation: importance, scope, and status. *International Journal of Innovative Research in Technology,* 9(8), 276-278.

Soman, S., Gnanasekaran, R., Natarajan, G. and ALSaidi, F. K. S. (2024). Applications of UAV-AD (Unmanned Aerial Vehicle-Agricultural Drones) in Precision Farming. In: Balasubramanian, S., Natarajan, G., Chelliah, P.R. (eds) Intelligent Robots and Drones for Precision Agriculture. Signals and Communication Technology. Springer, 307-325.

Statista, https://www.statista.com/statistics/536746/worldwide-it-services-spending,Global IT services market 2013-2018.

Tarun, R. Katapally, Jasmin Bhawra and Pinal Patel (2020). A systematic review of the evolution of GPS use in active living research: A state of the evidence for research, policy, and practice, *Health and Place*, *66,* 102453.

Toriyama, K. (2020). Development of precision agriculture and ICT application thereof to manage spatial variability of crop growth. *Soil Science and Plant Nutrition*, *66*(6), 811-819.

Triantafyllou, A., Tsouros, D.C., Sarigiannidis, P. and Bibi, S. (2019). An architecture model for smart farming. In: *15th International Conference on Distributed*

Computing in Sensor Systems (DCOSS), Santorini Island, Greece, 385-392.
Vishnoi, S. K., Tripathi, A. and Bagga, T. (2019). Intelligent automation, planning and implementation: A review of constraints. *International Journal on Emerging Technologies*, *10*(1a), 174-178.
Walter, A., Finger, R., Huber, R. and Buchmann, N. (2017). Smart farming is key to developing sustainable agriculture. *Proc. Natl. Acad. Sci., 114*(24), 614-6150.
Yang, F., Wang, K., Han, Y. and Qiao, Z. (2018). A cloud-based digital farm management system for vegetable production process management and quality traceability. *Sustainability*, *10*(11), 4007-4010.
Yuan, T., Zhang, S., Sheng, X., Wang, D., Gong, Y. and Li, W. (2016). An autonomous pollination robot for hormone treatment of tomato flower in greenhouse. In *3rd international conference on systems and informatics (ICSAI)*, Shanghai, China, 108-113.
Zhang, L., Dabipi, I. K. and Brown, W. L. (2018). Internet of Things applications for agriculture. In: Hassan, Q.F. (ed.), *Internet of things: A to Z technologies and applications,* Wiley Publishers, New Jersey, 507-528.

How to cite this article: Rakhi R. and Geetha Radhakrishnan (2024). Comprehensive Analysis of Precision Farming Technologies and their Impact on Sustainable Crop Management. *Biological Forum – An International Journal, 16*(4): 234-242.