Review

The role of sensor technology in sustainable and efficient agricultural production - Review

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Abstract: Agricultural sensor technology has become a cornerstone of modern precision farming over the past two decades. Our research focused on the applications of remote and proximal sensing technologies, with an emphasis on satellite, drone-based, soil-embedded, and plant-mounted sensors. The study analyzed the presence of sensors in scientific publications and the evolution of research trends. The results showed that the number of scientific publications on sensor technology has grown exponentially, particularly in the last decade, reflecting increasing scientific and practical interest in the field. It was found that modern advancements, such as nanotechnology, have significantly contributed to reducing sensor size and enhancing their sensitivity, thereby supporting sustainable agricultural practices. Sensor applications enable the optimization of water, nutrient, and energy use, contributing to agricultural sustainability. Our research highlighted the importance of sensor technology in improving production efficiency and addressing global agricultural challenges.

Keywords: precision agriculture, smart farming, agricultural sensors, plant-based sensors, sensor integration

Academic Editor: Adrienn Széles

Received: 14th March 2025
Revised: 29th May 2025
Accepted: 10th June 2025
Published: 15th July 205

1. Introduction

The new digitized model of farming, interchangeably referred to as "precision farming," "digital farming," or "smart farming," promises to enhance efficiency and productivity through the use of data-driven precise or "intelligent" inputs [14]. Data-driven technologies are rapidly advancing and are becoming a defining element of the future of agriculture [40, 41]. As smart machines and sensors become more prevalent on farms, and the volume and scope of agricultural data continue to grow, farming processes are increasingly becoming data-driven and data-dependent [4]. Innovation serves as the driving force of growth, requiring competitive enterprises to consistently implement innovations to gain a market advantage [10,9]. The increasing global population and decreasing availability of arable land necessitate a significant improvement in agricultural production efficiency. To address these challenges, the application of advanced technologies becomes essential. The intensive use of modern technologies is expected to play a crucial role in overcoming these issues [1]. Significant changes in agricultural systems are anticipated due to the convergence of new digital technologies, including real-time monitoring through sensors, big data, the Internet of Things, and machine learning [18].

As a critical tool for data collection, sensing technology has become an indispensable component of modern agricultural systems and infrastructures [6], marking the beginning of the evolution of sensing technologies. The application of agricultural sensor technology began in the 1980s with the advent of photoelectric sensors and soil moisture meters, which laid the foundation for integrated sensor systems. In the 1990s, advances in wireless communication technologies led to the development of sensor nodes that can be deployed at multiple locations near the target object, enabling the establishment of wireless sensor networks [19]. The introduction of WSN systems opened new horizons in rural management, especially in data collection and information flow [2].

In recent years, the development of sensor technology has been significantly accelerated by the integration of cloud computing, edge computing, artificial intelligence and big data [32]. These technologies have not only enabled more accurate data analysis and intelligent decision making, but have also greatly increased the efficiency and adaptability of agricultural production systems [37, 17].

Artificial intelligence and big data have now become widely used tools for the optimisation and automation of agricultural production processes [36].

However, current agricultural IoT data sensing systems still face several challenges and limitations [34]. Existing technologies do not always guarantee comprehensive, reliable and real-time data collection, which is crucial for modern agriculture [16]. Further advancements are needed to make data collection and analysis processes more comprehensive and dependable, fostering the realization of intelligent agriculture.

I collected and analyzed data to illustrate the global market value trends of the Internet of Things (IoT) in Agriculture during the 2021–2030 period (Figure 1).The data indicate consistent and steady growth, starting at $12.5 billion in 2021 and projected to reach $28.56 billion by 2030. The annual growth rate ranges between $1.5 and $2.5 billion, reflecting the stable adoption of the technology and the continuously increasing demand for IoT solutions. A significant surge can be observed during the 2024–2025 period, likely driven by faster technological adaptation, industry expansion, and increased innovation investments. Overall, the figure highlights the critical role of IoT technologies as a driving force of economic and technological development while projecting sustained long-term growth.

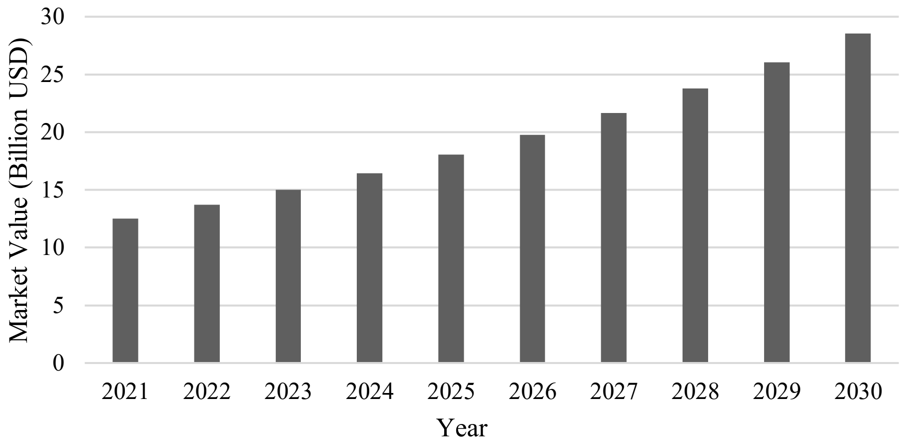

Figure 1. Global market value trends of the Internet of Things (IoT)

2. Materials and Methods

This review employed a narrative methodology, conducting a literature search across multiple databases, including Web of Science (WoS), Scopus, and Google Scholar. Articles that explicitly examined the role of sensor technology in sustainable and efficient agricultural production. The identified literature was thoroughly analyzed, synthesized, and summarized.

The study was carried out in several phases. All records initially retrieved (including articles, reviews and reports) were screened for relevance based on topic, type of research and alignment with the focus of the study. The majority of the literature was retrieved from widely recognized and authoritative databases such as Scopus/ScienceDirect, Web of Science (WOS), Springer, MDPI, Wiley, Tandfonline, Directory of Open Access Journals (DOAJ), and Google Scholar for grey literature. Initially, efforts were focused on retrieving recent literature from the last five years (2017-2024), but later the search was extended to include publications published since 2000. The keywords used in the search were ("crop monitoring ") + "environment sensor" + ("field sensors" OR "Application") + "crop sensing sensor")) narrowed by topic, including title, abstract and keywords for the period 2000-2024. The retrieved records were further assessed for relevance to the review's title and keywords, with eligible literature selected based on its timeliness and significance, while non-relevant records were excluded. The distribution of publications by subject category for the period 2000-2024 is illustrated in Figure 2. This overview highlights recent advances in sensor technology in field agriculture, especially for cereals and vegetables, and in environmental sciences. The last two decades have seen a significant increase in sensor research and applications in these areas.

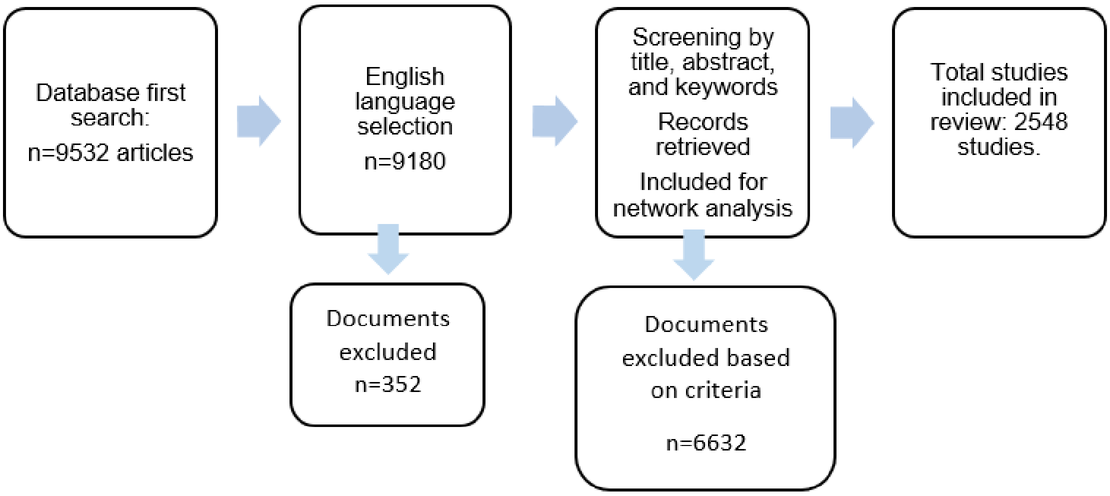

Figure 2. PRISMA diagram of the present study sources 2000-2024

The relevant notes were collected and imported into EndNote software, a reference management tool. Duplicate and irrelevant records were excluded following the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses [31]. After screening, the bibliography was assessed based on the topic relevance, the sources retrieved, the types of literature, and the year of publication.

Based on our research, the number of scientific publications in the field of agricultural sensor technology has multiplied significantly between 2000 and 2024 (Figure 3.). The data clearly indicate exponential growth, particularly in the past decade, reflecting the increasing scientific interest and research activity in this field. During the initial period (2000–2010), the number of publications was moderate, indicative of the early developmental phase of the technology, with research activity growing at a slower pace. In the subsequent period (2010–2020), the number of publications increased rapidly, driven partly by advancements in sensing technologies and the rise of agricultural informatics and precision farming. Post-2020, the growth accelerated further, highlighting the pivotal role of sensor technology in agricultural research, particularly in addressing innovations related to sustainability, productivity, and environmental efficiency. This exponential trend also suggests that the application of agricultural sensors remains a priority research area, as these tools play a fundamental role in the widespread adoption of precision farming and in tackling global agricultural challenges.

3. Results and discussion

3.1. Number of studies on the topic

Public and international funding, along with industrial investments, further fueled the development of this field. The high fit of the exponential trendline (R2=0.9937) confirms that the number of studies is expected to continue growing in the coming years. This forecast indicates that research on agricultural sensor technologies will remain a key factor in the digitalization of agriculture, contributing to maximizing crop yields, reducing environmental impact, and enhancing food security to meet the needs of the growing global population.

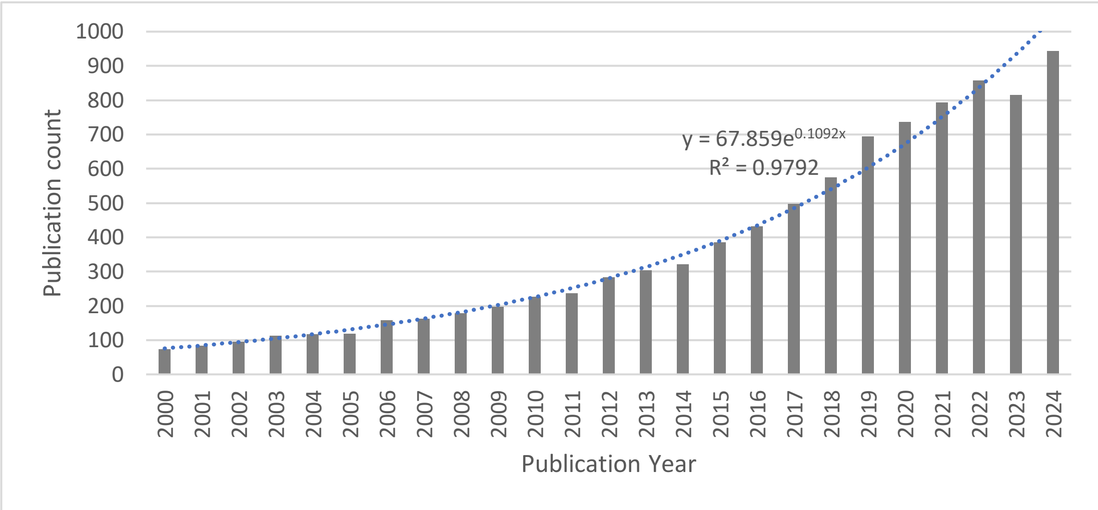

Figure 3. The number of scientific publications in the field of agricultural sensor technology

Figure 4 shows the distribution of the literature used by topic, emphasising its interdisciplinary nature. Agricultural and biological sciences are dominant, reflecting the primary focus of the research, while environmental sciences represent the second largest proportion, emphasising the importance of ecological and sustainability considerations. The strong presence of engineering emphasises the role of technological and engineering applications, particularly in relation to sensor technologies. Chemistry, together with biochemistry, genetics and molecular biology, is represented to a lesser extent, with a complementary role in materials analysis and molecular process studies. The analysis shows that research takes a broad spectrum approach, integrating biological, environmental and technological factors.

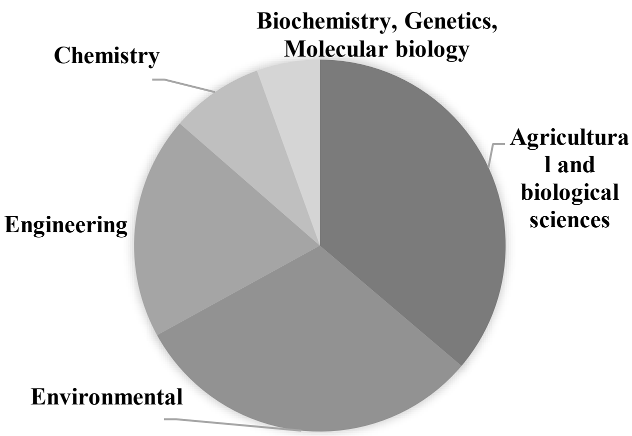

Figure 4. Utilized Literature by Topics

3.2. The most active research countries

The following presents the number of scientific publications in the field of agricultural sensor technology by country during the period from 2000 to 2024 (Figure 5.). According to the data, the United States holds a leading position with more than 2,000 publications, far surpassing the contributions of any other country. China ranks second, also with a significant number of publications, although lower compared to the United States. The middle-ranking countries include Germany, India, Italy, Spain, and France, each contributing several hundred publications to the advancement of agricultural sensor technology. Countries such as Brazil, Canada, Australia, England, and Japan show more moderate but still notable scientific activity in this field. The results indicate that the application of sensor technology in agriculture is gaining increasing attention worldwide, with contributions varying among countries in an international research environment dominated by the United States and China.

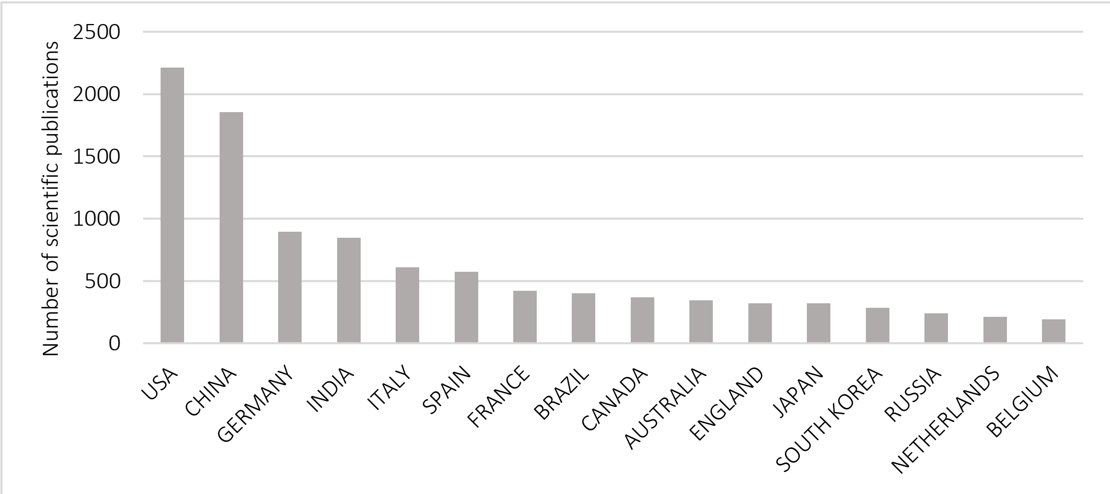

Figure 5. Number of scientific publications in the field of agricultural sensor technology by country

3.3. Research directions and applications

Figure 6 illustrates the conceptual relationships within agricultural sensor technology, where the different colours and scales reflect the meaning and context of the different themes. The central element, 'remote sensing', dominates visualisation as the most significant and interconnected concept. Remote sensing is strongly linked to key themes such as "crop monitoring", "vegetation indices", "yield", "growth" and "data fusion", highlighting its primary role in monitoring crop status, forecasting yield and integrating different data sources.

The figure also highlights specific technologies and applications, such as "optical sensors", "active optical sensors", "spectral reflectance" and "UAVs" (unmanned aerial vehicles). These tools and methods facilitate accurate crop monitoring, biomass analysis and irrigation optimisation, highlighting their importance in agricultural practice.

In addition, terms such as "wheat" and "agriculture" feature prominently, indicating that research often focuses on wheat cultivation and agricultural production in the broader sense. Other notable themes such as "irrigation", "energy balance" and "crop stress" indicate a focus on sustainable agricultural practices and environmental mitigation.

Peripheral but related topics such as "ambient illumination" and "chlorophyll fluorescence" relate to advanced sensing techniques, while terms such as "modal data" and "SAR" emphasise the importance of satellite data in this area. Overall, the visualisation summarises the complexity of agricultural remote sensing technologies and demonstrates the interconnectedness of research efforts to promote the sustainability and efficiency of agricultural systems.

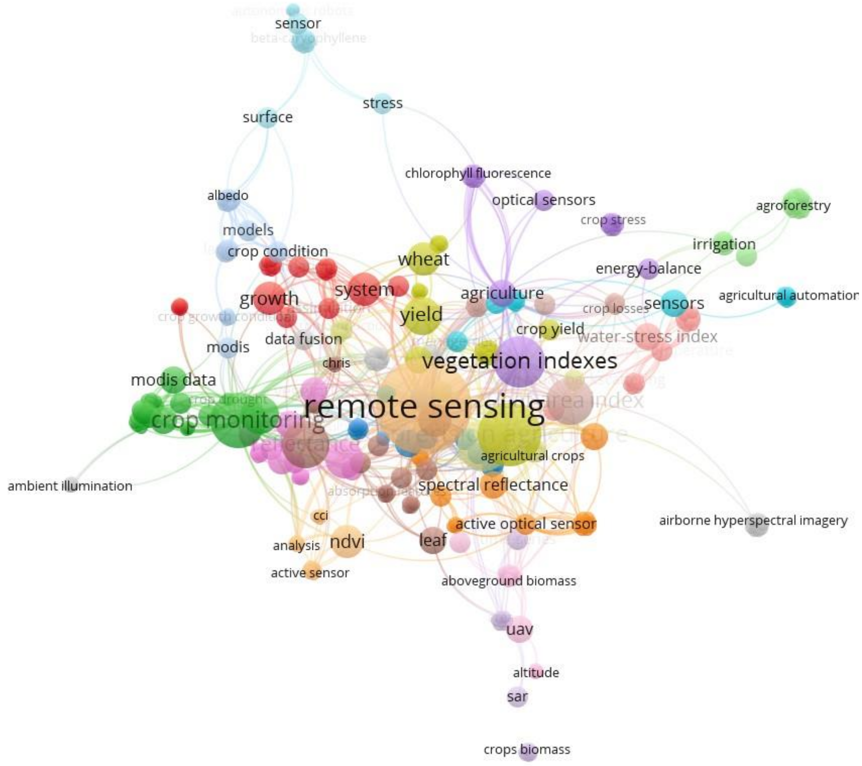

Figure 6. The co-occurrence network of all author keywords based on web literature searches between 2000 and 2024

The classification of the position of measurement sensors highlights a number of sensing options in agriculture, all of which contribute to improving accuracy and efficiency in different aspects of crop production (Table 1). Remote sensing using satellite and drone measurements provides large-scale and high-resolution data on environmental conditions, crop health and soil properties [5, 23]. Satellite-based sensing offers global and periodic monitoring capabilities, while drone-mounted sensors enable flexible and targeted data collection with higher spatial and temporal resolution, especially beneficial for detecting localized crop stress or variability [29,12].

Proximal crop measurements using machine-mounted or in-plant sensors provide detailed and real-time insights during field operations [30]. Machine-mounted devices are commonly used for tasks such as variable rate application of fertilizers, pesticides and water, allowing for site-specific management. Sensors placed directly in the crop improve the monitoring of environmental and physiological conditions within the field, such as microclimate changes and canopy temperature [8].

Plant-attached and intra-plant sensors offer advanced opportunities for understanding plant physiology and responses to stress [43]. For example, moisture sensors measure intra-plant water transport, while leaf-attached sensors can monitor photosynthetic activity, transpiration rates, and even early signs of disease (13,15,11,21]. These approaches provide critical data for optimising water use efficiency, predicting yield and identifying biotic or abiotic stress factors at the plant level.

Soil-based sensors complement these methods by offering detailed soil parameter measurements, including moisture, temperature, salinity, and nutrient levels [35, 7]. These insights are vital for scheduling irrigation, monitoring soil health, and understanding the interaction between plant roots and the surrounding soil environment [26, 2].

Table 1. Measurement methods in arable crop production.

	Position of measuring sensors
Remote sensing:	Measurements from satellites
	Measurements from drones
Proximal plant measurements	Measuring devices mounted on machinery
	Measuring devices placed in crop stands
	Measuring devices attached to plants
	Measuring devices placed inside plants
	Measuring devices placed in the soil

Overall, these sensor-based methodologies enable a multi-scale, multi-dimensional approach to agricultural monitoring and management [20]. They facilitate the integration of environmental, plant physiological, and soil data, empowering precision agriculture to address key challenges such as resource optimization, yield maximization, and environmental sustainability [42]. As sensor technologies advance, their synergistic application promises transformative impacts on modern agriculture [25].

Plant growth is profoundly influenced by environmental factors, highlighting the necessity for precise, high-resolution data on these parameters to effectively predict and manage biomass production [24]. The evaluation of the rooting medium can be achieved through the use of soil moisture sensors employing electrical, gravimetric, and microwave techniques. Furthermore, advanced conductance and optical methodologies offer critical insights into soil pH levels and ionic composition, providing a deeper understanding of soil conditions essential for optimal plant development [27]. Sensor modules comprising environmental sensors, physiological sensors and dedicated electronics for power and communication are distributed throughout the crops and wirelessly connected to a central processor. The main sensor applications are summarized in the table 2.

Table 2. Different sensors in arable crop production.

	Measured Concept	
	Environmental parameters	**Plant physiology**
Measurement Objective	Humidity sensors	Diseases and pests sensors
	Temperature sensors	Sap flow sensors

Airflow speed sensors	Colour and sound sensors
Soil parameters sensors	Stem diameter sensors

The size of sensors has a significant impact on their placement. Advances in modern fabrication technologies, in particular micro- and nanofabrication technologies, enable reliable handling of sensors to achieve micro- and sub-micron accuracy [5]. This not only increases sensor performance, but also reduces sensor size to meet spatio-temporal resolution requirements. In addition, recent advances in nanotechnology offer untapped potential to mitigate severe stressors on agricultural food and energy production while optimizing the use of limited resources such as water and nutrients [22].

In summary, the use of agricultural sensor technology has become a key enabler for modern crop production, as it promotes sustainable and efficient farming practices. The continued development of sensors and related technologies will bring significant benefits and support improvements in global food security and environmental sustainability. The data shows that sensor research and practical applications will continue to be a priority and will become a cornerstone of the future of agriculture.

4. Conclusions

The dynamic development of agricultural sensor technology has had a significant impact on modern agricultural production, especially in the context of precision farming. Over the last two decades, the number of scientific publications in the field of sensor technology has grown exponentially, reflecting a steady increase in research interest and activity. This growth has accelerated particularly in the last decade, driven by the widespread diffusion of technological innovations such as nanotechnology, micro- and macro-manufacturing processes and sensing technologies. The data show that China and the US dominate research in sensor technologies, while India has made remarkable progress, particularly in recent years. The more moderate activity of European and Japanese participants indicates that these countries play a more complementary role in global research.

The applications of sensors are diverse and can be categorised by their measurement positions. Remote sensing, including satellite and drone-based observations, provides large-scale and high-resolution data on environmental factors, crop health and soil properties. These tools are particularly valuable for identifying local stress conditions and variations, as well as for global monitoring tasks. In contrast, proximal sensing, such as sensors mounted on machines, in crop stands or directly on or inside plants, can provide detailed and real-time information on the physiological state of plants and environmental conditions. This data is particularly relevant for site-specific operations such as variable rate fertiliser or water application, allowing more accurate and efficient resource management.

Soil-based sensors play a critical role in agriculture by providing accurate information on soil moisture, temperature, salinity and nutrient levels. This data is essential for optimising irrigation schedules, maintaining soil health and monitoring root zone conditions. The size and sophistication of the sensors determine their placement and the spatio-temporal resolution of their measurements. Modern advances in nanotechnology have made it possible to significantly reduce the size of sensors while increasing their sensitivity and efficiency. These innovations allow sensors to be discreetly placed in crop fields, minimising environmental impact and improving the accuracy of data collection.

The development and use of sensors not only increases production efficiency, but also contributes to sustainability goals. Optimising energy and material use and reducing environmental impacts are key priorities in precision agriculture. Nanotechnology offers the potential to mitigate the severe stresses on food and energy-based production, while maximising the efficient use of limited resources such as water and nutrients. Integrating sensor-generated data into agricultural decision-making will enable adaptive management, which is essential to address global food security challenges.

In summary, the use of agricultural sensor technology has become a key enabler for modern crop production, as it promotes sustainable and efficient farming practices. The continued development of sensors and related technologies will bring significant benefits and support improvements in global food security and environmental sustainability. The data shows that sensor research and practical applications will continue to be a priority and will become a cornerstone of the future of agriculture.

References

1. Adão, T., Hruška, J., Pádua, L., Bessa, J., Peres, E., Morais, R. Hyperspectral imaging: A review on UAV-based sensors, data processing, and applications for agriculture and forestry. *Remote Sensing* **2017**, *9(11)*, pp. 1110–1140. https://doi.org/10.3390/rs9111110.
2. Ali, A., Hassan, M. U., Kaul, H. P. Broad Scope of Site-Specific Crop Management and Specific Role of Remote Sensing Technologies Within It—A Review. *Journal of Agronomy and Crop Science* **2024**, *210(4).*
3. Attri, I., Kumar, L., Sharma, T., Rathee, P. (2023). A review of deep learning techniques used in agriculture. *Ecological Informatics* **2023**, *77*, pp. 423–486.
4. Barmpounakis, S., Kaloxylos, A., Groumas, A., Katsikas, L., Sarris, V., Dimtsa, K., Fournier, F., Antoniou, E., Alonistioti, N., Wolfert, S. Management and control applications in the agriculture domain via a future Internet business-to-business platform. *Information Processing in Agriculture* **2015**, *2*, pp. 51–63.
5. Bégué, A., Arvor, D., Bellon, B., Betbeder, J., de Abelleyra, D., Ferraz, R. P. D., Lebourgeois, V., Lelong, C., Simoes, M., Verón, S. R. Remote Sensing and Cropping Practices: A Review. *Remote Sensing (Basel, Switzerland)* **2018**, *10(1)*, pp. 99.
6. Billon, M., Lera-Lopez, F., Marco, R. Differences in digitalization levels: A multivariate analysis studying the global digital divide. *Review of World Economics* **2010**, *146(1)*, pp. 39–73.
7. Chang, Z. X., Zhang, F. S., Xiong, J., Ma, J. Q., Jin, B. H., Zhang, D. Q. Sensor-Free Soil Moisture Sensing Using LoRa Signals. *Proceedings of ACM on Interactive, Mobile, Wearable, and Ubiquitous Technologies* **2022**, *6(2)*, pp. 1.
8. Chauhan, S., Darvishzadeh, R., Boschetti, M., Pepe, M., Nelson, A. (2019). Remote Sensing-Based Crop Lodging Assessment: Current Status and Perspectives. *ISPRS Journal of Photogrammetry and Remote Sensing* **2019**, *151*, pp. 124.
9. Chen, H. S. Remote sensing calibration systems: An introduction. *Oakland: A. Deepak Publishing* **1997**, ISBN 978-0-937194-*38-6*.
10. Colomina, I., Molina, P. Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing* **2014**, *92*, pp. 79–97.
11. de Queiroz, D. M., Coelho, A. L. D., Valente, D. S. M., Schueller, J. K. Sensors Applied to Digital Agriculture: A Review. *Ciência Agronômica* **2020**, *51*.
12. Dunmoye, I., Awodele, K., Winberg, S. (2021). Power Consumption of Crop Sensing Systems for Monitoring Crops Growth. *International Conference on Electrical, Computer and Energy Technologies (ICECET)* **2021**, pp. 1930.
13. Fahey, T., Pham, H., Gardi, A., Sabatini, R., Stefanelli, D., Goodwin, I., Lamb, D. W. Active and Passive Electro-Optical Sensors for Health Assessment in Food Crops. *Sensors (Basel, Switzerland)* **2021**, 21(1), pp. 171.
14. Fielke, S., Taylor, B., Jakku, E. Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. *Agricultural Systems* **2020**, *180*, pp. 432–462.
15. Fuentes-Penailillo, F., Gutter, K., Vega, R., Silva, G. C. Transformative Technologies in Digital Agriculture: Leveraging Internet of Things, Remote Sensing, and Artificial Intelligence for Smart Crop Management. *Journal of Sensor and Actuator Networks* **2024**, *13(4)*, pp. 39.

16. Hamimed, S., Mahjoubi, Y., Abdeljelil, N. Chemical sensors and biosensors for soil analysis: Principles, challenges, and emerging applications. *Advanced Sensor Technology* **2023**, pp. 669–698. https://doi.org/10.1016/B978-0-323-90222-9.00014-5.
17. Herrero, R., Cadirola, M., Ingle, V. K. Preprocessing and compression of hyperspectral images captured onboard UAVs. *In Proceedings of the SPIE 9647, Unmanned/Unattended Sensors and Sensor Networks XI; and Advanced Free-Space Optical Communication Techniques and Applications* **2015**, pp.964–975.
18. Hueske, A. K., Endrikat, J. D., Guenther, E. External environment, the innovating organization, and its individuals: A multilevel model for identifying innovation barriers accounting for social uncertainties. *Journal of Engineering and Technology Management* **2015**, *35*, pp.45–70.
19. Ison, L. C., San Pedro, J. A. B., Ramizares, J. Z., Magwili, G. V., Hortinela, C. C. Precision agriculture detecting NPK level using a wireless sensor network with mobile sensor nodes. *2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)* **2021**, *1–6*. https://doi.org/10.1109/HNICEM54116.2021.9732000.
20. Jafarbiglu, H., Pourreza, A. A comprehensive review of remote sensing platforms, sensors, and applications in nut crops. *Computers and Electronics in Agriculture* **2022**, *197*. DOI: 10.1016/j.compag.2022.106844.
21. Karthikeyan, L., Chawla, I., Mishra, A. K. A Review of Remote Sensing Applications in Agriculture for Food Security: Crop Growth and Yield, Irrigation, and Crop Losses. *Journal of Hydrology (Amsterdam)* **2020**, pp. 586.
22. Kumari, A., Singh, D. K., Sarangi, A., Hasan, M., Sehgal, V. K., Kumar, S. N., Verghese, C. Integrated Sensing Device for Irrigation Scheduling: Field Evaluation and Crop Water Stress Index Estimation of Wheat. *Water Practice and Technology* **2024**, *19(5)*, pp. 1676.
23. Laveglia, S., Altieri, G., Genovese, F., Matera, A., Di Renzo, G. C. Advances in Sustainable Crop Management: Integrating Precision Agriculture and Proximal Sensing. *AgriEngineering* **2024**, *6(3)*, pp. 3084.
24. Liu, C. A., Chen, Z. X., Shao, Y., Chen, J. S., Hasi, T., Pan, H. Z. Research Advances of SAR Remote Sensing for Agriculture Applications: A Review. *Journal of Integrative Agriculture* **2019**, *18(3)*, pp. 506.
25. Liu, J. Y., Zhao, Y., Xiao, X. R., Meng, R., Liu, J. CAS: Crop Aerial Sensing Simulation in Smart Farming. *2023 20th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)* **2023**, pp. 48.
26. Love, C., Nazemi, H., El-Masri, E., Ambrose, K., Freund, M. S., Emadi, A. A Review on Advanced Sensing Materials for Agricultural Gas Sensors. *Sensors (Basel, Switzerland)* **2021**, *21(10)*, pp. 3423.
27. Machichi, M. A., Mansouri, L. E., Imani, Y., Bourja, O., Lahlou, O., Zennayi, Y., Bourzeix, F., Houmma, I. H., Hadria, R. Crop Mapping Using Supervised Machine Learning and Deep Learning: A Systematic Literature Review. *International Journal of Remote Sensing* **2023**, *44(8)*, pp. 2717.
28. Maes, W. H., Steppe, K. Perspectives for remote sensing with unmanned aerial vehicles in precision agriculture. *Trends in Plant Science* **2019**, *24(2)*, pp. 152–164. https://doi.org/10.1016/j.tplants.2018.11.007.
29. Ndlovu, H. S., Odindi, J., Sibanda, M., Mutanga, O. A Systematic Review on the Application of UAV-Based Thermal Remote Sensing for Assessing and Monitoring Crop Water Status in Crop Farming Systems. *International Journal of Remote Sensing* **2024**, *45(15)*, pp. 4923.
30. Omia, E., Bae, H., Park, E., Kim, M. S., Baek, I., Kabenge, I., Cho, B. K. (2023). Remote Sensing in Field Crop Monitoring: A Comprehensive Review of Sensor Systems, Data Analyses and Recent Advances. *Remote Sensing (Basel, Switzerland)* **2023**, *15(2)*, pp. 354.
31. Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews, **2020**. pp. 372.
32. Petrovic, B., Kononets, Y., Csambalik, L. Adoption of drone, sensor, and robotic technologies in organic farming systems of Visegrad countries. *Heliyon* **2025**, *11(1)*, pp.45–53.
33. Pinke, Zs., Ács, T., Fabók, V., Kalicz, P., Jámbor, A. A magyar mezőgazdaság modernizációs törekvései és kudarcai az aszálykárok és a globális mezőgazdasági alapanyag-túltermelési válság kapcsán. *Gazdálkodás* **2024**, *68(3)*, pp.220–243.
34. Postolache, S., Sebastião, P., Viegas, V., Postolache, O., Cercas, F. IoT-based systems for soil nutrients assessment in horticulture. *Sensors* **2022**, *23(1)*,pp. 403. https://doi.org/10.3390/s23010403.
35. Putra, B. T. W. New Low-Cost Portable Sensing System Integrated with On-the-Go Fertilizer Application System for Plantation Crops. *Measurement: Journal of the International Measurement Confederation* **2020**, pp. 155
36. Sayyad, B., Shaikh, M. A., Anpat, S. M., Kolapkar, M. M. IoT-based soil monitoring for precision agriculture. *Remote Sensing in Precision Agriculture*, **2024**, pp. 43–59. https://doi.org/10.1016/B978-0-323-91068-2.00026-6.

37. Scholkopf, B., Smola, A. J. Learning with kernels: Support vector machines, regularization, optimization, and beyond. *Cambridge: MIT Press* **2001**. ISBN 978-0-262-19475-4.
38. Seelan, K., Laguette, S., Casady, G. M., Seielstad, G. A. Remote sensing applications for precision agriculture: A learning community approach. *Remote Sensing of Environment* **2003**, *88(1–2)*, pp. 157–169. https://doi.org/10.1016/j.rse.2003.04.007.
39. Sikka, P., Corke, P., Valencia, P., Crossman, C., Swain, D., Bishop Hurley, G. Wireless adhoc sensor and actuator networks on the farm. *IPSN'06 Proceedings of the 5th International Conference on Information Processing in Sensor Networks, New York* **2006**, pp. 492–499. http://dx.doi.org/10.1145/1127777.1127852.
40. Verdouw, C. Internet of things in agriculture. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **2016**, *11*, pp. 35–42. https://doi.org/10.1079/PAVSNNR201611035.
41. Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M. J. Big data in smart farming – a review. *Agricultural Systems* **2017**, *153*, pp. 69–80. https://doi.org/10.1016/j.agsy.2017.01.023.
42. Wu, B. F., Zhang, M., Zeng, H. W., Tian, F. Y., Potgieter, A. B., Qin, X. L., Yan, N. N., Chang, S., Zhao, Y., Dong, Q. H. Challenges and opportunities in remote sensing-based crop monitoring: A review. *National Science Review* **2023**, *10(4)*. DOI: 10.1093/nsr/nwac290.
43. Yan, B. P., Zhang, F., Wang, M. Y., Zhang, Y. K., Fu, S. L. Flexible wearable sensors for crop monitoring: A review. *Frontiers in Plant Science* **2024**, *15*. DOI: 10.3389/fpls.2024.1406074.