Computers and Electronics in Agriculture 235 (2025) 110420

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Potential applications of quantum sensors in agriculture: A review

C. Maraveas [a,*], K.G. Arvanitis [b], T. Bartzanas [a], D. Loukatos [b]

[a] Farm Structures Lab, Department of Natural Resources and Agricultural Engineering, Agricultural University of Athens, Greece
[b] Farm Machine Systems Lab, Department of Natural Resources and Agricultural Engineering, Agricultural University of Athens, Greece

ARTICLE INFO

Keywords:
Classical
Quantum
Sensors
Adoption
Agriculture
Limitations
Advantages

ABSTRACT

In precision agriculture, farmers adopt sensors to improve decision-making, monitor the conditions of the soil, optimize fertilizer and herbicide application, and enhance overall yields from farms. Traditional sensors are based on IoT components that relay signals from soil and the farm to servers where data management operations improve decision-making. However, cyber threats, high costs of maintenance, and poor connectivity to the internet challenges hinder the adoption of the sensors. To address such shortcomings, quantum sensors, based on quantum mechanics principles, are adopted in agriculture based on their higher sensitivity and chemical inertness. The focus of this review article was to investigate the different perspectives on how quantum sensors are used in agriculture. The review article assessed the potential applications of quantum sensors in agriculture, where 119 studies sourced from different scientific databases were examined. The insights showed that quantum sensors were applied in agriculture to enhance seedling growth and emergence due to the chemical inertness and solubility. Additionally, the sensors enhanced crop growth through the provision of nutrients and antioxidants to promote the growth of crops. The findings further indicated that sensors were used to detect harmful pollutants and chemicals from water sources and agricultural foods such as pumpkin seeds. Other applications included monitoring the soil fertility levels. The analysis also showed that the sensors were used as measuring instruments to evaluate photosynthetically active radiation (PAR) in evaluating plant photosynthesis. The recommendations from the review article advocate for the continued adoption of quantum sensors as they outperform the classical sensors due to their atomic-level sensitivity. However, in the future, scholars ought to focus on investigating methods that are cheaper to integrate quantum sensors in large-scale farming operations.

1. Introduction

1.1. The emergence and spread of agriculture 4.0

The emergence and spread of Agriculture 4.0, also known as smart farming (SF), focuses on promoting the sustainable production of crops using advanced technologies. Subsequently, diverse emerging technologies, including artificial intelligence (AI), big data, the Internet of Things (IoT), sensors, GPS, and robots, are being integrated into modern agriculture (Fragomeli et al., 2024). The transformation of Agriculture from 1.0 to 4.0 is illustrated in Fig. 1.1.

As showcased in Fig. 1, the evolution of agriculture is showcased from the reliance on human and animal resources in Agriculture 1.0 to mechanization in Agriculture 2.0, automation and high-speed applications in Agriculture 3.0, and smart agriculture using emerging technologies in Agriculture 4.0. In the current Agriculture 4.0, sensors are adopted in precision agriculture to undertake diverse functions.

1.2. Sensors in precision agriculture

Precision agriculture relies on sensors to enhance the production and monitor the growth of crops. Taylor (2023) describes precision agriculture as a management strategy to enhance the resolution of decision-making in agriculture in response to production variability. El-Sharkawy et al. (2016) add to Taylor (2023) and report that precision agriculture entails an advanced method where farmers optimize inputs, including fertilizer and water, to improve the yield, quality, and productivity of agriculture. As such, classical sensors are employed in agriculture to enable farmers to detect changes in the quality of soil, temperature, and humidity (Friha et al., 2021; Liu et al., 2024). According to El-Sharkawy et al. (2016), the sensors enable precise assessments of harvest weight yield by distance, GPS area estimated, or time. Yield mapping applies spatial directional data derived from GPS sensors to boost and promote smart agriculture. Laura et al. (2024) and Liang, Wong, and Lisak (2023) presented similar arguments, noting that the sensors support fertilizer

* Corresponding author.
E-mail address: maraveas@aua.gr (C. Maraveas).

https://doi.org/10.1016/j.compag.2025.110420
Received 17 February 2025; Received in revised form 9 April 2025; Accepted 14 April 2025
Available online 18 April 2025

application instruments, variable rate, yield maps, and optical overviews by shading to control vaporous compost materials, granular, and fluid. Variable rate regulators are manually or physically controlled using an onboard personal computer directed by a GPS area. Taylor (2023) revealed that sensors' precision supports weed mapping through administration contribution and understanding to create maps by denoting the area with a data logger and GPS collector. The weed events are covered with manure guides, yield maps, and shower maps. As Ghani et al. (2024) and Aierken et al. (2024) reported, variable spraying regulators help to turn herbicide shower blasts off and on and modify the sum of the splash applied. When the weed areas are planned and recognized, the blend and volume of the shower are not wholly settled. In addition, boundaries and geography are recorded using high-accuracy GPS that considers an extremely exact field portrayal geographically.

Sensors are also applied to monitor the properties of soils. A case example is studies such as Najdenko et al. (2024), where insights show that sensors are effective in monitoring soil properties, including the levels of plant nutrients, pH, and nitrates. Xing and Wang (2024) add to Najdenko et al. (2024) and observe that spectral soil sensors indicate the level of available nutrients in plants and soil pH while electrochemical sensors enable farmers to accurately determine the nitrate levels and soil pH. Toselli et al. (2023) support Najdenko et al. (2024) and report that electrical and electromagnetic sensors have been adopted for the non-invasive measurement of the nutrient concentration in soil by assessing the electrical conductivity of the soil and its ability to conduct electrical charge. An illustration of the measurement of the electrical conductivity of soil is showcased in Fig. 2 below.

In Fig. 2, the electrical conductivity of the soil is measured using three separate electrodes to enable farmers to determine the levels of nutrients, such as nitrates, within the soil. Getahun, Kefale, and Gelaye (2024) support the views of Toselli et al. (2023) and show that using sensors to monitor soil nutrients enables farmers to make informed decisions regarding the application of fertilizer to promote overall productivity, leading to high-quality yields from the farms. The inferences from these studies indicate that employing sensors to monitor various qualities of the soil, such as nutrient levels and pH, improves informed decision-making among farmers. As a result, farmers can apply fertilizers or water crops when required.

Farmers employ precision agriculture to ensure nutrients, herbicides, and pesticides are applied specifically and at the right rate and time to crops using variable rate technologies (VRT). In their study, Pawase et al. (2024) showed that VRTs were important in agriculture as they ensured that nutrients could be integrated into soils cost-effectively and sustainably within large-scale farms to promote the yield of crops. Other studies also identified the importance of VRTs in controlling weeds and pests within farms (Baklaga, 2023; Mannone et al., 2023). Additionally, insights indicated that using VRTs limited the negative impact of insecticides and pesticides in the environment by spraying them more efficiently and minimizing the effects on soil and water bodies (Taseer and Han, 2024). A close inspection of these insights indicates that precision agriculture using VRTs was effective in the application of different chemicals to control weeds and pests while reducing the environmental impact of the harmful chemicals on soils and water bodies. The farmers also incurred lower costs due to the minimal wastage of the chemicals associated with VRTs. The features of an agrochemical precision sprayer mounted on a push-type frame are detailed in Fig. 3 below.

As showcased in Fig. 3, the precision sprayer is adopted to ensure precise spraying of chemicals such as herbicides to control weeds. The sprayer uses VRTs to ensure that minimal quantities of herbicides are used to eradicate weeds.

Classical sensors are further adopted in precision agriculture to ensure mundane and repetitive tasks within large-scale farms can be automated. A case example regards the automation of the spraying of herbicides in large-scale farms using unmanned aerial vehicles (UAVs) (Li and Wu, 2024). As a result, the farmers can cost-effectively distribute chemicals compared to manual methods of spraying. Ghani et al. (2024) support Li and Wu (2024) and report that the efficiency of UAVs in spraying herbicides is 60 % more than the traditional manual processes, where it generates less impact on soil structure and crops. Pandiselvam et al. (2024) add to Ghani et al. (2024) and demonstrate how UAVs can be adopted for spraying pesticides to ensure higher efficiency and reduce labor and application timelines for farmers. The insights from these studies indicate that automating the application of fertilizers and

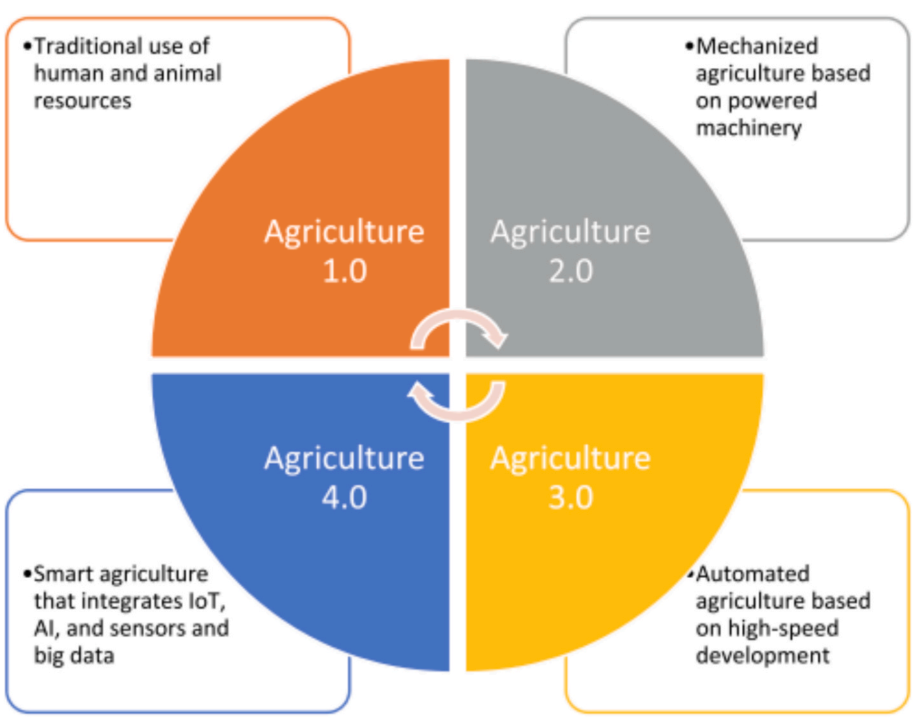

Fig. 1. Evolution from Agriculture 1.0 To 4.0 (Maraveas et al., 2022).

Fig. 2. Measuring the electrical conductivity of soil using sensors (Toselli et al., 2023).

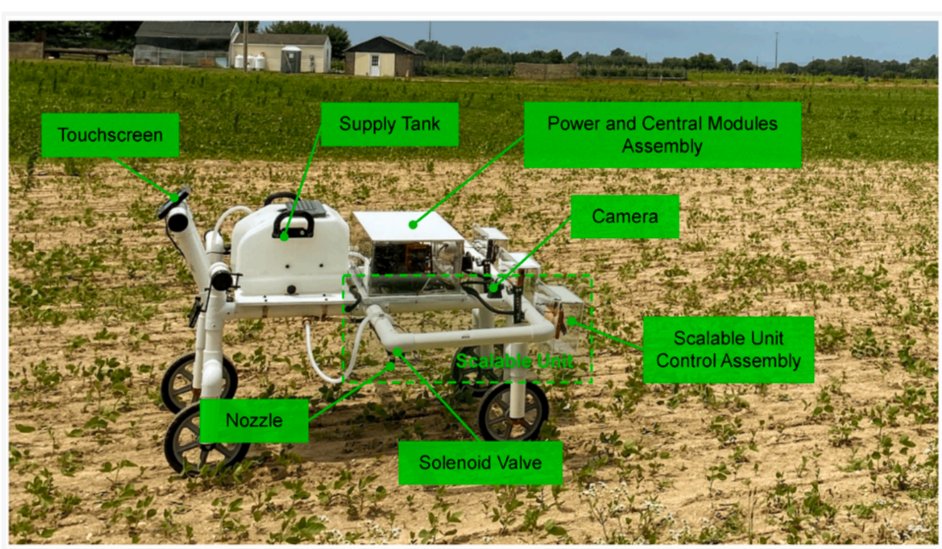

Fig. 3. Components of an agrochemical precision sprayer (Sanchez and Zhang, 2022).

agrochemicals using UAVs is unsupervised, allowing farmers to kill weeds in large farms and generating benefits such as improved efficiency in controlling weeds compared to using manual methods.

The review of different studies also shows that classical sensors are employed to promote farming efficiency through the application of machines that are guided by the global positioning system (GPS) such as drones to monitor crop health. Hafeez et al. (2022) reveal that using UAVs to monitor farming activities ensures farmers can obtain diversified insights concerning soil variety, water systems, and fungal infestations. As such, remote sensing using GPS-guided drones allows farmers to efficiently monitor the health of crops in a way that cannot be done using human efforts, while the technology also enables the farmers to monitor the yield of the crops at a higher frequency, such as hourly, daily, and weekly. Laura et al. (2024) reiterated Hafeez et al. (2022) and also revealed that using aerial remote sensing systems that were guided by GPS ensured the ease in monitoring the health of broccoli crops to allow farmers identified those that were affected by pathogens and diseases. The YOLO v5x algorithm was adopted to accurately detect the affected crops by the pathogens. The work by Aierken et al. (2024) also revealed that enhancements were possible by using imagery from UAVs and combining it with methods of machine learning to monitor the growth and production of cotton. Aierken et al. (2024) and De Ocampo and Montalbo (2024) also indicated that the multi-vision monitoring (MVM) framework could be adopted to recognize activities within farms and evaluate the health of crops in smart agriculture. The different techniques were essential in improving the management and production of crops. The work by El Alaoui et al. (2024) also highlighted the use of drones in large-scale farms to detect and monitor disease, thereby, enhancing the management of farming operations. The implication is that classical sensors are effective in precision agriculture to ensure the health of crops can be monitored and high yields also obtained.

1.3. Quantum sensors in precision agriculture

Despite the benefits of precision agriculture in reducing labor costs and increasing the efficiency of farming operations, different challenges are still faced leading to food insecurity (Albiero et al., 2022). The classical precision sensors are highly expensive and also complex to maintain due to the consumption of high levels of energy (Renius, 2020). Additionally, some farmers deal with internet connectivity issues and lack technical skills in using the technologies (Klerkx et al., 2019). Alahe et al. (2024) added to Klerkx et al. (2019) and showed that smart sensors were also at risk of cyberattacks due to the sensitive data they transmitted from farms to servers. Yazdinejad et al. (2021) also explained that the vulnerability of smart sensors to cyberattacks arose from negligent security practices among farmers, which led to a high likelihood of attack. Subsequently, the level of advanced technology adoption in agriculture remains relatively low, as only 31 % of farmers in the EU use smart sensors to measure crucial data related to plant and animal development (Neo and Santos, 2022). The analysis of the limitations of precision agriculture technologies shows that issues arise from poor internet connectivity and their likelihood of being compromised by malicious hackers.

However, one emerging technology that has attracted more attention due to its potential to enhance agricultural production is quantum sensors. Quantum sensors refer to technologies that rely on quantum mechanics principles, such as quantum superposition and entanglement, to achieve a high level of accuracy and sensitivity that is not attained in other classical sensing methods (Raparthi, 2022). According to Rubino et al. (2021), quantum superposition refers to the combination of two valid quantum states to produce the other authorized state. Fein et al. (2019) note that in quantum computers, quantum states are represented as a qubit, unlike classical computers, which use binary states of 0 or 1. As such, quantum superposition indicates that two or more quantum states can be superposed or combined to form another valid state. In quantum computers, the state of a qubit can be both 0 and 1 simultaneously, whereas traditional computers assume only one binary state, either 0 or 1 (Fein et al., 2019). Due to the quantum superposition concept, Gauglitz (2021) explains that more sensitive quantum sensors can be developed including atomic clocks, enhanced accelerometers, and gyroscopes. Khan et al. (2024a) also explain that quantum superposition has contributed to more secure communication channels that are not susceptible to eavesdropping. Fig. 4 illustrates the quantum superposition concept, where qubits can simultaneously assume either state 0 or state 1.

In Fig. 4, quantum superposition is illustrated, where the qubits can assume either a 0 or 1 state simultaneously with a 50 % probability. However, in classical computing, the bits can assume a state as either

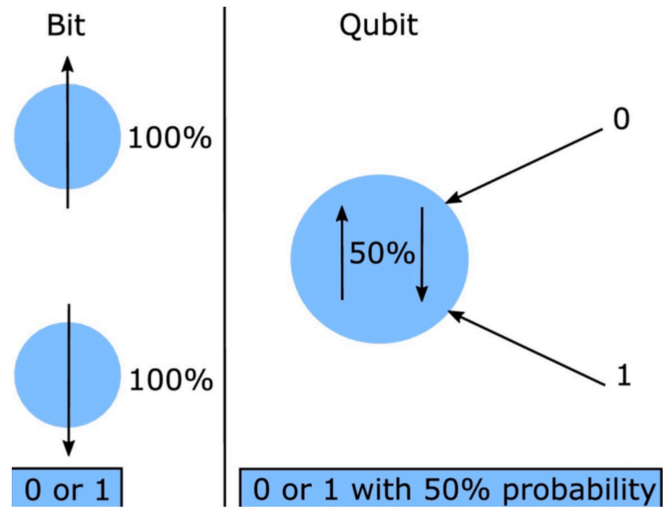

Fig. 4. Quantum superposition (Khan et al., 2024a).

0 or 1 (100 % probability).

The second quantum concept is quantum entanglement. Erhard et al. (2020) posit that quantum entanglement is a property of quantum physics in which quantum particles share information and interact with each other at a distance. Nishanth et al. (2022) note that with quantum entanglement, two particles become connected in such a way that the state of one particle cannot be described independently of the state of the other particle, regardless of the distance between them. As such, when quantum particles are entangled, they are inextricably linked regardless of their temporal or spatial separation and the photons in these states are indistinguishable. The result is that the quantum states in the qubits cannot be factored into individual states and the particles are inseparable. Fig. 5 below illustrates the concept of quantum entanglement.

As illustrated in Fig. 5, the wave function describing the entangled particles cannot be defined independently for each particle, implying that the measurement of one particle will instantaneously affect the other, regardless of the distance between them. As such, information in one particle is not fully determined until the information about the other

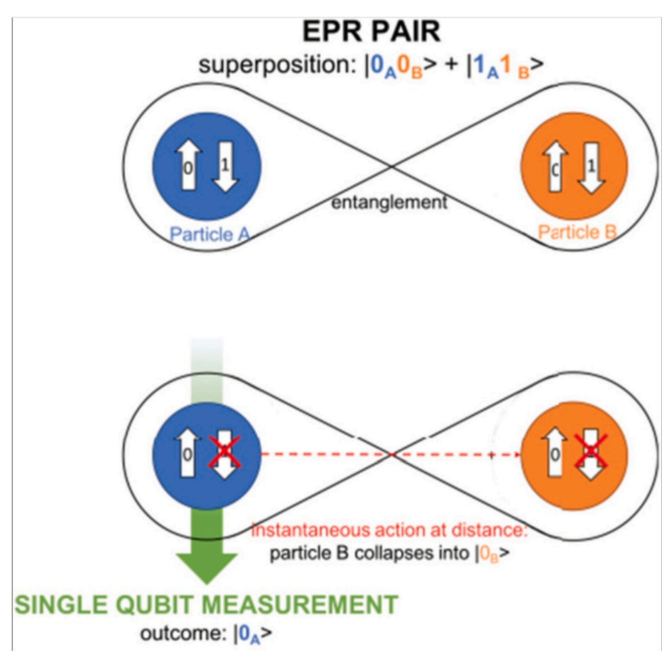

Fig. 5. Quantum entanglement (Khan et al., 2024a).

particle becomes fully available.

Unlike conventional sensors, which are prone to error accumulation caused by noise and manufacturing faults, quantum sensors detect changes in the environment at the atomic level and are considered ten times more sensitive than conventional sensors to environmental changes (Kantsepolsky et al., 2023). Quantum technologies use various agents, including artificial atoms, photonic qubits, atomic vapors, superconducting circuits, and trapped ions (Kantsepolsky et al., 2023). Marciniak et al. (2022) add to Kantsepolsky et al. (2023) and observe that quantum sensors are currently considered the most mature and advanced technologies in sensing and are applied in various fields, including chemistry, biology, navigation, physics, and medicine. In support, Soller (2024) estimated that the quantum sensing industry will increase from $0.7 billion in 2023 to $6 billion by 2040, disrupting the existing sensor technology market. The inferences from these studies indicate that significant growth in the quantum sensing market is expected due to their higher sensitivity to changes in the environment compared to conventional sensors.

Various studies have further examined how quantum sensors can be adopted in precision agriculture applications. The work by Matlali and Fischer (2023) showed that quantum sensors promoted the growth of plants and ensured minimal resources were used to enhance farming yields. The reported findings highlighted how quantum dot sensors such as the $CuInS_2/ZnS$ quantum dot (QD) films were used in enhancing the growth of lettuce plants by converting ultraviolet/blue photons into red emissions (Parrish et al., 2021). Subsequently, the quantum sensors promoted the total leaf area, edible fresh mass, and edible dry mass levels. The inferences from these studies showed that QD films were effective in promoting the photosynthetic efficiency of lettuce and enhancing greenhouse productivity due to higher availability of ultraviolet photons, which improved conversions. The work by Shahzad et al. (2024) supported Parrish et al. (2021) and showed that using quantum dot sensors reduced plant stress and improved the antioxidants in soil, leading to higher growth levels. The implications were that the combination of quantum dots biochar (QDBC), gibberellic acid (GA) used to regulate cell division and plant growth, and rhizobacteria (RB) led to enhanced fenugreek shoot weight, root fresh weight, root dry weight, and shoot dry weight (Shahzad et al., 2024). Alotaibi et al. (2024) added to the views of Shahzad et al. (2024) and demonstrated that using Zn-quantum dot biochar (QDB) enhanced the growth rate and emergence of rapeseed seedlings, contributing to higher height of the plants and improving the number of pods and branches from the plants while reducing drought stress. Therefore, the inputs enhanced the content of water in leaves. The insights from these studies indicated that quantum sensors have been adopted in agriculture to enhance crop growth, which leads to improved yields and drought resistance.

Essentially, quantum sensors are among the advanced technologies that are expected to enhance agricultural efficiency from 4.0 to 5.0, as shown in Fig. 6.

According to Polymeni et al. (2023), Agriculture 5.0 is distinguished by super-efficient technologies such as the anticipated sixth-gen IoT that allows extended and sophisticated device-to-network connections. Other researchers have also highlighted that unlike Agriculture 4.0, which only focuses on gathering general data on soil, climate, plant, and animal health, Agriculture 5.0 is about gathering and analyzing highly precise data individualized to each plant, thereby enhancing decision-making (Bergier et al., 2024). Moreover, according to Vanghele et al. (2020), a standout feature of Agriculture 5.0 will be remote sensing and cloud computing, where large volumes of gathered data can be safely and efficiently transferred to cloud storage for analysis and decisions made autonomously by technologies on the best response systems. Researchers predict that Agriculture 5.0 technologies will help to enhance agricultural productivity due to improvements in disease detection and water management, thereby promoting global food security (Ferreira et al., 2022). Therefore, exploring quantum sensors is crucial because it is considered one of the advanced technologies that can promote the transition from Agriculture 4.0 to 5.0.

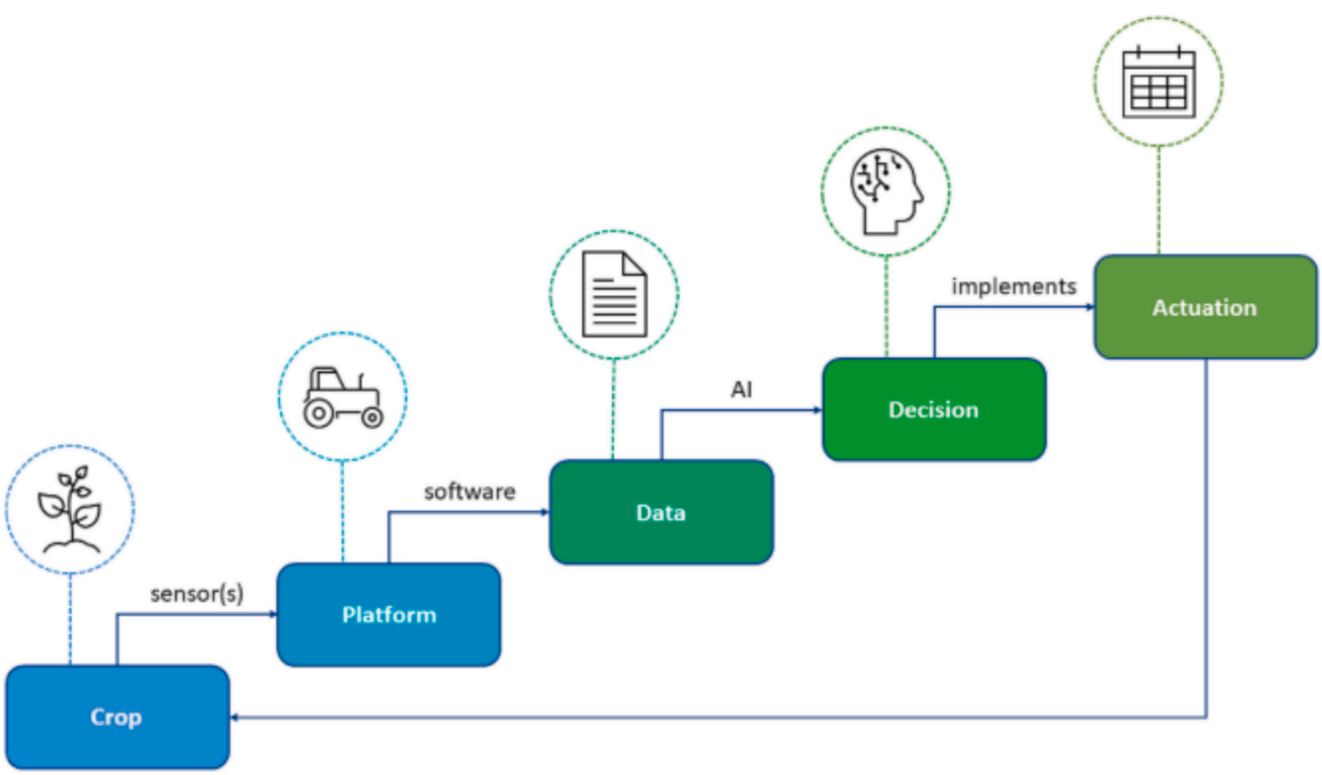

Fig. 6. Agriculture 5.0 Needs Precise Agricultural Data (Polymeni et al., 2023).

1.4. Novelty of the research

The novelty of this review article arises from its significance in improving insights into how SF practices could be improved by adopting quantum sensors. Extensive research has been done concerning quantum sensors in different fields, including biology, navigation, physics, and medicine (Marciniak et al., 2022; Kantsepolsky et al., 2023). However, there is little research on how quantum sensors can be applied to improve agricultural efficiency and output. To the best of the researcher's knowledge, there are minimal review articles that have compared classical sensors in precision agriculture to quantum sensors to identify their advantages and disadvantages, indicating an existing research gap.

The review article is also novel as it benefits policymakers in the agricultural sector by outlining the framework within which quantum sensors can be applied effectively in agriculture. A comparison of quantum sensors with other conventional sensors helps identify their key strengths and areas where they can be best applied in agriculture. Therefore, findings from this study will help policymakers to adequately prepare for the possible disruption by quantum sensors in the industry. Finally, the findings of this review paper will help commercial farmers understand how they can improve agricultural output by incorporating advanced technologies and mitigating the different risks associated with classical precision sensors to improve the efficiency of SF practices.

This review article aims to explore the different perspectives on how quantum sensors are used in agriculture. The question answered in this paper is:

What are the potential applications of using quantum sensing in agriculture?

The specific objectives to be addressed include:

i. To examine the practical applications of quantum sensing in agriculture.
ii. To compare current smart farming sensors and quantum sensors.
iii. To explore the future direction of quantum sensing in agriculture.

The rest of the article is divided into four sections. The materials and methods are detailed in the subsequent section to enable readers to replicate this study and verify the obtained results. Thereafter, the results from the narrative review are presented in the third section under various subtopics. The subtopics consider various aspects of quantum sensors in agriculture, including operation mechanisms, comparison with classical sensors, and potential benefits and challenges. A discussion of the review findings is presented in the fourth section, and finally, the fifth section highlights the conclusion drawn from this review.

2. Materials and methods

A narrative review design was employed in this review to understand the potential of quantum technology applications in agriculture and the related challenges and benefits. The core purpose of a narrative review is to present a general overview of a phenomenon, thereby setting a foundation for future research. Narrative review design also presents a crucial advantage of allowing flexibility in data gathering and analysis to identify the practical approaches to improving practice in a certain field. In this regard, the review findings can be beneficial to different stakeholders in a specific field. A further benefit of a narrative review is increasing knowledge on under-researched topics by highlighting trends, showing gaps, and revealing context for future research (Basheer, 2022). For this study, a narrative review was deemed suitable because it allowed the expansion of the literature on the application of quantum sensors in agriculture, which has previously attracted little attention from researchers. The review findings are expected to reveal how food security and low productivity issues can be addressed. The practical approach used in the narrative review also considered how quantum sensors compare with conventional classical sensors. In a narrative review, the first step is to frame the research question to ensure clarity on the key aspects to consider in a study. In this respect, the question considered in this review entails the applications of quantum sensors in agriculture as well as the associated benefits, challenges, and future directions.

A comprehensive strategy was developed to search for relevant articles, which helped in addressing the research goals. Adopting a detailed search strategy improves the replicability of a review since it provides clarity on keywords and phrases and the scope of the search. Firstly, reputable databases were identified, which ensured that diverse, high-quality articles on the topics could be accessed. Four databases were considered in this study, including *JSTOR, Elsevier, Research Gate*, and *PubMed.* Several keywords were considered during the search, including 'quantum,' 'sensors,' 'agriculture,' 'technology,' applications,' 'perspectives,' 'detection,' 'smart,' 'challenges,' and 'benefits.' Boolean operators, including AND and OR, were considered to combine the search terms and form relevant phrases, which helped to refine the search. Some of the phrases developed include Quantum sensors AND agriculture, Quantum sensors AND applications, Quantum sensors AND challenges OR benefits, and Smart agriculture AND quantum sensors.

Although narrative reviews do not need detailed selection criteria like systematic review, the clear framework for selecting articles is crucial to enable the replicability of the review. The researcher developed inclusion and exclusion criteria, as shown in Table 1, to narrow down the selected studies.

As shown in Table 1, the first inclusion criterion involved selecting articles that focused on quantum computing and sensor technologies in agriculture. As such, articles that focused on technologies other than sensors were excluded. The other inclusion criteria involved studies published between 2014 and the present, ensuring that only the latest trends on the topic are considered, thereby excluding any outdated information, and enabling accurate and reliable findings. Although the sampled articles are not restricted to primary research and can include books and systematic reviews, articles were excluded if they are based on social media commentaries or blogs. This strategy was crucial in ensuring that the sources sampled were reputable. Only studies published in English were considered to avoid the challenges of translation, which can affect the interpretation of the studies.

The PRISMA tool was further utilized in screening the selected articles, as illustrated in Fig. 7.

An initial search of articles yielded 465 articles. However, after considering articles published in English in 2014, 225 articles were eliminated, and the remaining 240 articles were screened for relevance. Out of the 240 articles, 22 were removed because they focused on the analysis of sensors in sectors other than agriculture. Another 67 were removed because they did not consider advanced technologies in agriculture. The remaining 151 articles were assessed for quality, and 32 were removed because they were from non-academic websites, including social media and news. Eventually, 119 articles were sampled

Table 1
Inclusion and exclusion criteria.

Aspect	Inclusion Criteria	Exclusion Criteria
Scope	Studies focused on potential applications of using quantum and classical sensing in agriculture	Studies focused on topics other than the applications of quantum and classical sensing in agriculture
Application domain	All agricultural sensors	Sensors specific to agricultural applications such as soil monitoring
Publication Language	English	All non-English languages
Publication Year	2014–2025	Before 2014
Research design	Laboratory experiments, field experiments	Secondary reviews
Sources	Peer-reviewed journal articles	Personal Blogs

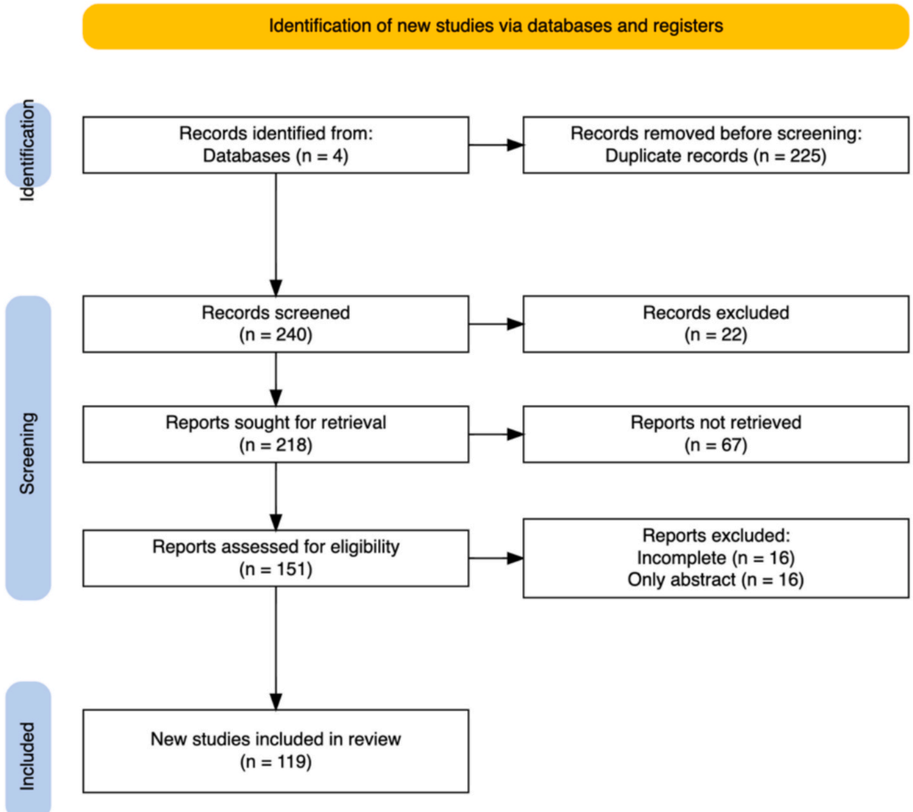

Fig. 7. PRISMA Flowchart.

Table 2
Search Output of Different Databases.

Database	Search Query	All articles	Articles identified after applying the search filter
PubMed	Quantum AND sensors AND agriculture OR (Smart AND farming)	346	10
	Quantum AND sensors AND applications OR detection	3,806	12
	Quantum AND sensors AND perspectives AND challenges OR benefits	192	7
Research Gate	Quantum AND sensors AND agriculture OR (Smart AND farming)	367	10
	Quantum AND sensors AND perspectives AND challenges OR benefits	122	8
	Quantum AND sensors AND applications OR detection	89	6
Elsevier	Quantum AND sensors AND perspectives AND challenges OR benefits	10,997	19
	Quantum AND sensors AND applications OR detection	74,010	13
	Quantum AND sensors AND agriculture OR (Smart AND farming)	19,535	11
JSTOR	Quantum AND sensors AND applications OR detection	3,883	6
	Quantum AND sensors AND agriculture OR (Smart AND farming)	1,686	9
	Quantum AND sensors AND perspectives AND challenges OR benefits	727	8

for narrative review. The sources extracted from each database are shown in Table 2.

From Table 2 above, it is noted that most articles were chosen from Elsevier (n = 43), followed by PubMed (n = 29), Research Gate (n = 24), and JSTOR (n = 23) for 119 articles. The details of the selected studies are showcased in Appendix II.

A critical appraisal of the sampled studies was undertaken to assess their quality before inclusion in the review. The primary goal of critical appraisal is to distinguish relevant articles from assumptions, opinions, and irrelevant papers. For this review, critical assessment was done using the SANRA tool (Scale for the Quality Assessment of Narrative Review Articles), which is important in evaluating various aspects of studies, including focused aim and objectives, alignment between objectives and findings, proper citation, and adequate evidence that addresses the research goals. Appendix I indicates the summary of the critical appraisal conducted.

The sampled articles were analyzed using thematic analysis, where patterns regarding quantum sensors were identified in different studies. Thematic analysis entailed the review of the sources to understand the core ideas shared from the collected articles. The first phase involved evaluating the sources to gain familiarity with the shared insights. In the subsequent phase, codes were identified from the reviewed data, illustrating the main ideas that were shared. The codes represented noteworthy features of quantum sensors that allowed them to be applicable in agriculture. The third phase entailed the generation of themes from the outlined codes. In the fourth step, themes were reviewed to guarantee accuracy and ensure alignment with supporting data and codes. In the fifth phase, themes were reviewed and named to ensure relevance and address the main objectives of the review article. The sixth phase entailed the report of the findings within the results section.

3. Results

3.1. Applications of classical sensors in agriculture

The analyzed studies revealed that classical sensors were utilized in diverse precision agriculture activities. For example, research was conducted by Bongs et al. (2019) on sensors' effectiveness in solving problems in agriculture. The studies focused on sensors and their contributions to precision agriculture in areas such as GPS-guided mechanization, variable rate technology (VRT) for assessing how chemicals could be dispensed in agriculture, and site-specific management of crops. Therefore, traditional sensors were used in many areas based on their small size. Similarly, Albiero et al. (2022) noted that sensors are adopted and applied in swarm tractors to foster mechanized farm processes. The study revealed how sensors help mechanize agricultural activities and processes on large-scale farms. Therefore, sensors are vital in tractors, as they promote mechanization and foster the field capacity of the machinery deployed.

The analysis also showed that smart sensors are combined with wireless networks to deliver precise and accurate measurements from the field to cloud-based systems to support agricultural processes and techniques. The synthesis of Berger et al. (2021) and De la Concepción et al. (2015) showed that using wireless sensor networks led to the characterization of the micro-climatic behavior in agricultural fields where sensors integrated different units to enhance physical parameters. Further analysis indicated that sensors could lower the consumption of power and were more reliable while lowering the need for more energy-harvesting machines. Subsequently, the insights from the findings identified the value of classical wireless sensors in affirming environmental conditions in farms and monitoring environmental conditions to assess parameters of microclimate behavior within fields and tracking physical parameters. Gsangaya et al. (2020) supported the work by De la Concepción et al. (2015) and showed that using precision agriculture sensors led to high profits within smart farming applications. The adopted sensors were important in ensuring farmers could make operational decisions promptly using the current environmental conditions and historical data through wireless sensor network systems. The implication was the improvement of decision-making due to the high-quality information regarding the prevailing environmental conditions within farms. The use of precision sensors and microcontrollers ensured environmental data including temperature, content of soil moisture, and humidity were also easily captured.

Precision sensors also allow farmers to access insights on farming operations and relay them to data management systems through internet-enabled devices. As a result, the sensors display parameters and ensure agricultural systems can be easily monitored. Dwarkani et al. (2015), Kumar and Reddy (2020), and Kim et al. (2021) noted that using smart irrigation systems and smart sensors based on wireless communication technology is largely effective in smart agriculture. The sensors are applied to measure physical parameters, including nutrient content, soil pH, and soil moisture content. The smart sensors ensured accurate monitoring of the physical and chemical parameters of the soil and guided decision-making in smart farming. Kayad et al. (2020) supported Dwarkani et al. (2015) and demonstrated how smart sensors were used to promote profitability in agriculture by monitoring the moisture content of the soil, temperature in winter wheat and tree health, and spray drifts in vineyards. As a result, sensors led to improved farm management, including the digitalization of food systems. However, Khan et al. (2024) misaligned with Dwarkani et al. (2015) and Kayad et al. (2020) and reported that smart sensors in agriculture were challenged by limited resources, leading to issues when dealing with repetitive operations and they were low-energy devices that were involved in excessive broadcasting and listening which resulted in passive listening and overhearing. The contradiction showed that using smart sensors in agriculture contributed to negative outcomes where the devices led to delays in transmitting data and congestion within communication channels. Thus, to mitigate these bottlenecks, Khan et al. (2024a) developed a scheme known as "Self-Adaptive and Content-Based Scheduling (CACS) to reduce idle listening and over-hearing in securing the quantum IoT sensors. The simulation of the CACS system also showed that lower levels of energy were consumed, reducing the operational costs for the developed scheme. The implication is that systems were not overwhelmed and appropriate energy was provided. Kumar and Sharma (2020) supported Khan et al. (2024a), showing that using smart wireless sensor networks enhanced agricultural applications including the control of irrigation, measurement of soil quality, and precision agriculture. As such, the benefits of sensor technologies in precision agriculture were emphasized as they promoted crop production and management.

3.2. Quantum sensing Key concepts

The assessment of diverse studies also indicated different features of the quantum sensing applications. The findings revealed that quantum sensors were based on core quantum mechanics concepts including high resolution, solid-state spins, and spatial sensitivity (Bonato et al., 2016). The findings also indicated that adaptive methods were used to promote the optimal performance of the quantum sensors. As such, the uncertainty associated with high dynamic ranges and significant time investments were minimized due to the adoption of the quantum sensors. Various studies (Kutas et al., 2022; Rademacher et al., 2020; Rajak et al., 2023) reiterated the findings, and revealed that quantum sensing was based on using light and photons were used to transfer data from one spectral range to another. The implication is that the accuracy of data transmission guarantees that precision agriculture can be realized and the potential harms to systems and applications can also be easily addressed. In agreement, Bongs et al. (2023) pointed out that quantum sensors are applied in taking measurements by leveraging the core atom properties and light where the quantum states of particles are environmentally sensitive. These sensors are critical in decision-making in precision agriculture to avoid losses and increase production. El Morsalani (2024) and Pievanelli et al. (2016) agree with Bongs et al. (2023), observing that quantum sensors transform precision measurements and enhance the measurement of distance, time, magnetic and electric fields, and temperature with higher sensitivity than conventional/traditional sensors, such as seismometers and microscopes. Quantum sensors exploit light properties where quantum particle states are extremely sensitive to the environment. In this context, quantum particles are used as probes that quantify gravity, magnetic fields, time passage, and rotation better than classical devices, which are based on chemical or electric signals.

Further to the principles of quantum sensing, the results from the analyzed studies revealed that quantum sensors are applied in diverse fields. Quantum sensing is applied to monitor various aspects, including energy consumption, environment, navigation applications, and geographic surveys. The analysis of Kantsepolsky et al. (2023) showed that quantum sensors were adopted across different fields including magnetometers and imaging diagnosis in medical fields, oil exploration, GPS systems such as atomic clocks, and navigation gyroscopes. Boddice et al. (2017) also reiterated Kantsepolsky et al. (2023) and revealed that quantum technologies were adopted in geographical regions to enhance the identification of features outside the detectable range based on size and depth levels. The efficiency of quantum sensors within environmental monitoring also led to the adoption of geographic surveys. The studies by Paul et al. (2022) and Oh et al. (2024) were aligned with the work by Boddice et al. (2017), indicating that quantum sensors were effective in diverse commercial applications based on their higher levels of accuracy, robustness, and good stability. Therefore, different quantum sensing applications including magnetic resonance gyroscopes, gravimeters, and gravity gradiometers were reported.

In practice and principle, different methods are applied to develop quantum sensors. Arvand et al. (2016) showed how nano-composite quantum sensors are developed using graphene quantum dots, carboxylated multi-walled carbon nanotubes, and magnetic nanoparticles for glassy carbon electrode surface modification. Quantum sensors demonstrate good selectivity and sensitivity with lower potential for L-DOPA determination with the range of 3.0 to 400 μmol L^{-1} as well as a detection limit of 14.3 μmol L^{-1}. Thus, modified electrodes provide synergistic augmentation on voltammetric L-DOPA's electrochemical oxidation behavior. The arguments of Facure et al. (2020) supported Arvand et al. (2016), noting that the graphene quantum dots are OD materials in the carbon-based family, which can be combined with graphene to produce good chemical-physical properties. Thus, combining the GQDs with various materials generates nano-composites with remarkable properties and superior performance. However, Farahmandzadeh et al. (2025) provided a varying perspective from those of Facure et al. (2020), supported by Arvand et al. (2016), pointing out that fluorescence-based quantum sensors are generated using chemical processes where Lead ions are involved. The authors noted that a ZnSe/CdTe QDs-based sensor utilizing a simple and rapid photochemical method to synthesize thioglycolic acid-stabilized ZnSe/CdTe core–shell quantum dots. Fluorescence-based quantum sensors are validated and have high Pb^{2+} sensitivity and a 31.8 nM detection limit, as well as a linear range of 50 Nm – 10 μM. The sensor shows reliable performance against river water, tap water, and agricultural water based on the Inductively Coupled Plasma (ICP) analysis. Omia et al. (2023), Pyingkodi et al. (2022), and Du et al. (2024) agreed with Farahmandzadeh et al. (2025), observing that a dual template molecularly imprinted double emission ratio fluorescence sensor was applied in selective detection of aristolochic (Aas) and methyl eugenol (ME). The sensors demonstrated dual emission peaks at 515 nM and 650 nM, encompassing $CsPb(BR/I)_3$ and $CsPbBr_3$ perovskite quantum dots that are molecularly imprinted polymers. Thus, molecular approaches are effective in developing quantum sensors. Quantum sensor derivation from diamonds was initiated and showed significant success in precision agriculture. For example, Ho et al. (2022) and Webb et al. (2021) demonstrated that single qubit solid-state materials are applied as versatile platforms for quantum data, including the nitrogen-vacancy (NV) center in diamond used for quantum sensors to detect various physical parameters like temperature, magnetic fields, force, and electric fields a high precision and resolution. In this regard, Hamlin and Zhou (2019) and Liu et al. (2022) pointed out that nitrogen vacancies are used for manufacturing superlative sensors of material properties at high pressure. Thus, the nitrogen-vacancy centers in diamonds arise when detecting optical NMR signals coming from chemically modified thin films and address its limitations relating to sensitivity to probe small spins at surfaces and interfaces. Tsukamoto et al. (2022) supported Hamlin and Zhou (2019) and Liu et al. (2022), observing that nanodiamonds were excellent quantum sensors for local magnetic field measurements and further demonstrated magnetic field imaging with a high accuracy of 1.8 μT where nano-diamond ensemble (NDE) was combined with machine learning without any physical models. A nanovacancy in diamond is showcased in Fig. 8 below.

In Fig. 8 above, a schematic nitrogen-vacancy center in a diamond sensor is showcased. In Fig. 9 below, the experimental setup of the nanodiamond is illustrated.

In Fig. 9, the experimental setup of the diamond sensor was showcased, indicating the glass slip, objective lens, and Helmholtz coil.

An examination of different studies reveals the quantum advantages of NVs in agricultural contexts. Pogorzelski et al. (2024) demonstrated that NVs were promising technologies in magnetic-field sensors due to their high accuracy and cost-effectiveness. Wang et al. (2025) and Toural et al. (2023) also added that NVs were adopted in the development of magnetometers where external magnetic fields could be measured at high accuracy. The NVs in diamond showed high accuracy in detecting anomalies and were effective in the development of magnetometers. Several studies also underscored the high promise of NVs in diamond sensors when measuring physical parameters like temperature,

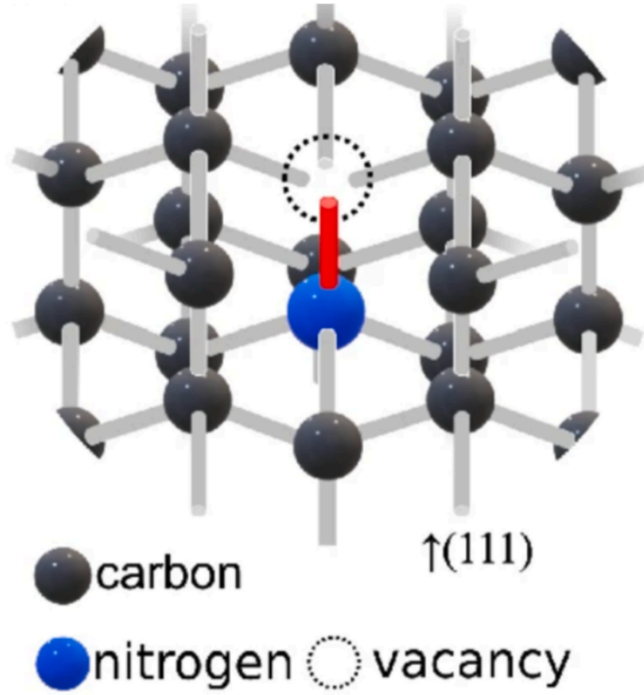

Fig. 8. Nitrogen-vacancy in Diamond Sensor (Tsukamoto et al., 2022).

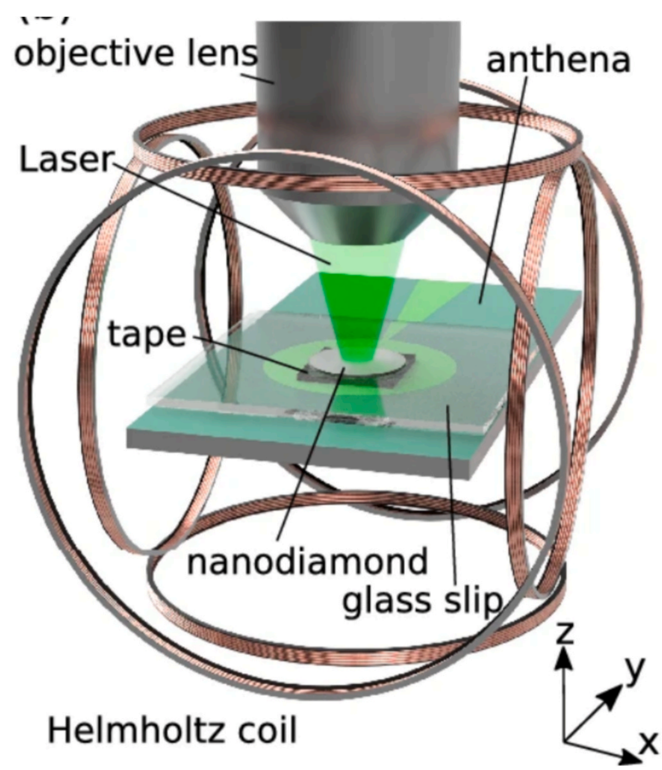

Fig. 9. Experimental setup of the diamond sensor (Tsukamoto et al., 2022).

magnetic fields, force, and electric fields a high precision and resolution. Wu and Weil (2022) reported that nano-diamond quantum sensing technology delivered high promise in ultrasensitive diagnosis, where it probed sub-cellular parameters at ambient conditions and facilitated measuring quantities at nano-scale where the vacuum and low-temperature issues were faced. The results showed that atom defects within the nano-diamond lattice ensured stable emissions and spindependent photoluminescence. The inferences indicated that nano-diamond quantum sensors could detect physical conditions, including magnetic fields, strain, electric fields, and local temperatures. Xie et al. (2022) supported Wu and Weil (2022), arguing that diamond-based quantum sensors generated a new class of biophysical sensors and diagnostic devices that were used for cancer screening and ultrasensitive immunoassays. The analysis of these findings indicated that using quantum engineering with single-molecule biophysics ensured that DNA molecules could be immobilized and individual proteins emerged on the surface of bulk diamond crystals that were made of nitrogen-vacancy qubit sensors. The insights from the studies further indicated that there was precise control over the absorption density of bio-molecules associated with the thin functionality architecture, showing near-surface coherence of cubits that approached 100 μs (Ullo and Sinha, 2021; Thakur et al., 2019; Strangfeld et al., 2023).

In addition to the example showcasing the nano-vacancy approach in quantum sensors for detecting physical parameters, a second method utilizes quantum precision measurement based on the spin-exchange relaxation-free (SERF) effect. The work by Zhai et al. (2022) demonstrated the applications of SERF for the precise measurement of magnetic field and inertia. Fig. 10 showcases spin-exchange collisions.

In Fig. 10, spin-exchange collisions are showcased including spin-exchange relaxation (A) and spin-exchange relaxation-free states (B). Zhai et al. (2022) demonstrated that the spin-exchange relaxation-free state effect has high measurement potential due to its ultra-high sensitivity, making it applicable in fields such as inertial navigation, biomedicine, and fundamental physics. In Fig. 11, a schematic diagram showcasing the operation of a SERF atomic magnetometer is also represented.

In Fig. 11, the operational principle of a SERF atomic magnetometer is showcased, where the magnetic field (B) and magnetic moment (M) are illustrated. The example demonstrated that the pump light-induced spin polarization in alkali metal atoms. The frequency of the Larmor precession of the magnetic moment was represented as w. When exposed to an external magnetic field, the magnetic moment of the atomic spin underwent Larmor precession, and a different beam of probe light was irradiated perpendicularly to the pump light to detect the Larmor precession. The example showed the applications of the SERF magnetometer in measuring high-precision physical states.

Fig. 12 further illustrates the schematic diagram of an inertial measurement based on SERF principles.

In Fig. 12, the SERF inertial measurement is illustrated, where the initial state is represented in (A) and the rotation of the SERF regime is

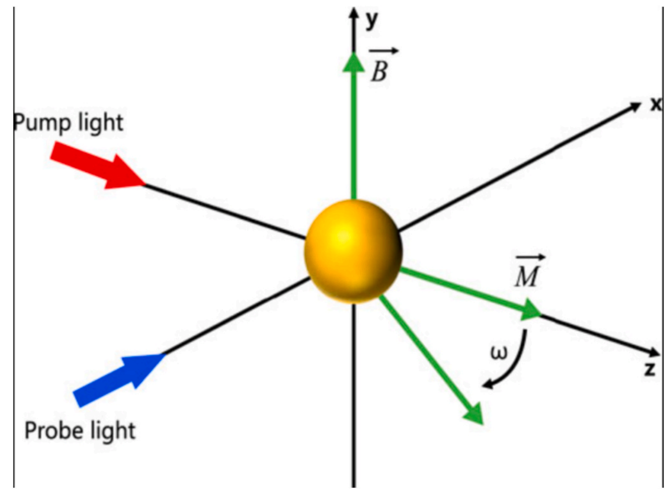

Fig. 11. Operation principle of a SERF atomic magnetometer (Zhai et al., 2022).

shown in (B). The nuclear spin of the noble (P^n) and the electro spin of the alkali metal atom were also shown (P^e). Strong coupling between the nuclear spin of the noble gas and the electron spin of the alkali metal atom ensures that the nuclear spin of the noble gas can follow and compensate for changes in the external magnetic field. As such, the static magnetic field felt by the electron spin of the alkali metal is close to zero and is sensitive only to inertial rotation.

Further comparison of the NV and SERF quantum technologies also reveals scenario-specific trade-offs. The insights from Zhai et al. (2022) showed that SERF technologies were more sensitive to anomalies in magnetic changes although more expensive to implement. However, Tsukamoto et al. (2022) showed that nano-diamonds were excellent quantum sensors for local magnetic field measurements and also more deployable. The implication was that the implementation of NV technologies in field applications such as geophysical surveys was more feasible than SERF due to practicability and lower costs. Therefore, the synthesis of the various studies underscored the importance of quantum sensors that were developed using different methods such as diamond non-vacancies and fluorescence-based approaches. The inferences also showed that quantum sensors were anchored in the exploitation of the basic properties of atoms and light. Therefore, the adopted quantum

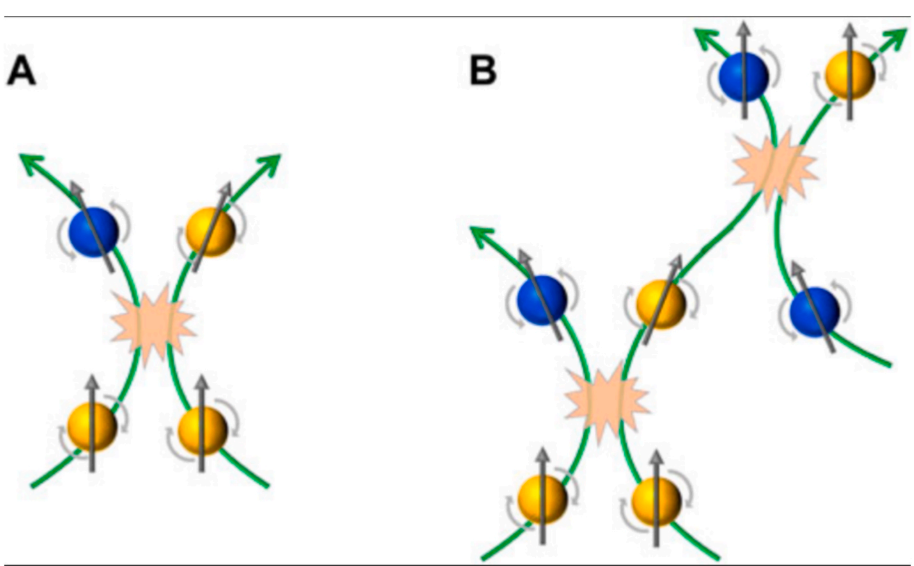

Fig. 10. Spin-exchange collisions (Zhai et al., 2022).

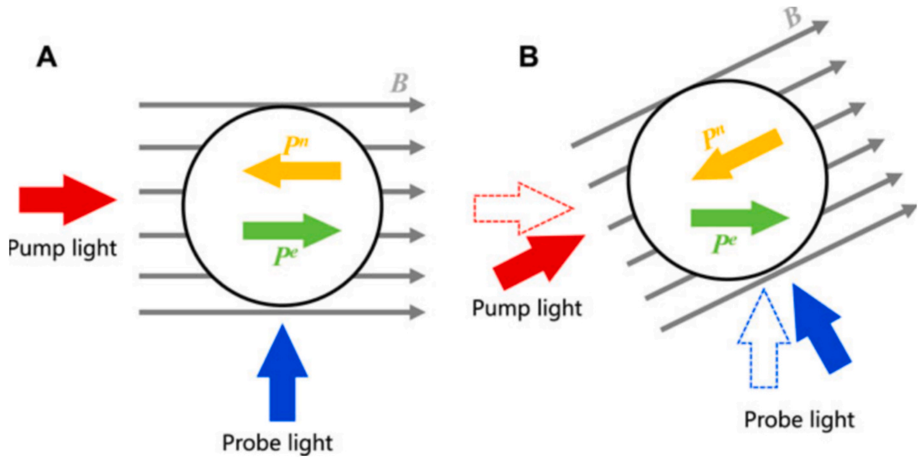

Fig. 12. SERF inertial measurement (Zhai et al., 2022).

sensors ensured their efficacy in different sectors to provide access to geological data to evaluate the environmental conditions.

3.3. Quantum sensors in agriculture

3.3.1. Quantum dot sensor applications

In their study, Dong et al. (2024) showed how carbon quantum dots (CQDs) are used as sensors and plant growth promoters to improve crop tolerance and bioimaging applications. The findings revealed that CQDs exhibit good attributes, including higher solubility, chemical inertness, and easy modification. Similarly, Agnol et al. (2021) pointed out that CQDs are employed to enhance plant production and growth where thermal lysis of micro-algae, Spirulina sp is performed to promote lentil growth when used at a concentration between 0.05 – 0.1 mg/ML. Using quantum sensors to speed up plant growth and maintain high productivity is common in smart agriculture. Liang, Wong, and Lisak (2023) corroborated the findings of Agnol et al. (2021) by observing that CQDs manufactured from plastic wastes were used for plant development via seed nano-priming of pea plants at various phases, including germination rate acceleration, increasing the lengths of roots and shoots, root moisture levels, and biomass accumulation. All these processes are undertaken in precision agriculture to support favorable plant growth in varying climatic conditions. Subsequently, the analysis of the studies indicates the importance of quantum sensors in enhancing precision agriculture within large-scale farming operations. The process of nano-priming using CQDs is further detailed in Fig. 13 below.

The process of developing carbon quantum dots from PET bottles using pyrolysis and hydrothermal synthesis and their applications in promoting the germination and development of seedlings through nano-priming are showcased in Fig. 13.

The synthesis of different studies also revealed that quantum dot sensors were effective in the detection of harmful pollutant chemicals and contaminants within agricultural food products. In the work by Arvand et al. (2016) and Raparthi (2022), insights showed that GDQs developed from citric acid pyrolysis were employed in the detection of L-DOPA electrochemical within agricultural food samples. As such, the inferences indicated the efficacy of GDQ sensors in detecting hazardous L-DOPA electrochemicals in foods such as pumpkin seeds, sunflowers, and sesame. The insights by Arvand et al. (2016) were supported in the work by Liu et al. (2020) where inferences indicated that the quantum dot sub-microbeads-based immune-chromatographic assay (QB-ICA) was adopted to detect parathion from agricultural food products. However, further discussions by Le et al. (2017) contrasted the insights from Liu et al. (2020) and Arvand et al. (2016) by demonstrating a fluorescent immune-chromatographic strip test (ICST) using CQDs for 1-amino-hydanton (AHD) detection, a metabolite in animal tissues. To prepare and activate the conjugates comprised of CdSe/ZnS quantum dots and monoclonal antibodies, an ester method is adopted. As such, the ICST reveals a high correlation and high reliability when utilized with liquid chromatography-tandem mass spectrometry. Despite the contradicting findings, these studies agree that quantum sensors are applied to enhance food item surveillance with high accuracy and reliability scores. The work by Zhang et al. (2023) also reiterated the insights from the previous studies (Arvand et al., 2016; Le et al., 2017; Liu et al., 2020) and reported that quantum sensors were effective in detecting poultry disease in large farms. The work by Zhou et al. (2018)

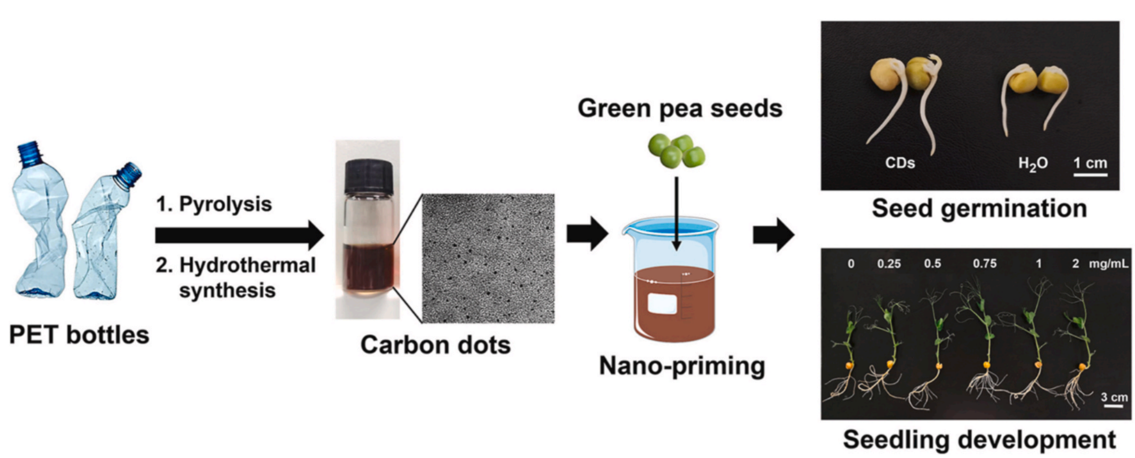

Fig. 13. CQDs Applied to Enhance Seed Germination (Liang, Wong, and Lisak, 2023).

supported Zhang et al. (2023) and demonstrated the effectiveness of CDQs in the detection of veterinary drug residues and pesticides. Therefore, the quantum sensors enhanced the detection of harmful pollutants from diverse agricultural food products.

The discussion of the studies further demonstrated how graphene quantum dots (GQD) were applied in detecting pollutants from agricultural applications due to their chemical-physical properties. The work by Facure et al. (2020) and Benavides-Mendoza et al. (2023) showcased the efficacy of GDQs as biosensors used to detect harmful pollutants including pesticides and heavy metals. The applications arose due to the good physical–chemical properties of GDQs as graphene was mixed with a tunable band gap. The work by Facure et al. (2020) was supported in other studies such as Abbasi et al. (2014) and Marukhyan et al. (2025) which underscored the efficacy of urease as an enzymatic sensor that was combined with CdSe quantum dots to ensure the detection of the presence of metals within aqueous environments. The work showed that the enzyme catalyzed the urea hydrolysis and contributed to the release of ammonia and carbon dioxide to increase pH and raise QD fluorescence. However, contradictory insights were reported by Bilmes et al. (2021) who showed that the presence of heavy metals such as Pb contributed to declined activities of enzymes and led to minor changes in the QDs fluorescence and pH. The work by Khoshnoud et al. (2020) and Khushaini et al. (2024) supported the insights and reported that a fluorescence-based quantum sensor developed from CdTe/ZnSe core–shell showed a high Pb ion sensitivity. The insights also indicated that the fluorescence-based quantum sensor of CdTe/ZnSe was adopted in processes of monitoring the environmental processes and when detecting the presence of heavy metal ions in tap and river water. The discussions also indicated the efficacy of quantum sensors in monitoring the conditions of the environment to ensure harmful heavy metals were detected and poisoning of food and water systems was avoided. The detection of lead ions using a fluorescence-based sensor is showcased in Fig. 14 below.

The analysis of Fig. 14 shows how a fluorescence-based sensor was applied to detect heavy metal ions (Pb) in river and tap water environments.

The synthesis of the different studies also showed that quantum dot

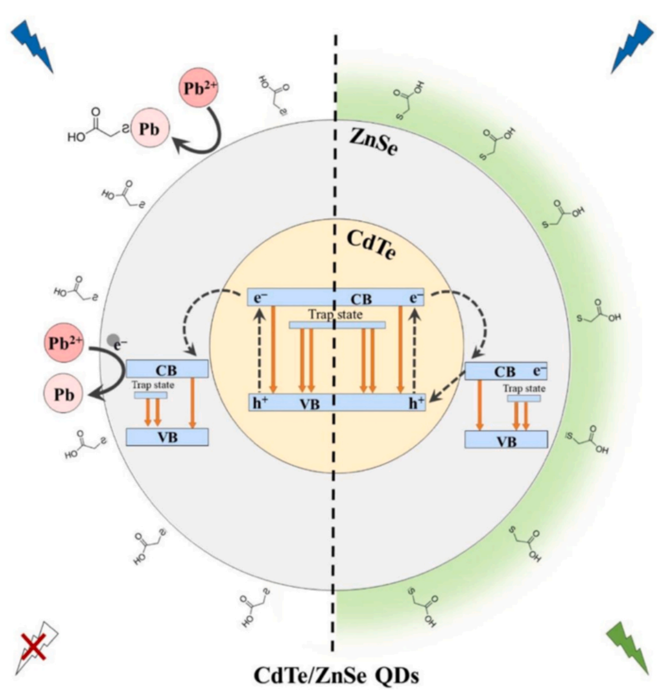

Fig. 14. The fluorescence-based sensor in environmental monitoring to detect Pb ions (Farahmandzadeh et al., 2025).

sensors were utilized to detect the levels of moisture in soils. The work by Kalita et al. (2016) showed that GDQ sensors were employed to detect the soil moisture levels in white and bentonite clays, classified as passive and active soils. The results indicated that the conductance of the interdigitated electrodes (IDE) in white clay increased from 0.06×10^{-6} $1/\Omega$ to 0.68×10^{-6} $1/\Omega$ based on the increase in moisture levels from 4 to 45 %. However, the bentonite soil showed poorer results where the conductance of the IDE rose from 0.06×10^{-6} $1/\Omega$ to 0.48×10^{-6} $1/\Omega$ as a result of increasing the levels of moisture from 11 to 90 % (Kalita et al., 2016). The analysis indicated that quantum sensors were showing higher levels of sensitivity at higher moisture content levels. The work by Kayad et al. (2020) aligned with Kalita et al. (2016) and revealed that the quantum sensors were useful in the detection of soil moisture to prevent risks of too much application of water and stress associated with the low soil moisture levels. As such, the discussions showed that quantum dot sensors were effective when detecting soil moisture content within soils to ensure farmers could monitor the quality of soil when detecting different types of crops.

In summary, the application domains of the quantum dot sensors are showcased in Table 3 below.

3.3.2. Measurement instruments based on quantum sensors

The second application of quantum sensors in agriculture was identified in measurement instruments. The findings indicated that quantum measuring instruments were effective in monitoring crop health and growth. The work by Akitsu et al. (2017) showed how quantum sensors were adopted to assess the photosynthetically active radiation (PAR) and photosynthesis in plants. As PAR refers to light in the wavelengths of 400–700 nm adopted by plants for photosynthesis, the quantum sensors allowed farmers to assess the levels of the light to guarantee high crop yields. The insights from Akitsu et al. (2017) indicated the accuracy of quantum sensor products involving the assessment of spectral responses and cosines. The results indicated the accuracy of LI-COR and LI-190 quantum sensors when assessing photosynthesis with minimal errors in external housing that was weather-proof. Further work by Caya et al. (2018) supported Akitsu et al. (2017) and demonstrated that the results generated by the Apogee SQ-520 quantum sensor were comparable to those of the VTB8440BH sensor when measuring the levels of PAR in different agricultural applications. The work by Hegemann et al. (2022) supported Caya et al. (2018) and demonstrated the efficacy of quantum sensors in the precise measurement of the photosynthetic photon flux density (PPFD) in modern agricultural horticultural systems. The synthesis of the studies indicated that the adoption of quantum sensors ensured higher accuracy in the measurement of PAR compared to traditional sensors and led to better light management in greenhouses to promote optimal crop growth. The analysis also showed that quantum sensors were adopted to measure soil properties. The work by Mukhamedieva (2024) showed the use of quantum sensors in measuring the levels of soil fertility by measuring the physical and chemical soil properties, including pH, nitrogen, phosphorus, and potassium. The discussions underscored the future

Table 3
Application domains of the quantum dot sensors.

Application Domain	Types of Sensors	Sample Studies
Plant growth promoters	CQD, GQD,	Dong et al. (2024), Agnol et al. (2021), Liang, Wong, and Lisak (2023),
Detection of harmful pollutant chemicals and contaminants within agricultural food products	CQDs, GQD, quantum dot sub-microbeads-based immune-chromatographic assay (QB-ICA), CdSe quantum dots	Arvand et al. (2016), Raparthi (2022), Liu et al. (2020), Le et al. (2017), Facure et al. (2020), Benavides-Mendoza et al. (2023)
Detection of the levels of moisture in soils	GQD	Kalita et al. (2016), Kayad et al. (2020)

potential applications of variational quantum chains (VQC) when characterizing soils in data analysis.

In summary, the application domains of the quantum sensor-based measuring instruments are detailed in Table 4 below.

3.4. Benefits and challenges of quantum sensors in agriculture

The analysis of the findings also revealed various advantages of using quantum sensors in agriculture compared to the classical sensors. The insights showed that one of the benefits was the improvement in the properties of the soil including higher nutrients and moisture levels. The study by Kalita et al. (2016) reported the benefits of GDQs in measuring the levels of moisture within soil contents where the conductance of the interdigitated electrodes (IDE) was assessed. The findings indicated that nano-scale GQDs were accurate in monitoring the soil moisture levels on a small-scale level. The findings from Mukhamedieva (2024) supported Kalita et al. (2016) and revealed that using measuring instruments based on quantum sensors led to improved measurement of soil fertility while accurately determining nitrogen and phosphorus levels where a model accuracy of 0.87 was reported. The analysis of the studies also showed a higher accuracy of quantum sensors in measuring soil moisture and nutrients compared to traditional sensors which relied on IoT communications to relate different insights to farmers.

The second advantage of using quantum sensors was the detection of minute changes within the environments, enabling farmers to achieve multiple functions. The analysis of the findings indicated that using quantum dot sensors led to the improved detection of the presence of hazardous pollutants and chemicals from food products and water sources. The work by Farahmandzadeh et al. (2025) also detected Pb ions from different water sources including tap and river water using the fluorescence-based quantum dot CdTe/ZnSe sensor. The insights from the study by Nsibande and Forbes (2016) further showed that the application of fluorescence-based quantum sensors enabled farmers to easily detect harmful chemicals and pollutants from water in fruits and vegetables. The analysis also indicated that quantum dot sensors were adopted in food surveillance applications to detect hazardous chemicals from the food products (Arvand et al., 2016; Le et al., 2017; Liu et al., 2020). The analysis of studies such as Khoshnoud et al. (2020) and Khushaini et al. (2024) also identified the environmental application of CdTe/ZnSe quantum dot sensors to ensure heavy metals could be identified from water sources. The synthesis of the findings showed that quantum sensors were ensuring increased benefits of accuracy and applicability in different environments to ensure heavy metals could be eliminated from water to avoid diseases. The use of quantum sensors to detect heavy metals and pesticides from food is illustrated in Fig. 15.

The analysis of Fig. 15 indicated the efficacy of quantum dot sensors from carbon in detecting the presence of heavy metals, pesticides, food additives, and residues of veterinary drugs in foods.

The analysis also highlighted the third benefit of quantum sensors in enhancing crop growth through the detection of stress in crops and providing necessary antioxidants to promote crop growth. The work by Liang, Wong, and Lisak (2023) also showed that CDQs were effective in improving the germination of pea seeds through nano-priming at different phases of growth. The use of quantum dot sensors ensured the improvement in the rate of germination and increased lengths of shoots and roots in diverse studies (Agnol et al., 2021; Liang, Wong, and Lisak, 2023; Dong et al., 2024; Sirohi et al., 2024). Therefore, quantum sensors were empowering farmers to increase the rate of seed germination and the development of seedlings in a more efficient manner. The quantum sensor instruments were also identified to improve the yield of crops. For example, the work by Akitsu et al. (2017) and Caya et al. (2018) reported that the instruments evaluated PAR with minimal errors and led to enhanced crop yields. The work by Hegemann et al. (2022) also cited that the quantum sensor measurement instruments were useful in the accurate determination of PPFD within modern horticultural systems. The insights were also identified in the work by Arvand et al. (2016) where the results showed the effectiveness of GDQs in the detection of L-DOPA in sunflower, sesame, and pumpkin seeds. The analysis showed that using quantum sensors enhanced the growth of crops by detecting hazardous chemicals and nano-priming seeds to promote the growth of shoots and roots.

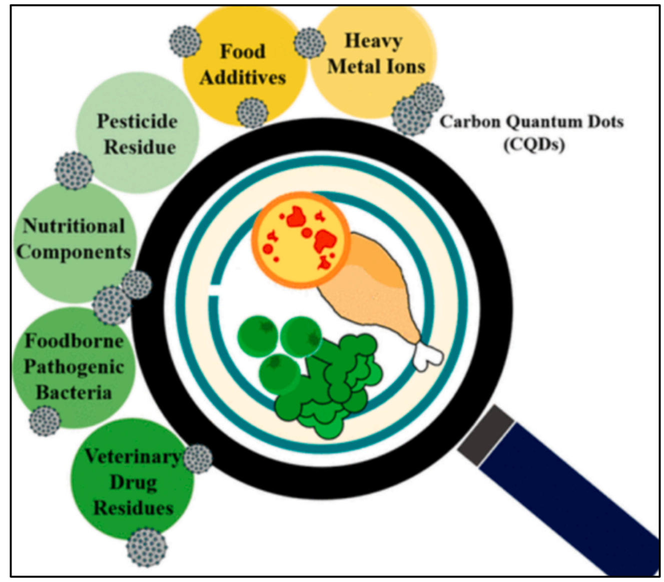

Fig. 15. Application of carbon quantum dots in detecting pesticides and metal ions in food (Tian et al., 2023).

The synthesis of the results also highlighted the benefits of quantum sensors based on the diverse methods used to synthesize them in agricultural applications. In the work by Dong et al. (2024), findings showed that the use of bottom-up and top-down methods led to the generation of carbon quantum dots. The bottom-up methods comprised the acidic oxidation, hydrothermal, and microwave approaches and the top-down methods comprised the electrochemical, laser ablation, and biomass decomposition. However, the synthesis showed that traditional sensors based on IoT components were adopted into agricultural machines to enhance data concerning the properties of the soils to enable farmers to enhance decision-making. The quantum dot sensors were also developed from diverse materials such as graphene (Arvand et al., 2016; Facure et al., 2020; Raparthi, 2022; Benavides-Mendoza et al., 2023), carbon (Hutzler, 2020; Agnol et al., 2021; Liang, Wong and Lisak, 2023), and fluorescence-based sensors (Nsibande and Forbes, 2016; Khoshnoud et al., 2020; Bilmes et al., 2021; Khushaini et al., 2024). The analysis of these findings showed that sensors were developed using multiple methods and could also be integrated into soil and water to measure different properties including nutrients and pollutants. The insights also showed that there were multiple types of quantum sensor instruments used in commercial applications to assess different agricultural properties such as soil fertility (Mukhamedieva, 2024), PAR (Akitsu et al., 2017; Caya et al., 2018), and photosynthetic photon flux density (Hegemann et al., 2022). The implication was that quantum sensors were effective in the measurement of different agricultural properties.

Table 4
Application domains of the quantum sensor measuring instruments.

Application Domain	Types of Sensors	Sample Studies
Assess the photosynthetically active radiation (PAR) and photosynthesis in plants	LI-COR and LI-190 quantum sensors, Apogee SQ-520 quantum sensor	Akitsu et al. (2017), Caya et al. (2018), Hegemann et al. (2022)
Soil fertility	variational quantum chains (VQC)	Mukhamedieva (2024)

However, further examination of the studies showed different disadvantages related to the use of quantum sensors within agricultural applications. The first issue regarded the high-cost implications of acquiring quantum-sensor-based instruments. In studies such as Akitsu et al. (2017), Caya et al. (2018), and Hegemann et al. (2022), high costs were incurred when acquiring commercially available quantum sensor instruments to evaluate photosynthetically active radiation. The analysis indicated that other alternative solar-based instruments to measure PAR in large-scale farms were cheaper compared to the quantum sensors. A similar weakness was identified when accessing graphene quantum dot sensors (Arvand et al., 2016; Facure et al., 2020; Raparthi, 2022; Benavides-Mendoza et al., 2023), carbon quantum dot sensors (Hutzler, 2020; Agnol et al., 2021; Liang, Wong and Lisak, 2023), and fluorescence-based quantum dot sensors (Nsibande and Forbes, 2016; Khoshnoud et al., 2020; Bilmes et al., 2021; Khushaini et al., 2024). Therefore, unlike traditional sensors that were based on IoT components, the quantum sensors were more specialized and were delivered as quantum dot films and particles. As such, the disadvantage encompassed the challenges in accessing and utilizing the quantum sensors on a large-scale basis. Further discussions concerning the high-cost challenges of large-scale implementation of quantum sensors also highlighted the difficulties related to stability and calibration, particularly in withstanding temperature and humidity fluctuations. In this context, wide variations in temperature across seasons and different times of the day can lead to inaccuracies in measurement due to the instrument's sensitivity to temperature changes. To address issues related to temperature variation, there is a need to incorporate temperature-stabilization mechanisms when integrating calibration routines to account for temperature fluctuations. Shielding the quantum sensors can also ensure the protection of sensitive components and prevent the entry of dust and moisture.

A second disadvantage regards the complex procedures involved in integrating quantum sensors in large-scale agricultural operations. The analysis of the findings showed that the reviewed applications were conducted in small-scale experimental settings. The synthesis of works including Arvand et al. (2016) and Raparthi (2022) indicated that GDQs were effective in detecting harmful chemicals from small samples of fruits and vegetables including sesame, sunflower, and pumpkin. In other works, such as Abbasi et al. (2014), Facure et al. (2020), and Marukhyan et al. (2025), results indicated the adoption of CdSe quantum dots in detecting the presence of metals within aqueous environments in small-scale setups. The work by Kalita et al. (2016) and Kayad et al. (2020) further showed that small-scale applications of quantum sensors were useful in the detection of the levels of moisture from soil. The analysis also indicated small-scale experiments using quantum sensor-based instruments such as the measurement of PAR levels in greenhouses (Akitsu et al., 2017; Caya et al., 2018). PAR measurement using a quantum sensor measuring tool is illustrated in a small-scale experiment in Fig. 16 below.

The analysis of Fig. 16 showed that using a measuring instrument based on quantum sensors ensured easier measurement of PAR within a field setup. However, the limitations of adopting quantum sensor instruments on a small scale led to a challenge in scaling the applications to replace the classical sensors. Additionally, the setup processes were time-consuming and challenged different agricultural contexts. However, classical sensors based on the use of IoT were readily scaled by integrating more electronic components to measure moisture, pH, soil, and nutrients within large-scale farms. The discussion concerning the complexity of implementing quantum sensors further considers challenges in data processing and interpretation. While the technology maturity level is still limited to laboratory and field testing, challenges are expected when transforming the generated data into actionable agricultural insights. The reviewed findings showed that most quantum sensors were discussed in small-scale setups, and no examples of large-scale, real-world scenarios where the sensors were deployed were showcased. As such, the technology maturity level was designated as early field testing, where controlled conditions were provided. To expand into large-scale commercial adoption of quantum sensors, the future outlook should focus on ensuring that the sensors are not protected, thereby avoiding variations in sensor readings based on changes in environmental conditions. Future work should also develop interfaces that ensure the high-sensitivity data generated by quantum sensors can

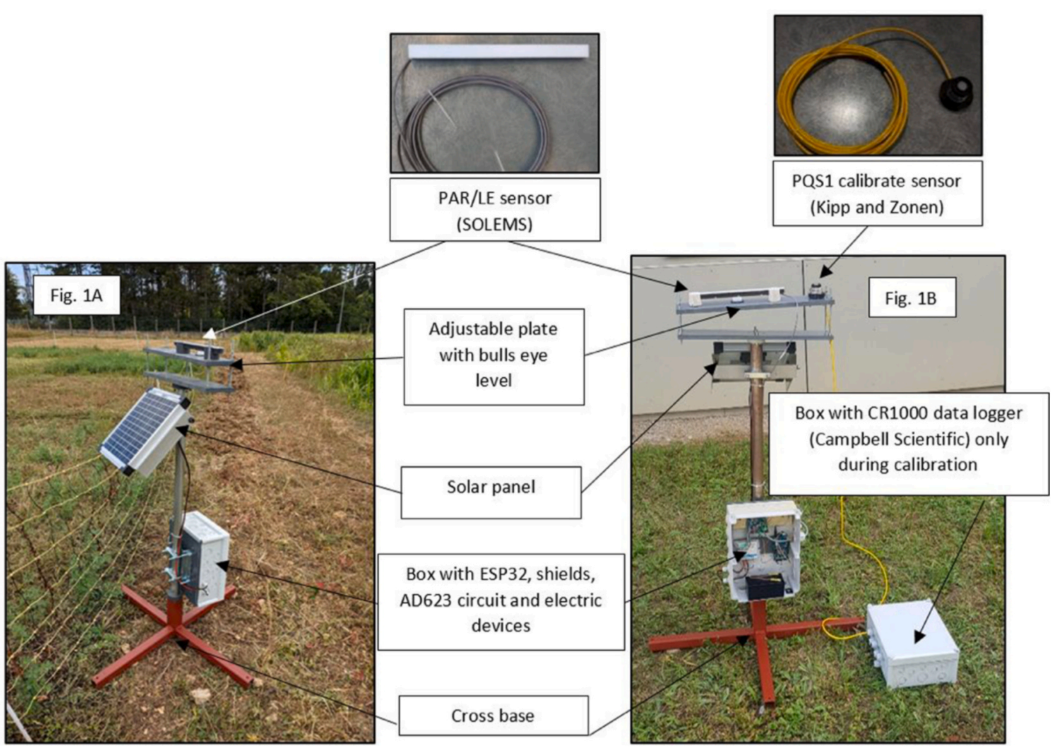

Fig. 16. PAR measurement using a quantum-based sensor (Coffin et al., 2021).

be effectively transformed into actionable agricultural insights, thereby easing the interpretation and integration of data.

In summary, the research methods adopted in the reviewed studies are showcased in Table 5 below.

4. Discussion

4.1. Potential applications of quantum sensing in agriculture

The current review article examined the research question investigating the potential applications of quantum sensing in agriculture. The reported insights from the studies revealed that they were useful in promoting the rate of crop growth and seedling germination in different types of crops. The work by Dong et al. (2024) showed that quantum sensors had properties including high solubility, chemical inertness, and ease of modification which contributed to their applications in enhancing the growth rates of crops. However, contradictions showed that classical sensors involved the application of IoT electronic equipment to measure environmental changes in soil and relay them to farmers. The insights indicated that quantum sensors could be adopted in applications where classical sensors were not feasible. The analysis of findings from Dong et al. (2024) emphasizing the benefits of quantum sensors in promoting crop growth was aligned with past literature where Agnol et al. (2021) reported that CDQs were used in promoting the growth of lentil crops. As such, the key insights indicated that quantum sensors could be adopted at small-scale levels to enhance crop growth as they were added to soils and were easily soluble. The work by Akitsu et al. (2017) and Caya et al. (2018) further showed that quantum sensors were useful in promoting the photosynthesis of plants and led to high yields. The findings were aligned with the work by Hutzler (2020) and Liang, Wong, and Lisak (2023), showing how CDQs were improving the growth of roots and shoots through seed nano-priming. The implication was that farmers could leverage quantum dot sensors to promote the yields in farms where they directly applied quantum sensors in soils due to high levels of solubility and sensitivity to the conditions within the environment, leading to higher lengths of roots and shoots. The discussion also indicated that quantum sensors were contributing to higher levels of crop growth by reducing the levels of stress faced by plants. Such insights were aligned with previous literature where Shahzad et al. (2024) showed that quantum sensors were applicable in reducing plant stress and controlling the access to nutrients and antioxidants, leading to improved shoot weight, root fresh weight, root dry weight, and shoot dry weight of fenugreek crops. Such findings corroborated past work by Alotaibi et al. (2024), which revealed that quantum sensors enhanced the emergence of rapeseeds and contributed to increased weight, number of seeds, pods, and branches in the selected plants. The insights showed that farmers could leverage the quantum dot sensors to enhance the growth of roots and shoots based on how sensitive they were to changes within the environment. The solubility and ease of modification also guaranteed that quantum sensors could be used in different types of soils to increase the yield of crops from agricultural processes. However, the findings misaligned the work by Coffin et al. (2021) where insights showed that quantum sensors were limited in agricultural processes due to the complicated integration in agricultural applications. The complexity also implied that farmers were unable to enhance the yields from agriculture due to the challenges in integrating the quantum sensors in the soils to promote overall yields. As such, although quantum sensors were associated with good chemical-physical properties, the complicated approaches to using them in large-scale farms challenged the adoption by farmers. The direct implication is the identification of a research gap where further work is needed to examine the most efficient methods that can be adopted to improve the integration of quantum sensors in large-scale farms to promote crop growth and yields.

Table 5
Research methods adopted in the reviewed studies.

Application Domain	Research methods	Sample Studies
promoting plant photosynthesis, detecting harmful contaminants in food products, detecting food-borne pathogens	Laboratory experiment	Sandeep et al. (2024), Sari et al. (2024), Sirohi et al. (2024), Wang et al. (2024), Xiao et al. (2024)
Promoting crop growth, monitoring moisture content in soil	Field experiment	Liang, Wong and Lisak (2023), Kayad et al. (2020)

The synthesis of the findings also indicated that quantum sensors were adopted to detect hazardous chemicals and harmful contaminants from water sources and food products. The inspection of these insights showed that the features of quantum sensors including chemical inertness and solubility ensured they could be adopted to promote the growth of crops and improve the detection of hazardous chemicals and contaminants from foods. The work by Arvand et al. (2016) indicated that GDQs were effective in detecting L-DOPA electrochemical in agricultural food products including seeds from pumpkins, sunflower, and sesame. The insights indicated that the high sensitivity of quantum sensors promoted their adoption in the detection of hazardous chemicals in agricultural foods. The work by Marukhyan et al. (2025) also showed how CdSe quantum dots were used in the detection of heavy metals within aqueous environments. The analysis of these findings showed that quantum sensors were beneficial based on the wide range of applications they could be put into when detecting hazardous chemicals including parathion and harmful analytes. Therefore, farmers could leverage the same quantum sensors to detect pollutants and hazards from water and food. However, the work by Bilmes et al. (2021) contradicted the arguments from Marukhyan et al. (2025) and Arvand et al. (2016) and showed that heavy metals were likely to inhibit enzyme activities for quantum sensors based on enzymes and contributed to changes in pH and QD fluorescence. The contradictions showed that quantum dot sensors were less effective in the detection of heavy metals when mixed with heavy metals. The findings implied that quantum sensors were effective in selected environments particularly when enzymes were integrated which could lead to pH changes. The insights also revealed an existing future research gap involving the examination of methods to ensure heavy metals did not affect the enzyme activities for quantum sensors based on enzymes. Despite such differences in the results, further work by Khoshnoud et al. (2020) and Khushaini et al. (2024) demonstrated that CdTe/ZnSe fluorescence-based quantum sensors were also more effective when detecting lead ions. The insights from the findings showed that the adoption of quantum sensors contributed to enhanced environmental impacts where they ensured minimal deposition of hazardous chemicals into water and soil. Additionally, the findings showed that CdTe/ZnSe sensors could be adopted in addition to graphene and carbon to develop the quantum sensors. The insights showcasing the effectiveness of CdTe/ZnSe fluorescence-based quantum sensors in the detection of hazardous chemicals and heavy metals were aligned with the previous work by Marciniak et al. (2022) where insights showed that quantum sensors were highly advanced technologies used for sensing which were applied in diverse fields to lower the negative impact of pollutants on the environment. Therefore, using the quantum sensors promoted environmental conservation by lowering the impact on soils and water bodies. The findings emphasizing the benefits of quantum sensors in the detection of hazardous chemicals corroborated previous work by Kantsepolsky et al. (2023) where insights indicated that quantum sensors performed better than traditional sensors when responding to environmental changes. As such, quantum sensors were appropriate in the rapid and accurate detection of harmful pollutants and heavy metals from water sources and soil as they contributed to enhanced environmental outcomes in water bodies where hazards were eliminated.

4.2. Comparison of classical and quantum sensors in agriculture

Further discussion also compared the quantum and classical sensors to identify their differences and similarities in their application. From the analysis of the different studies, a commonality observed in the classical and quantum sensors was the monitoring of soil properties which contributed to enhanced agricultural outcomes. Results revealed that quantum sensors were effective in monitoring the moisture content in active and passive soils where the conductance of the interdigitated electrodes (IDE) in white clay increased from 0.06×10^{-6} 1/Ω to 0.68×10^{-6} 1/Ω based on the increase in moisture levels from 4 to 45 % while the bentonite soil showed poorer results where the conductance of the IDE rose from 0.06×10^{-6} 1/Ω to 0.48×10^{-6} 1/Ω as a result of increasing the levels of moisture from 11 to 90 % (Kalita et al., 2016). Further work by Kayad et al. (2020) corroborated Kalita et al. (2016) and showed that quantum sensors were used to accurately measure soil moisture levels. The insights also showed that quantum sensors were effective in measuring soil fertility due to the sensitivity to nutrients, moisture, and pH levels where a model accuracy of 0.87 was reported (Mukhamedieva, 2024). The insights showed that farmers obtained highly accurate scores related to soil conditions including fertility and moisture and enhancing decisions regarding the integration of fertilizers to enhance soil nutrients. The findings showcasing the quantum sensor applications were reiterated in the traditional sensors where Dwarkani et al. (2015) reported that classical sensors were useful in measuring the content of moisture and temperature in soils during winter seasons. The evaluation of the applications indicated that although quantum sensors differed from classical sensors in their application mechanism, they were useful in monitoring the environmental conditions in soil including temperature, nutrients, and fertility. The results resonated with the work by Najdenko et al. (2024) which indicated that classical sensors were effective in the measurement of soil properties including nutrients, pH, and nitrates. The findings also corroborated the work by Xing and Wang (2024) which revealed that the spectral soil sensors were useful in the detection of pH and soil nutrients. The findings also aligned with the past work by Toselli et al. (2023) where findings showed that traditional sensors were useful in measuring the levels of nutrients within soils. The findings from the literature and the studies demonstrated the efficacy of classical and quantum sensors in monitoring the properties of soils including pH and nutrients. Subsequently, farmers were able to enhance soil fertility using classical and quantum sensors. Despite the applications, differences also emerged in that the quantum sensors were applied in soils as soluble nanoparticles while the classical sensors involved the combination of IoT instruments to detect changes in the soils using electrodes.

Further differences also emerged between the quantum and classical sensors such as their application areas and where each type was feasible. The work by Dong et al. (2024) reported that quantum sensors were effective in enhancing the growth of plants due to their higher solubility, ease of modification, and chemical inertness. The discussion also revealed that CDQs were appropriate in enhancing the growth of lentils when applied in small concentrations between 0.05 and 0.1 mg/ML (Agnol et al., 2021). The work by Liang, Wong, and Lisak (2023) and Hutzler (2020) also showed that CDQs could be used for nano-priming pea plants to enhance the growth of shoots and roots. The analysis of these findings indicated that quantum sensors were used directly in soils as small particles that dissolved in soils to enhance roots and shoots. The synthesis also indicated that quantum dot sensors could also be added in soils to enhance growth and germination rates. The findings concerning the effectiveness of quantum sensors in promoting the germination of seeds were aligned with the previous literature work by Matlali and Fischer (2023) where reports indicated that quantum sensors enhanced the growth and development of crops. Therefore, the quantum sensors could be leveraged to enhance the yields from farms. The analysis also showed that findings were aligned with the work by Parrish et al. (2021) which indicated that $CuInS_2/ZnS$ quantum dot (QD) films were effective in promoting the growth of lettuce plants. Further synthesis indicated the alignment of the findings with past literature where Shahzad et al. (2024) reported that quantum dot biochar (QDBC) promoted the rate of the growth of fenugreek plants including the root dry weight, shoot dry weight, and fresh weight. The insights also aligned with past literature where Alotaibi et al. (2024) revealed that Zn-quantum dot biochar (QDB) promoted the emergence of rapeseed seedlings and the height of the plants. The insights indicated that the literature aligned with the results and showed the efficacy of quantum sensors in promoting the growth of plants due to the soluble nature. However, the findings misaligned the past literature studies by Pawase et al. (2024) where insights showed that classical sensors were appropriate in promoting the yield of crops through the VRT solutions where nutrients were added into soils at a variable rate and time. The contradiction showed that quantum sensors were more accurate than classical sensors when they were applied at a specific rate using VRTs to enhance crop growth.

The analysis of the findings also indicated that quantum sensors were important in detecting hazardous materials and pollutants from water and food products. The findings also revealed the efficacy of GDQs in detecting L-DOPA electrochemicals from sunflower, sesame, and pumpkin seeds in the range 3.0 to 400 μmol L^{-1}, with a detection limit of 14.3 nmol L^{-1} (Arvand et al., 2016). Further inferences showed that CdSe quantum dot sensors were effectively adopted to detect heavy metals from water sources with a detection limit of 0.2 μM (Marukhyan et al., 2025). The work by Khoshnoud et al. (2020) and Khushaini et al. (2024) further indicated the efficacy of fluorescence-based quantum sensor of CdTe/ZnSe in the detection of Pb ions from tap and river water. As such, quantum sensors were soluble and could be used to detect pollutants, pesticides, and heavy metals from water sources and food products. The insights from these findings indicated that quantum sensors were effective in the detection of diverse pollutants and hazardous chemicals including parathion, Pb, and L-DOPA. The direct implication was that farmers could apply the quantum sensors to enhance environmental safety within agriculture. The insights highlighting the detection of pollutants by quantum sensors aligned with the work by Raparthi (2022), which showed that quantum sensors led to high sensitivity and accuracy that was not reported in classical sensors. The results were also aligned with the previous literature work by Kantsepolsky et al. (2023) which showed that quantum sensors were more sensitive and accurate than classical sensors. The insights indicated that quantum sensors were adopted due to their sensitive environmental changes that enabled farmers to detect pollutants and heavy metals from water bodies. Subsequently, quantum sensors enhanced safety in farms and mitigated the negative outcomes arising from the consumption of pollutants including crop and animal diseases. However, the findings misaligned the work by El-Sharkawy et al. (2016) which showed that classical sensors detected changes in the environment using IoT-based electronic components that sent the data to servers for further assessment to ensure accurate farming decisions. The comparison of the classical and quantum sensors is showcased in Table 6.

In Table 6, the comparison of quantum and classical sensors is showcased, where aspects such as costs, precision, operations, and applications are examined.

4.3. Future directions of quantum sensors in agriculture

Based on the synthesis of the selected studies elaborating on the applications of quantum and classical sensors, various potential future directions were identified. First, there is a need for scholars to investigate how quantum sensors are adopted in large-scale agricultural applications. The limitation observed from the assessed studies was that they focused on small experimental setups and demonstrated the efficacy of the quantum sensors in enhancing the growth of crops based on the chemical inertness, high solubility, and ease of modification (Hutzler, 2020; Agnol et al., 2021; Dong et al., 2024; Liang, Wong and Lisak, 2023). The work by Liang, Wong, and Lisak (2023) adopted a

Table 6
Comparison of quantum and classical sensors.

Aspect	Quantum Sensors	Classical Sensors
Cost	More expensive to apply in agricultural operations	Cheaper to apply in agricultural operations
Operations	More complex to operate and requires specialized knowledge	Less complicated and can be integrated with data management systems
Precision	Highly accurate in detecting small changes in agricultural systems	Less accurate compared to quantum sensors
Types	Quantum optics, quantum magnetometers, atomic clocks	Soil sensors, weather sensors, optical sensors
Applications	It can be adopted in applications such as enhancing crop germination, seedling development, detecting hazardous chemicals in water and food	Adopted to measure changes in environmental conditions, including weather and soil

small experimental setup to assess seed priming using quantum carbon dots in small-scale concentrations to enhance the rates of germination and contribute to the growth of the shoots and roots.

Further inferences showed that small-scale experiments were used to detect hazardous pollutants from foods (Arvand et al., 2016; Raparthi, 2022), pollutants and heavy metals from water sources (Facure et al., 2020; Liu et al., 2020), and the assessment of soil properties including humidity, temperature, and fertility (Kalita et al., 2016; Kayad et al., 2020; Mukhamedieva, 2024). The analysis of the small-scale setups indicated that quantum sensors were appropriate in agricultural processes as they detected harmful chemicals and pollutants, measured soil moisture, and promoted the growth of shoots and roots. These small-scale setups imply that challenges are anticipated in extrapolating the applications from the small-scale to the real world due to variability in environmental conditions and cost-benefit trade-offs. A case example involves using quantum sensors to detect pollutants and heavy metals in large water bodies, which can lead to high costs and challenges due to the variability in environmental conditions. Knight, Khouakhi and Waine (2024) have shown that anticyclonic weather patterns during sowing, emergence, anthesis, grain-filling, and vernalization demonstrated a relationship with good crop yields where a Spearman correlation coefficient of 0.55 for a single weather pattern were reported. Additionally, cyclonic weather patterns were essential in improving yields during the terminal spikelet phenological phases. Zou et al. (2024) also identified that an increase in day-to-day temperature variability by one unit led to a 2 % decline in total factor productivity, indicating that agricultural productivity was sensitive to variations in temperature variability. Similar arguments were also advanced in studies, such as Kantsepolsky et al. (2023), which revealed that difficulties were faced in scaling quantum systems for real-world applications. Furthermore, to advance the research, there is a need for scholars to investigate whether the advantages of quantum sensors can be obtained when they are applied in large-scale agricultural setups to ensure they can replace the classical sensors and guarantee higher productivity and efficiency in agricultural applications. To support such claims, a cost-accuracy trade-off model is introduced to emphasize the economic potential of quantum sensors whereby:

U = represents net utility of adopting quantum sensors.
B = represents the benefits of quantum sensors such as higher precision, stability, and robustness to environmental conditions.
C = costs incurred in achieving quantum precision.
The cost-accuracy trade-off assumes that $U > 0$ and arises due to the relation:
$U = B - C$

Empirical work by Oh et al. (2024) demonstrates that adopting quantum sensors that outperform classical sensors in terms of stability, robustness to environmental effects, accuracy, and improved precision can outweigh the investment costs incurred in implementing the technology. As such, the trade-off arises where farmers can leverage the benefits of improved accuracy and robustness to environmental effects after investing in quantum sensors.

The assessment of the findings also showed that quantum sensors could be prepared using multiple complex processes that were highly expensive. The adopted processes involved pyrolysis and the hydrothermal synthesis of PET plastics when generating carbon quantum dot sensors (Liang, Wong, and Lisak, 2023) and citric acid pyrolysis used in the generation of graphene quantum dots adopted in the detection of electrochemical pollutants from pumpkin seeds, sesame, and sunflower (Arvand et al., 2016), and graphene quantum dots developed into nanofibers and films (Facure et al., 2020). The complex production processes of the quantum dot sensors limited their scalability in different scenarios. Therefore, in future work, there is a need to investigate the approaches that can be used to lower the scaling costs of quantum sensor measurements in agricultural applications.

The inferences from the discussion of the findings also indicated that traditional sensors were combined with advanced technologies including artificial intelligence and big data to promote the productivity and efficiency of agricultural processes. The work by Aierken et al. (2024) reported that UAV images were integrated into machine-learning algorithms to monitor the growth and production of cotton. The existing gap based on the analysis of these studies is that minimal studies have examined how artificial intelligence can be combined with quantum sensors to enhance accuracy in precision agriculture. As such, future work should focus on examining how quantum sensors can be used with emerging artificial intelligence technologies to promote agricultural processes such as eliminating pollution in the environment and promoting the growth of roots and shoots.

Furthermore, there is a need for researchers to also investigate the application of quantum sensors in combination with quantum computers, quantum AI, and quantum communications to transfer, process, and evaluate big data generated by quantum sensors and enhance precision agricultural applications. Future work should also explore the integration of quantum sensors with new material advancements, including nanostructures and superconducting technology, to lower sensor costs in agricultural applications. Additionally, potential breakthroughs should be explored by integrating quantum sensors with IoT systems to facilitate real-time data processing and enhance usability in agricultural applications. As a result, quantum sensors will enhance the productivity of agricultural processes and promote the sustainability of food production.

5. Conclusion

The research question advanced in this review article examined the potential applications of quantum sensors in precision agriculture. The analysis of the different studies showed that quantum sensors were different from traditional sensors based on different factors, such as how they were applied in agriculture. The first objective of the review article was addressed as the insights indicated that quantum sensors were applied in precision agriculture through integration into soils to enhance seedling emergence and crop growth. Furthermore, fluorescence-based quantum sensors were integrated into agricultural foods to enhance the detection of hazardous chemicals. The insights also demonstrated that quantum sensors in the form of films and nanofibers were adopted as absorbent materials and filtration membranes to eliminate contaminants from water bodies. Therefore, quantum sensors differed from the classical sensors that required further integration with data systems to sense and relay signals to servers where data was evaluated, and important farming decisions were made. As such, the classical sensors are considered IoT devices that detect environmental changes and communicate them to data hubs and servers. The implication was that quantum sensors demonstrated higher responsiveness to changes in the environment compared to classical sensors and required more interactions with data management systems to ensure decisions were made. The second objective in the review article was addressed, where quantum sensors were more accurate and responsive than traditional sensors in precise agriculture applications.

The diverse benefits of quantum sensors over traditional sensors were also reported in the review article. The analysis showed that quantum sensors could be adopted at a nano-scale, such as carbon and graphene quantum dots, to measure changes in soil properties and enhance the levels of nutrients to promote the growth of seeds. As a result, farmers adopted the sensors to alleviate plant stress and add antioxidants. Additionally, as nanofibers, the quantum sensors could be used to detect pollutants in water bodies and food products to eliminate contaminants. A further advantage was the availability of quantum sensor-based measurement instruments that were adopted to assess PAR levels and soil fertility. As such, different forms of quantum sensors were commercially available to help increase the efficiency and productivity of agriculture.

The research implies that quantum sensors are increasingly being showcased as more effective than classical sensors in different fields, including agriculture, where they facilitate the growth of crops, facilitate the detection of hazardous chemicals from water sources and foods, and enable farmers to monitor soil properties. However, diverse challenges have also been reported that hinder the adoption of quantum sensors, including expensive production processes and limitations to small-scale setups. As such, further work is required to ensure the limitations can be addressed and farmers can adopt the quantum sensors in large-scale operations. The third objective was addressed as future directions on the research topic were also outlined regarding the applications of quantum sensors and their integration with advanced and emerging technologies.

The recommendations from this research advocate for the continued adoption of quantum sensors within agricultural operations based on their higher sensitivity to changes in environmental conditions. As a result, more accurate decisions can be made in agricultural processes, such as improving the yields of crops and eliminating pollutants and hazardous chemicals from water bodies and food products. A further recommendation is that quantum sensors should also be combined with emerging technologies such as machine learning and artificial intelligence algorithms to enhance different agricultural processes and operations. The limitations in the current review article arose from the few studies that focused on quantum measurement instruments and their integration with advanced AI technologies.

CRediT authorship contribution statement

C. Maraveas: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation. **K.G. Arvanitis:** Conceptualization. **T. Bartzanas:** Writing – review & editing, Supervision. **D. Loukatos:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. . Quality assessment

SANRA checklist.

SANRA Checklist
Q1: The importance of article is justified to readers – The importance is explicitly justified
Q2: Research aim and questions are clearly outlined – One or more concrete aims or questions are formulated.
Q3: Literature review is presented – The literature search is described in detail, including search terms and inclusion criteria.
Q4: References – Key statements are supported by references.
Q5: Scientific reasoning – Appropriate evidence is generally present.
Q6: Appropriate data presentation – Accurate data outcome are appropriately presented.
Scores: ✓ is 2 points; * is 1 point, x is 0 points;

Critical Appaisal using SANRA Checklist.

No.	Authors and Year	Q1	Q2	Q3	Q4	Q5	Q6	Total (x/12)
	Abbasi et al. (2014)	✓	✓	✓	✓	✓	✓	12
	Agnol et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Akitsu et al. (2017)	✓	✓	✓	✓	✓	✓	12
	Albiero et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Arvand et al. (2016)	✓	✓	✓	✓	✓	✓	12
	Benavides-Mendoza et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Berger et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Bilmes et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Boddice et al. (2017)	✓	✓	✓	✓	✓	✓	12
	Bonato et al. (2016)	✓	✓	*	✓	✓	✓	11
	Bongs et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Bongs et al. (2019)	✓	✓	✓	✓	✓	✓	12
	Carney et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Caya et al. (2018)	✓	✓	✓	✓	✓	✓	12
	de la Concepción et al. (2015)	✓	✓	✓	✓	✓	✓	12
	Degen et al. (2017)	✓	✓	✓	✓	✓	✓	12
	Dong et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Du et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Dwarkani et al. (2015)	✓	✓	✓	✓	✓	✓	12
	El Morsalani (2024)	✓	✓	✓	✓	✓	✓	12

(continued on next page)

(*continued*)

No.	Authors and Year	Q1	Q2	Q3	Q4	Q5	Q6	Total (x/12)
	Facure et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Fang et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Farahmandzadeh et al. (2025)	✓	✓	✓	✓	✓	✓	12
	Foy et al. (2020)	✓	✓	✓	✓	✓	✓	12
	García de Arquer et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Gsangaya et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Gupta et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Hamlin and Zhou (2019)	✓	✓	✓	✓	✓	✓	12
	Hegemann et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Helguera et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Ho et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Hutzler (2020)	✓	✓	✓	✓	✓	✓	12
	Jin et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Kalita et al. (2016)	✓	✓	✓	✓	✓	✓	12
	Kantsepolsky et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Kayad et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Khan et al. (2024a)	✓	✓	✓	✓	✓	✓	12
	Khanal et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Khoshnoud et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Khushaini et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Kim et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Kumar and Sharma (2020)	✓	✓	✓	✓	✓	✓	12
	Kumar and Reddy (2020)	✓	✓	*	✓	✓	*	10
	Kumar et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Kutas et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Lau and Clerk (2018)	✓	✓	✓	✓	✓	✓	12
	Le et al. (2017)	✓	✓	✓	✓	✓	✓	12
	Li et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Liang, Wong and Lisak (2023)	✓	✓	✓	✓	✓	✓	12
	Liao et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Liu et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Liu et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Lyu et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Ma et al. (2024)	✓	✓	✓	✓	✓	*	11
	Maraveas et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Marciniak et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Martos et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Marukhyan et al. (2025)	✓	✓	*	✓	✓	✓	11
	Mehedi et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Memon et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Mirhosseini et al. (2017)	✓	✓	✓	✓	✓	✓	12
	Morchid et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Munawar and Surendro (2024)	✓	✓	✓	✓	✓	✓	12
	Mukhamedieva (2024)	✓	✓	✓	✓	✓	✓	12
	Nikolidakis et al. (2015)	✓	✓	✓	✓	✓	✓	12
	Nsibande and Forbes (2016)	✓	✓	✓	✓	✓	✓	12
	Oh et al. (2024)	✓	✓	x	✓	✓	✓	10
	Ojha et al. (2015)	✓	✓	✓	✓	✓	✓	12
	Omia et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Onojeghuo et al. (2018)	✓	✓	✓	✓	✓	✓	12
	Paul et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Pievanelli et al. (2016)	✓	✓	✓	✓	✓	✓	12
	Pyingkodi et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Rademacher et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Rahu et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Rajak et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Rajasekaran and Anandamurugan (2019)	✓	✓	✓	✓	✓	✓	12
	Raparthi (2022)	✓	✓	✓	✓	✓	✓	12
	Ravi et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Rivero-Angeles (2021)	✓	✓	✓	✓	✓	✓	12
	Rosell-Polo et al. (2015)	✓	✓	✓	✓	✓	✓	12
	Sandeep et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Sari et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Schmitt et al. (2017)	✓	✓	✓	✓	✓	✓	12
	Schuff et al. (2020)	✓	✓	✓	✓	*	*	10
	Singh and Singh (2020)	✓	✓	✓	✓	✓	✓	12
	Singh et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Singh and Khan (2023)	✓	✓	✓	✓	✓	✓	12
	Sirohi et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Sishodia et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Sotoodehfar et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Soussi et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Strangfeld et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Stray et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Sun et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Szigeti et al. (2021)	✓	✓	✓	✓	✓	✓	12

(*continued on next page*)

(continued)

No.	Authors and Year	Q1	Q2	Q3	Q4	Q5	Q6	Total (x/12)
	Tahmasbi and Bloch (2021)	✓	✓	✓	✓	✓	✓	12
	Tan et al. (2023)	✓	✓	✓	✓	✓	✓	12
	Tan et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Thakur et al. (2019)	✓	✓	✓	✓	✓	✓	12
	Tian et al. (2023)							
	Tong et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Tsukamoto et al. (2022)	✓	✓	*	✓	✓	✓	11
	Turkanović and Hölbl (2014)	✓	✓	✓	✓	✓	✓	12
	Udekwe and Seyyedhasani (2024)	✓	✓	✓	✓	✓	✓	12
	Ullo and Sinha (2021)	✓	✓	✓	✓	✓	✓	12
	Wang et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Webb et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Weiss et al. (2020)	✓	✓	✓	✓	✓	✓	12
	Wu and Weil (2022)	✓	✓	✓	✓	✓	✓	12
	Xiao et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Xie et al. (2022)	✓	✓	✓	✓	✓	✓	12
	Yan et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Yang et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Yashwanth et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Yu et al. (2021)	✓	✓	✓	✓	✓	✓	12
	Yu et al. (2024)	✓	✓	✓	✓	✓	✓	12
	Zaiser et al. (2016)	✓	✓	✓	✓	✓	✓	12
	Zhang et al., 2023	✓	✓	✓	✓	✓	✓	12
	Zhou et al. (2018)	✓	✓	✓	✓	✓	✓	12

Appendix 2. . Literature Matrix

No.	Article	Focus	Method	Main Findings	Relevance
	Abbasi et al. (2014)	Sensors in agriculture	Review article	Wireless sensors were widely adopted in agriculture to support sensor-based agriculture in precision farming. However, challenges such as limited computing power, small memory, and data security were identified	The review article reveals the significance of wireless sensors in agriculture
	Agnol et al. (2021)	Quantum sensors in agriculture	Experiment	CQDs were employed to enhance plant production and growth where thermal lysis of micro-algae, *Spirulina sp* is performed to promote lentil growth	The study showcased the application of CDQ sensors
	Akitsu et al. (2017)	Quantum sensors in agriculture	Experiment	Quantum sensor instruments to evaluate photosynthetically active radiation (PAR) observation sites and assess plant photosynthesis	The study showcased the application of quantum sensors in measuring PAR
	Albiero et al. (2022)	Sensors in agriculture	Review Article	The findings reveal that swarm robots could be used in mechanized agricultural applications, demonstrating the increase in the field capacity of the machines	The article examines the applicability of swarm robots in mechanized agriculture. However, challenges such as high operational costs, increased emissions, and high acquisition costs were reported.
	Arvand et al. (2016)	Quantum Sensors in Agriculture	Experimental study	The findings showed that the modified electrode demonstrated good sensitivity and selectivity with low overpotential for determining L-DOPA in the range 3.0 to 400 μmol L^{-1} with a detection limit of 14 nmol L^{-1}.	The study demonstrated the effectiveness of a nanocomposite comprised of graphene quantum dots, magnetic nano particles, and carboxylated multi-walled carbon nanotubes for glassy carbon electrode surface modification
	Benavides-Mendoza et al. (2023)	Quantum Sensors in Agriculture	Critical book chapter	The review showed that quantum nanomaterials were increasingly adopted in agriculture to develop agrochemicals and nano sensors	The review described the applications of quantum nanomaterials for the development of quantum nano sensors used in agriculture
	Berger et al. (2021)	Quantum Sensors in Agriculture	Review article	The review revealed the use of quantum sensors as a high-impact use case to mitigate climate change in agriculture	The review identified the applications of quantum sensors in high-impact use-cases in quantum technologies
	Bilmes et al. (2021)	Quantum Sensors in Agriculture	Experimental method	The results showed that there was strong evidence of strong interaction between coherent Two-Level-System (TLS) in the sample material.	The research showed that quantum sensors could be adopted to investigate the structure of microscopic tunneling systems
	Boddice et al. (2017)	Key Concepts of Quantum Sensors	Simulation experiment	The results showed that quantum technology sensors offered an advancement in locating features that lay outside detectable ranges in terms of depth and size.	The research showed the potential of quantum sensors in the location of subsurface features
	Bonato et al. (2016)	Key Concepts of Quantum Sensors	Experimental study	The results showed that adaptive protocols offered distinctive advantages over non-adaptive protocols when accounting for overheads and limited estimation time.	The study demonstrated solid-state sensors for which real-time knowledge of the measurement history was exploited to obtain optimal performance
	Bongs et al. (2023)	Key Concepts of Quantum Sensors	Critical Review	The results showed that quantum sensors exploited the properties of light and atoms to make measurements. The sensors were integrated	The research indicated the basic concepts related to quantum sensors and the use of photonic microchips.

(continued on next page)

(*continued*)

No.	Article	Focus	Method	Main Findings	Relevance
				in photonic microchips to use light rather than electrons.	
	Bongs et al. (2019)	Key Concepts of Quantum Sensors	Critical Review	The insights showed that atom interferometers were being adopted in real-world applications as ultraprecise quantum sensors in space, civil engineering, and navigation.	The research discussed the concept of atom interferometry in quantum sensors and their real-world applications
	Carney et al. (2021)	Key concepts of quantum sensors	Critical review	Showed that quantum sensors were adopted in diverse areas including astrophysical observations	Demonstrated key features of quantum sensors
	Caya et al. (2018)	Quantum Sensors in Agriculture	Experiment	The Apogee SQ-520 quantum sensor generated comparable results to the VTB8440BH sensor in measuring PAR levels in an agricultural application	The study highlighted the benefits of quantum sensors in measuring PAR
	de la Concepción et al. (2015)	Classical sensors in agriculture	Experiment	Using wireless sensor networks characterizes the micro-climatic behaviors of agricultural fields, where sensors are equipped with specific units to gauge varying physical parameters	The study showcased the benefits of classical sensors in agriculture
	Degen et al. (2017)	Key concepts of Quantum Sensors	Critical review	Quantum sensors examples include magnetometers based on superconducting quantum interference devices	The study described key concepts of quantum sensors.
	Dong et al. (2024)	Quantum sensors in agriculture	Experiment	Carbon quantum dots (CQDs) were used as sensors and plant growth promoters to improve crop tolerance and bio-imaging applications	The study showed how quantum sensors improved plant growth
	Du et al. (2024)	Quantum sensors in agriculture	Experiment	Demonstrated the effectiveness of the $CsPbBr_3$ and $CsPb(Br/I)_3$ perovskite quantum dots molecularly imprinted polymer sensor in detecting methyl eugenol and aristolochic acid	Showed the effectiveness of a quantum sensor in detecting hazardous chemicals
	Dwarkani et al. (2015)	Classical sensors in agriculture	Experiment	Showed a smart sensor-based system to measure soil moisture, nutrient contents, and pH	The study showed how classical sensors could be adopted to measure soil properties.
	El Morsalani (2024)	Key concepts of Quantum Sensors	Critical review	Demonstrated different quantum sensing methods including neutral atoms, trapped ions, and nitrogen vacancy centers	The study described the key concepts of quantum sensors and sensing methods
	Facure et al. (2020)	Quantum sensors in agriculture	Critical review	Showed that graphene quantum dot sensors were applicable in diverse environmental and agricultural applications to detect contaminants	The study showed that quantum sensors were adopted in agricultural applications
	Fang et al. (2024)	Key concepts of Quantum Sensors	Critical review	Demonstrates how optically addressable spin defects could be combined with 2D vdW materials while identifying the challenges of the defects	Highlighted the key concepts of quantum sensors and their combination with vdW materials
	Farahmandzadeh et al. (2025)	Comparison of Classical and Quantum Sensors in Agriculture	Experiment	The presence of Pb ions was detected in tap and river water by using fluorescence-based quantum dot CdTe/ZnSe sensor	The study described the benefits of quantum sensors in eliminating harmful pollutants.
	Foy et al. (2020)	Key Concepts Quantum Sensors	Experiment	Showed that exceptional temperature and magnetic field sensitivity of nitrogen vacancy spins were effective in generating wide-field magnetic fields and temperature at the device level.	The study showed how high sensitivity of quantum sensor measurement could be achieved.
	García de Arquer et al. (2021)	Key Concepts Quantum Sensors	Critical review	Reviewed the recent advancements in the synthesis and functionality of quantum dots	Showed key concepts related to quantum dot production.
	Gsangaya et al. (2020)	Classical Sensors in agriculture	Experiment	sensors are effectively used in precision agriculture to support profitable farming.	The study examined the applications of classical sensors in agriculture
	Gupta et al. (2022)	Key Concepts Quantum Sensors	Critical review	Revealed that quantum sensors were classified into different groups and surface modifications led to different applications.	The study described the key features of quantum dot sensors
	Hamlin and Zhou (2019)	Key Concepts Quantum Sensors	Critical review	Showed that quantum sensors were synthesized at extreme temperature and nitrogen vacancies offered important tools for probing matter	The study described the key features of quantum dot sensors
	Hegemann et al. (2022)	Quantum Sensors in Agriculture	Experiment	Quantum sensors were effective in the precise determination of the photosynthetic photon flux density (PPFD) in modern agricultural horticultural system	The study showed the benefits of quantum sensors in agriculture
	Helguera et al. (2022)	Quantum Sensors in Agriculture	Experiment	Showed that quantum sensors were effective in quantifying light interception and leaf area index	The study identified how quantum sensors were used in measuring light interception for wheat crops
	Ho et al. (2022)	Key concepts of Quantum Sensors	Critical review	The nitrogen vacancy (NV) centre in diamond was used in quantum sensors to detect various physical parameters like temperature, magnetic fields, force, and electric fields a high precision and resolution	The study showcased the benefits of quantum sensors in agriculture
	Hutzler (2020)	Key concepts of Quantum Sensors	Critical review	Demonstrated how laser cooled polyatomic molecules could be adopted for precision measurements	Illustrated concepts of laser-cooled quantum sensors
	Jin et al. (2020)	Key concepts of Quantum Sensors	Critical review	Demonstrated methods to enhance the performance of graphene-based sensor actuators	Showed key concepts of quantum sensors

(*continued on next page*)

(*continued*)

No.	Article	Focus	Method	Main Findings	Relevance
				and soft robotics based on sensitivity and selectivity	
	Kalita et al. (2016)	Quantum sensors in agriculture	Experiment	GQD sensor could be adopted to detect the moisture levels in different types of soils including white and bentonite clays which were passive and active soils	The study showcased the benefits of GQD sensors in moisture detection
	Kantsepolsky et al. (2023)	Key concepts of Quantum Sensors	Critical review	quantum sensors were more sensitive and accurate than classical sensors	
	Kayad et al. (2020)	Classical Sensors in Agriculture	Experiment	smart sensors were used to promote profitability in agriculture by monitoring the moisture content of the soil, temperature in winter wheat and tree health	The study highlighted the applications of classical sensors in agriculture
	Khan et al. (2024a)	Comparison of Classical and Quantum Sensors in Agriculture	Critical review	smart sensors in agriculture were challenged by limited resources leading to issues when dealing with repetitive operations.	The study showcased the limitations of classical sensors
	Khanal et al. (2020)	Classical Sensors in Agriculture	Critical review	Showed how classical sensors were adopted to measure soil moisture, monitor crop health, and crop grain quality	Demonstrated applications of classical sensors in agriculture
	Khoshnoud et al. (2020)	Key concepts of Quantum Sensors	Critical review	Demonstrated key features of quantum sensors including their synthesis and applications in polarization	Showed the core concepts of quantum sensor synthesis
	Khushaini et al. (2024)	Key concepts of Quantum Sensors	Critical review	Elaborated on the fundamental basics of quantum sensors including their synthesis	Demonstrated the efficacy of quantum sensing technologies
	Kim et al. (2021)	Key concepts of Quantum Sensors	Critical review	Reported on the basics of quantum sensors and their applications in different fields.	Demonstrated the importance of quantum sensing technologies
	Kumar and Sharma (2020)	Classical Sensors in Agriculture	Experiment	smart wireless sensor networks are essential in agriculture applications, such measuring soil quality, precision agriculture, and irrigation control	The study highlighted the benefits of classical sensors in agriculture
	Kumar and Reddy (2020)	Classical sensors in agriculture	Critical review	Reported on the applications of wireless sensor networks in agricultural monitoring applications	Showed the benefits and challenges of classical sensors
	Kumar et al. (2021)	Classical sensors in agriculture	Critical review	Demonstrated how classical sensors were adopted in monitoring soil health and the growth of crops	Revealed the applications of classical sensors in agriculture
	Kutas et al. (2022)	Key concepts of Quantum Sensors	Critical review	Showed that quantum sensors could be synthesized using light at different frequencies.	Demonstrated the effectiveness of synthesizing quantum sensors using light
	Lau and Clerk (2018)	Key concepts of Quantum Sensors	Critical review	Demonstrated the limits and non-reciprocal approaches of non-Hermitian quantum sensing	Reported on the limitations of non-Hermitian quantum sensing
	Le et al. (2017)	Quantum sensors in agriculture	Experiment	Demonstrated how a fluorescent immune-chromatographic strip test (ICST) using CQDs for 1-amino-hydanton (AHD) could detect metabolites in animal tissues	The study showed how quantum sensors were adopted in detecting pollutants in animal tissues.
	Li et al. (2022)	Classical Sensors in Agriculture	Critical Review	Demonstrated how classical sensors could be integrated in machine-vision-based weeding robots	Reported on how sensors were adopted to enhance farming efficiency
	Liang, Wong and Lisak (2023)	Quantum Sensors in Agriculture	Experiment	CQDs manufactured from plastic wastes were used for plant development via seed nano-priming of pea plant at various phases	The study showed that quantum sensors were adopted to improve plant growth.
	Liao et al. (2024)	Key concepts of Quantum Sensors	Critical review	Reported on the potential of quantum sensors in addressing problems faced by classical sensors	Demonstrated the benefits of quantum sensors over classical sensors
	Liu et al. (2020)	Quantum sensors in agriculture	Experiment	a quantum dot sub-microbeads-based immune-chromatographic assay (QB-ICA) was applied in detecting parathion in agricultural products	The study showed how quantum sensors could be adopted in agriculture
	Lyu et al. (2022)	Key concepts of Quantum Sensors	Experiment	Reported that boron vacancy centers were effective in sensing strain under working conditions	Showed that vacancy centers were adopted in quantum sensing
	Ma et al. (2024)	Classical Sensors in Agriculture	Experiment	Demonstrated how classical sensors in robot systems could be adopted to automate the inspection of dead poultry and promote hygiene in large scale farms	Showed the effectiveness of classical sensors in agricultural operations.
	Maraveas et al. (2024)	Quantum Sensors in Agriculture	Critical review	Reported on the applications of quantum sensing to predict crop disease and improve agricultural productivity	Demonstrated that quantum sensors were effective in enhancing agricultural productivity
	Marciniak et al. (2022)	Key concepts of Quantum Sensors	Critical review	quantum sensors are currently considered the most mature and advanced technologies in sensing, and are applied in various fields	The study described the widespread adoption of quantum sensors
	Martos et al. (2021)	Classical Sensors in agriculture	Critical review	Wireless sensors in agriculture are effective in remote monitoring of crop health and production	Showed how classical sensors were adopted in remote sensing applications
	Marukhyan et al. (2024)	Quantum Sensors in agriculture	Experiment	CdSe quantum dots could detect metals within aqueous environments	The study showed the applications of quantum sensors in detecting pollutants in water
	Mehedi et al. (2024)	Classical Sensors in agriculture	Critical review	Demonstrated the limitations of classical sensors in crop monitoring and yield forecasting	Showed how classical sensors were adopted to enhance farming efficiency

(*continued on next page*)

(*continued*)

No.	Article	Focus	Method	Main Findings	Relevance
	Memon et al. (2024)	Key concepts of Quantum Sensors	Experiment	Demonstrated the properties of a CdSe/CdS/ZnS core–shell quantum dot/TiO sensor used for detecting cardiac troponin-I (cTnI) biomarkers.	Showed the various properties of quantum dot sensors.
	Mirhosseini et al. (2017)	Key concepts of Quantum Sensors	Experiment	Showed that a wireless sensor network designed based on quantum sensors had the highest performance and fulfilled the requirements of the network.	Illustrated the properties of wireless sensor networks based on quantum sensing.
	Morchid et al. (2024)	Classical Sensors in agriculture	Critical review	Showed that classical sensors were applicable in boosting agricultural sustainability and food security through detecting crop diseases, improving fertilizer application, and monitoring climatic conditions.	Revealed the effectiveness of classical sensors in agriculture.
	Munawar and Surendro (2024)	Quantum Sensors in agriculture	Critical review	Reported that quantum sensors were applicable in reducing greenhouse gas emissions and promoting carbon neutrality	Showed the benefits of quantum sensing in lowering carbon emissions.
	Mukhamedieva (2024)	Quantum sensors in agriculture	Experiment	Quantum sensors were adopted to measure soil fertility by assessing the physical and chemical properties of soil	The study showed how quantum sensors were adopted to measure soil fertility.
	Nikolidakis et al. (2015)	Classical Sensors in agriculture	Experiment	Demonstrated that classical sensors were adopted to automate water management in cultivated fields.	The study elaborated on the benefits of classical sensors in automated irrigation.
	Nsibande and Forbes (2016)	Quantum Sensors in Agriculture	Experiment	fluorescence-based quantum sensors were allowing farmers to detect hazardous pollutants from foods such as vegetables and fruits	The study showed how quantum sensors were adopted to detect pollutants from foods
	Oh et al. (2024)	Key Concepts of Quantum Sensors	Critical Review	Reported that the quantum sensors were adopted in measurement tools such as gravitational sensors, gravitometers, and accelerometers.	Revealed that quantum sensors were more effective than classical sensors due to higher sensitivity.
	Ojha et al. (2015)	Classical sensors in agriculture	Critical review	Demonstrated that classical sensors were effective in different farming operations and improved productivity.	Showed the effectiveness of classical sensors in promoting agricultural productivity.
	Omia et al. (2023)	Classical Sensors in agriculture	Critical review	Reported that the classical sensors were effective in crop monitoring and improving decision-making.	Demonstrated the importance of classical sensors in enhancing the efficiency of agricultural production.
	Onojeghuo et al. (2018)	Classical Sensors in Agriculture	Experiment	Reported that hyper-sensing in Chinese agriculture led to numerous benefits including maximizing yields, mapping crops, and specifying requirements of fertilizers.	Reported that classical sensors were useful in promoting farming efficiency.
	Paul et al. (2022)	Classical Sensors in agriculture	Critical review	Revealed that classical sensors enhanced agricultural production.	Reported the benefits of classical sensors in promoting agricultural productivity.
	Pievanelli et al. (2016)	Classical Sensors in agriculture	Experiment	Showed how classical wireless sensors detected microwave-based leaf wetness.	Revealed the benefits of classical sensors in agriculture.
	Pyingkodi et al. (2022)	Classical Sensors in Agriculture	Critical review	Demonstrated applications of IoT sensors in precision agriculture	Reported the benefits of classical sensors in precision agriculture.
	Rademacher et al. (2020)	Key concepts of Quantum Sensors	Critical review	Reported that quantum sensing technologies were adopted in gravimetry instruments.	Showed the emerging quantum sensing technology and its commercial applications.
	Rahu et al. (2022)	Classical Sensors in Agriculture	Experiment	Demonstrated the efficacy of wireless sensor networks in promoting the quality and efficiency of wheat production	Elaborated on the applications of wireless sensors in promoting agricultural productivity.
	Rajak et al. (2023)	Classical Sensors in Agriculture	Critical review	Reported that classical sensors were adopted to measure conditions such as humidity, temperature, and soil composition.	Revealed the significance of classical sensors in smart farming.
	Rajasekaran and Anandamurugan (2019)	Classical Sensors in Agriculture	Critical review	Revealed that classical sensors were adopted to promote environmental monitoring and precision farming.	Showed that classical sensors were effective in enhancing precision agriculture operations.
	Raparthi (2022)	Key concepts of Quantum Sensors	Critical review	quantum sensors were associated with a high level of sensitivity and accuracy not available in classical sensors	The study illustrated the applications of quantum sensors
	Ravi et al. (2023)	Key Concepts of Quantum Sensors	Critical review	Demonstrated how graphene quantum dot sensors were adopted in diverse commercial applications	Revealed the benefits of quantum sensors over classical sensors
	Rivero-Angeles (2021)	Key Concepts of Quantum Sensors	Critical review	Revealed how quantum sensors were adopted in monitoring networks.	Showcased the importance of quantum sensors in wireless communications.
	Rosell-Polo et al. (2015)	Classical Sensors in Agriculture	Critical review	Reported the benefits of classical sensors in enhancing precision agriculture and improving decision-making	Showed that classical sensors were effective in improving farming efficiency.
	Sandeep et al. (2024)	Quantum Sensors in Agriculture	Experiment	Showed that fluorescent carbon dot quantum sensors were important in improving the growth of seedlings through nano-priming.	Reported the benefits of quantum sensing in promoting crop growth.
	Sari et al. (2024)	Quantum Sensors in Agriculture	Experiment	Showed that the BB84 quantum sensor was effective in improving the security of aeroponic smart farming.	Revealed the applications of quantum sensors in promoting crop growth.
	Schmitt et al. (2017)	Key Concepts of Quantum Sensors	Critical Review	Reported that quantum sensors were effective in detecting tiny variations in magnetic field.	Showed that quantum sensors were adopted for sensing magnetic fields.

(*continued on next page*)

(*continued*)

No.	Article	Focus	Method	Main Findings	Relevance
	Schuff et al. (2020)	Key Concepts of Quantum Sensors	Critical Review	Demonstrated that quantum sensors could be enhanced using reinforcement learning.	Revealed the properties of quantum sensors.
	Singh and Singh (2020)	Classical Sensors in Agriculture	Critical Review	Reported the limitations of classical sensors in agriculture and their impacts.	Elaborated on the challenges of classical sensors in agriculture.
	Singh et al. (2020)	Classical Sensors in Agriculture	Critical Review	Showed the challenges of classical sensors in agricultural applications	Reported on the limitations of classical sensors in precision agriculture.
	Singh and Khan (2023)	Quantum Sensors in Agriculture	Experiment	Reported on the benefits of integrating quantum sensors with deep learning in agricultural applications.	Showed that quantum sensors were adopted in agriculture to promote smart farming
	Sirohi et al. (2024)	Quantum sensors in agriculture	Experiment	Revealed that quantum dot sensors were enhancing greenhouse farming by promoting PAR and plant photosynthesis.	Showed that quantum sensors were adopted in promoting greenhouse operations.
	Sishodia et al. (2020)	Classical Sensors in Agriculture	Critical review	Showed that classical sensors were adopted to improve agricultural production and reduce input losses	Revealed the benefits of classical sensors in precision agriculture.
	Sotoodehfar et al. (2024)	Key Concepts of Quantum Sensors	Experiment	Revealed that quantum sensors were effective in predicting the full magnetic dependence of the transient absorption signal.	Revealed concepts of quantum dot sensors.
	Soussi et al. (2024)	Classical Sensors in Agriculture	Critical review	Showed that quantum sensors were effective in promoting intelligent farming	Showed the benefits of quantum sensors in agriculture.
	Strangfeld et al. (2023)	Key Concepts of quantum sensors	Experiment	Reported that quantum sensors were adopted in earth observations due to higher accuracy levels.	Reported the benefits of quantum sensors.
	Stray et al. (2022)	Quantum sensors in agriculture	Experiment	Reported the applications of quantum sensors in mapping water tables and assessing the impact of the water table.	Showed the benefits of quantum sensors in agriculture
	Sun et al. (2022)	Key concepts of quantum sensors	Experiment	Demonstrated how quantum sensors based on lithium ions detected chemical analytes.	Showed the key concepts of quantum sensors
	Szigeti et al. (2021)	Key concepts of quantum sensors	Experiments	Demonstrated how quantum entanglement was adopted to enhance cold-atom sensors	Showed the key concepts of quantum sensors
	Tahmasbi and Bloch (2021)	Key concepts of quantum sensors	Experiments	Showcased quantum entanglement to estimate unknown parameters.	Demonstrated the benefits of quantum entanglement.
	Tan et al. (2023)	Quantum sensors in agriculture	Experiment	Reported that quantum carbon dot sensors were effective in promoting crop growth by enhancing photosynthesis	Showcased the applications of carbon quantum dots in promoting crop growth
	Tan et al. (2021)	Quantum sensors in agriculture	Experiment	Demonstrated how quantum carbon dot sensors promoted crop growth by enhancing photosynthesis	Reported the benefits of quantum carbon dots to promote smart agriculture.
	Thakur et al. (2019)	Classical Sensors in Agriculture	Critical Review	Reported the benefits of wireless sensors in measuring environmental parameters such as pH, humidity, and moisture.	Showed the value of classical sensors in promoting smart farming.
	Tian et al. (2023)	Quantum sensors in agriculture	Experiment	Showed the application of quantum dot sensors for detecting pesticides and heavy metal ions in food	The study showed how quantum sensors were adopted to detect pesticides
	Tong et al. (2024)	Quantum Sensors in Agriculture	Experiment	Showed how PbS quantum dot (QD) image sensors were synthesized and adopted for green recycling applications	Reported the benefits of image sensors in green recycling.
	Tsukamoto et al. (2022)	Key Concepts of Quantum Sensors	Experiment	nano-diamonds were excellent quantum sensors for local magnetic field measurements	The study showed the role of nano-diamonds in measuring magnetic fields.
	Turkanović and Hölbl (2014)	Classical Sensors in Agriculture	Critical Review	Reported that classical sensors were limited when cryptography applications were adopted	The study revealed that classical sensors were limited due to poor security
	Udekwe and Seyyedhasani (2024)	Classical Sensors in Agriculture	Critical review	Showed that classical sensors in robots were enhancing automated smart farming applications such as harvesting	Explained the applications of classical sensors in agriculture
	Ullo and Sinha (2021)	Classical Sensors in Agriculture	Critical review	Reported on the applications of smart sensors in assessing weather conditions and soil quality.	Showed smart sensors applications in agriculture
	Wang et al. (2024)	Quantum Sensors in Agriculture	Experiment	Showed that a fluorescence-based sensor was effective in detecting insecticide residue in fruit juice	Demonstrated the benefits of quantum sensors in agriculture
	Webb et al. (2021)	Quantum Sensors in Agriculture	Experiment	Reported the application of quantum sensors in detecting biological signals from mammalian muscles	Demonstrated the benefits of quantum sensors in agriculture
	Weiss et al. (2020)	Classical Sensors in Agriculture	Critical Review	Revealed that classical sensors were adopted to monitor crop yield, crop breeding, and ecosystem services in relation to soil	Demonstrated the benefits of classical sensors in smart agriculture
	Wu and Weil (2022)	Key Concepts of Quantum Sensors	Experiment	nano-diamond quantum sensing technology delivered high promise in ultrasensitive diagnosis	The study highlighted the features of quantum sensors
	Xiao et al. (2024)	Quantum Sensors in Agriculture	Experiment	Demonstrated how carbon quantum dot sensors detected foodborne pathogens	Demonstrated the benefits of quantum sensors in agriculture
	Xie et al. (2022)	Key Concepts of Quantum Sensors	Experiments	Reported on the biocompatible surface functionalization architecture for diamond sensors	The features of quantum sensors were showcased
	Yan et al. (2024)	Key Concepts of Quantum Sensors	Critical review	Reported on the adoption of quantum sensing in robotics to promote smart agriculture	Demonstrated the benefits of quantum sensors in agriculture

(*continued on next page*)

(*continued*)

No.	Article	Focus	Method	Main Findings	Relevance
	Yang et al. (2021)	Quantum sensors in agriculture	Experiment	Showed how quantum sensors were adopted to detect pesticides in agricultural crops	Showed the benefits of quantum sensors in agriculture
	Yashwanth et al. (2024)	Quantum sensors in agriculture	Experiment	Showed how carbon quantum dot sensors were adopted in detecting glucose	Showed the benefits of quantum sensors in agriculture
	Yu et al. (2021)	Key Concepts of Quantum Sensors	Critical review	Elaborated on the synthesis of quantum dot sensors and their properties.	Showed the properties of quantum sensors
	Yu et al. (2024)	Quantum sensors in agriculture	Experiment	Showed how quantum sensors could be adopted to detect Zearalenone (ZEN).	Showed the benefits of quantum sensors in agriculture
	Zaiser et al. (2016)	Key Concepts of Quantum Sensors	Experiment	Showed how quantum sensors were synthesized and benchmarked their overall performance	Showed the properties of quantum sensors
	Zhang et al., 2023	Quantum Sensors in Agriculture	Experiment	Demonstrated how quantum sensors could be adopted to rapidly detect poultry disease.	Showed the benefits of quantum sensors in agriculture
	Zhou et al. (2018)	Quantum sensors in agriculture	Experiment	Revealed that quantum carbon dot sensors were adopted in detecting pesticides and veterinary drug residues.	Showed the benefits of quantum sensors in agriculture

Data availability

No data was used for the research described in the article.

References

Abbasi, A.Z., Islam, N., Shaikh, Z.A., 2014. A review of wireless sensors and networks' applications in agriculture. Comput. Stand. Interfaces 36 (2), 263–270.

Agnol, L.D., Neves, R.M., Maraschin, M., Moura, S., Ornaghi, H.L., Dias, F.T.G., Bianchi, O., 2021. Green synthesis of Spirulina-based carbon dots for stimulating agricultural plant growth. Sustain. Mater. Technol. 30, e00347. https://doi.org/10.1016/j.susmat.2021.e00347.

Aierken, N., Yang, B., Li, Y., Jiang, P., Pan, G., Li, S., 2024. A review of unmanned aerial vehicle-based remote sensing and machine learning for cotton crop growth monitoring. Comput. Electron. Agric. 227, 109601. https://doi.org/10.1016/j.compag.2024.109601.

Akitsu, T., Nasahara, K.N., Hirose, Y., Ijima, O., Kume, A., 2017. Quantum sensors for accurate and stable long-term photosynthetically active radiation observations. Agric. For. Meteorol. 237, 171–183. https://doi.org/10.1016/j.agrformet.2017.01.011.

Alahe, M.A., Wei, L., Chang, Y., Gummi, S.R., Kemeshi, J., Yang, X., Won, K., Sher, M., 2024. Cyber security in smart agriculture: threat types, current status, and future trends. Comput. Electron. Agric. 226, 109401. https://doi.org/10.1016/j.compag.2024.109401.

Albiero, D., Garcia, A.P., Umezu, C.K., de Paulo, R.L., 2022. Swarm robots in mechanized agricultural operations: a review about challenges for research. Comput. Electron. Agric. 193, 106608.

Alotaibi, N.M., Alotibi, M.M., Younis, U., Hussain, G.S., Dawar, K., Hareem, M., Ghoneim, A.M., Fahad, S., Danish, S., 2024. Zn-quantum dot biochar regulates antioxidants and nutrient uptake to improve rapeseed growth and yield in drought stress. Plant Stress (Amsterdam) 11, 100286. https://doi.org/10.1016/j.stress.2023.100286.

Arvand, M., Abbasnejad, S., Ghodsi, N., 2016. Graphene quantum dots decorated with Fe 3 O 4 nanoparticles/functionalized multiwalled carbon nanotubes as a new sensing platform for electrochemical determination of l-DOPA in agricultural products. Anal. Methods 8 (29), 5861–5868.

Baklaga, L., 2023. Revolutionizing sustainable energy production with quantum artificial intelligence: applications in autonomous robotics and data management. Green Low-Carbon Econ. 2023, 1–8.

Basheer, A., 2022. The art and science of writing narrative reviews. Int. J. Adv. Med. Health Res. 9 (2), 124–126.

Benavides-Mendoza, A., Juárez-Maldonado, A., Tortella-Fuentes, G.R., González-Fuentes, J.A., 2023. Quantum materials for emerging agrochemicals. In: Henini, M., Rodrigues, M.O. (Eds.), *Quantum Materials, Devices, and Applications*. Elsevier, pp. 117–153.

Berger, C., Di Paolo, A., Forrest, T., Hadfield, S., Sawaya, N., Stęchły, M. and Thibault, K., 2021. *Quantum technologies for climate change: preliminary assessment.* [Online] Available at: https://arxiv.org/abs/2107.05362 [Accessed 15 February 2025].

Bergier, I., Barbedo, J.G., Bolfe, É.L., Romani, L.A., Inamasu, R.Y., Massruhá, S.M., 2024. Framing concepts of agriculture 5.0 via bipartite analysis. Sustainability 16 (24), 1–22.

Bilmes, A., Volosheniuk, S., Brehm, J.D., Ustinov, A.V., Lisenfeld, J., 2021. Quantum sensors for microscopic tunneling systems. npj Quantum Inf. 7 (1), 1–6.

Boddice, D., Metje, N., Tuckwell, G., 2017. Capability assessment and challenges for quantum technology gravity sensors for near surface terrestrial geophysical surveying. J. Appl. Geophys. 146, 149–159.

Bonato, C., Blok, M.S., Dinani, H.T., Berry, D.W., Markham, M.L., Twitchen, D.J., Hanson, R., 2016. Optimized quantum sensing with a single electron spin using real-time adaptive measurements. Nat. Nanotechnol. 11 (3), 247–252.

Bongs, K., Holynski, M., Vovrosh, J., Bouyer, P., Condon, G., Rasel, E., Schubert, C., Schleich, W.P., Roura, A., 2019. Taking atom interferometric quantum sensors from the laboratory to real-world applications. Nat. Rev. Phys. 1 (12), 731–739.

Bongs, K., Bennett, S., Lohmann, A., 2023. Quantum sensors will start a revolution—if we deploy them right. Nature 617 (7962), 672–675.

Caya, M.V.C., Alcantara, J.T., Carlos, J.S. and Cereno, S.S.B., 2018, April. Photosynthetically active radiation (PAR) sensor using an array of light sensors with the integration of data logging for agricultural application. In: *2018 3rd International Conference on Computer and Communication Systems (ICCCS)*. IEEE, pp.377-381. doi: 10.1109/ccoms.2018.8463321.

Coffin, A., Bonnefoy-Claudet, C., Chassaigne, M., Jansen, A., Gée, C., 2021. PARADe: A low-cost open-source device for photosynthetically active radiation (PAR) measurements. Smart Agric. Technol. 1, 100018. https://doi.org/10.1016/j.atech.2021.100018.

De la Concepción, A.R., Stefanelli, R., Trinchero, D., 2015. January. Ad-hoc multilevel wireless sensor networks for distributed microclimatic diffused monitoring in precision agriculture. In: In *2015 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*. IEEE, pp. 14–16.

De Ocampo, A.L.P., Montalbo, F.J.P., 2024. A multi-vision monitoring framework for simultaneous real-time unmanned aerial monitoring of farmer activity and crop health. Smart Agric. Technol. 8, 100466. https://doi.org/10.1016/j.atech.2024.100466.

Degen, C.L., Reinhard, F., Cappellaro, P., 2017. Quantum sensing. Rev. Mod. Phys. 89 (3), 035002.

Dong, Z., Qi, J., Yue, L., Zhou, H., Chen, L., Gu, J., He, Y., Wu, H., 2024. Biomass-based carbon quantum dots and their agricultural applications. Plant Stress 11, 1–12.

Du, Z., Li, Y., Zeng, C., Zhong, Y., Wang, S., Liu, W., Chen, Q., Pang, M., Wang, Y., Zhu, R., Zhang, H., 2024. Dual-template molecularly imprinted double emission proportional fluorescence sensor based on CsPbBr3 and CsPb (Br/I) 3 perovskite quantum dots for visual, selective and sensitive detection of methyl eugenol and aristolochic acid A. Sens. Actuators B 417, 136189.

Dwarkani, C.M., Ram, G.R., Jagannathan, S., Priyatharshini, R., 2015. *Smart farming system using sensors for agricultural task automation.* IEEE Xplore. https://doi.org/10.1109/TIAR.2015.7358530.

El Alaoui, M., Amraoui, K.E., Masmoudi, L., Ettouhami, A., Rouchdi, M., 2024. Unleashing the potential of IoT, Artificial Intelligence, and UAVs in contemporary agriculture: a comprehensive review. J. Terramech. 115, 100986.

El Morsalani, M., 2024. *Quantum sensing: basics, algorithms, applications and the German ecosystem.* QWaveConsult.

El-Sharkawy, M.M., Sheta, A.S., Arafat, S.M., Abd El-Wahed, M.S., 2016. Precision agriculture using advanced remote sensing techniques for peanut crop in Arid Land. J. Hyperspectral Remote Sens. 6 (1), 72–81. https://doi.org/10.5935/2237-2202.20160007.

Erhard, M., Krenn, M., Zeilinger, A., 2020. Advances in high-dimensional quantum entanglement. Nat. Rev. Phys. 2 (7), 365–381. https://doi.org/10.1038/s42254-020-0193-5.

Fein, Y.Y., Geyer, P., Zwick, P., Kiałka, F., Pedalino, S., Mayor, M., Gerlich, S., Arndt, M., 2019. Quantum superposition of molecules beyond 25 kDa. Nat. Phys. 15 (12), 1242–1245. https://doi.org/10.1038/s41567-019-0663-9.

Facure, M.H., Schneider, R., Mercante, L.A., Correa, D.S., 2020. A review on graphene quantum dots and their nanocomposites: from laboratory synthesis towards agricultural and environmental applications. Environ. Sci. Nano 7 (12), 3710–3734.

Fang, H.H., Wang, X.J., Marie, X., Sun, H.B., 2024. Quantum sensing with optically accessible spin defects in van der Waals layered materials. Light Sci. Appl. 13 (1), 1–21.

Farahmandzadeh, F., Kermanshahian, K., Molahosseini, E., Molaei, M., Karimipour, M., 2025. Highly fluorescent CdTe/ZnSe quantum dot-based "turn-off" sensor for the on-site rapid detection of Lead ions in aqueous medium. Spectrochim. Acta A Mol. Biomol. Spectrosc. 324, 124914.

Ferreira, A.C.D.A., Titotto, S.L.M.C., Akkari, A.C.S., 2022. Urban agriculture 5.0: an exploratory approach to the food system in a super smart society. Int. J. Math., Eng. Manag. Sci. 7 (4), 455–475.

Foy, C., Zhang, L., Trusheim, M.E., Bagnall, K.R., Walsh, M., Wang, E.N., Englund, D.R., 2020. Wide-field magnetic field and temperature imaging using nanoscale quantum sensors. ACS Appl. Mater. Interfaces 12 (23), 26525–26533.
Fragomeli, R., Annunziata, A., Punzo, G., 2024. Promoting the transition towards agriculture 4.0: a systematic literature review on drivers and barriers. Sustainability 16 (6), 1–29.
Friha, O., Ferrag, M.A., Shu, L., Maglaras, L., Wang, X., 2021. Internet of things for the future of smart agriculture: a comprehensive survey of emerging technologies. IEEE/CAA J. Autom. Sin. 8 (4), 718–752.
García de Arquer, F.P., Talapin, D.V., Klimov, V.I., Arakawa, Y., Bayer, M., Sargent, E.H., 2021. Semiconductor quantum dots: technological progress and future challenges. Science 373 (6555), 1–15.
Gauglitz, G., 2021. The new generation: quantum sensors. Anal. Bioanalytical Chem./Anal. Bioanalytical Chem. 413 (23), 5679–5680. https://doi.org/10.1007/s00216-021-03554-7.
Getahun, S., Kefale, H., Gelaye, Y., 2024. Application of precision agriculture technologies for sustainable crop production and environmental sustainability: a systematic review. Scientif. World J. 2024 (1), 1–12. https://doi.org/10.1155/2024/2126734.
Ghani, A., Juraimi, A.S., Suhaizi, A., Ahmad-Hamdani, M.S., Islam, A.K.M.M., Motmainna, M., 2024. Chemical weed control in direct-seeded rice using drone and mist flow spray technology. Crop Prot. 184, 106853. https://doi.org/10.1016/j.cropro.2024.106853.
Gsangaya, K.R., Hajjaj, S.S.H., Sultan, M.T.H., Hua, L.S., 2020. Portable, wireless, and effective internet of things-based sensors for precision agriculture. Int. J. Environ. Sci. Technol. 17, 3901–3916.
Gupta, A., Mehta, S.K., Kunal, K., Mukhopadhyay, K., Singh, S., 2022. Quantum dots as promising nanomaterials in agriculture. In: López-Valdez, F., Fernández-Luqueño, F. (Eds.), *Agricultural Nanobiotechnology*. Woodhead Publishing, pp. 243–296.
Hafeez, A., Husain, M.A., Singh, S.P., Chauhan, A., Khan, Mohd.T., Kumar, N., Chauhan, A. and Soni, S.K., 2022. Implementation of drone technology for farm monitoring & pesticide spraying: a review. *Information Processing in Agriculture*, **10**(2), pp.192-203. doi: 10.1016/j.inpa.2022.02.002.
Hamlin, J.J., Zhou, B.B., 2019. Extreme diamond-based quantum sensors. Science 366 (6471), 1312–1313.
Hegemann, T., Balasus, J., Trinh, Q., Herzog, A., Khanh, T., 2022. Using spectral sensors to determine photosynthetic photon flux density in daylight – a theoretical approach. Light. Res. Technol. 54 (5), 429–440. https://doi.org/10.1177/14771535221077881.
Helguera, M.P.G., Lollato, R., Patrignani, A., 2022. Winter wheat light interception measured with a quantum sensor and images. Agron. J. 114 (4), 2334–2341.
Ho, K.O., Shen, Y., Pang, Y.Y., Leung, W.K., Zhao, N., Yang, S., 2022. Diamond quantum sensors: from physics to applications on condensed matter research. Funct. Diamond 1 (1), 160–173.
Hutzler, N.R., 2020. Polyatomic molecules as quantum sensors for fundamental physics. Quantum Sci. Technol. 5 (4), 044011.
Jin, X., Feng, C., Ponnamma, D., Yi, Z., Parameswaranpillai, J., Thomas, S., Salim, N.V., 2020. Review on exploration of graphene in the design and engineering of smart sensors, actuators and soft robotics. Chem. Eng. J. Adv. 4, 100034.
Kalita, H., Palaparthy, V.S., Baghini, M.S., Aslam, M., 2016. Graphene quantum dot soil moisture sensor. Sens. Actuators B 233, 582–590.
Kantsepolsky, B., Aviv, I., Weitzfeld, R., Bordo, E., 2023. Exploring quantum sensing potential for systems applications. IEEE Access 11, 31569–31582.
Kayad, A., Paraforos, D.S., Marinello, F., Fountas, S., 2020. Latest advances in sensor applications in agriculture. Agriculture 10 (8), 1–8.
Khan, M.N., Khalil, I., Ullah, I., Singh, S.K., Dhahbi, S., Khan, H., Alwabli, A., Al-Khasawneh, M.A., 2024a. Self-adaptive and content-based scheduling for reducing idle listening and overhearing in securing quantum IoT sensors. Internet Things 27, 101312.
Khan, M.A., Ghafoor, S., Hassan, M., Khan, H. and Ahmad, A. (2024). From Quantum Communication Fundamentals to Decoherence Mitigation Strategies: Addressing Global Quantum Network Challenges and Projected Applications. *Heliyon*, pp. e34331–e34331. doi:https://doi.org/10.1016/j.heliyon.2024.e34331.
Khanal, S., Kc, K., Fulton, J.P., Shearer, S., Ozkan, E., 2020. Remote sensing in agriculture—accomplishments, limitations, and opportunities. Remote Sens. (Basel) 12 (22), 1–29.
Khoshnoud, F., Quadrelli, M.B., Esat, I.I., Robinson, D., 2020. Quantum cooperative robotics and autonomy. Instrumentation J. 6 (3), 93–111.
Khushaini, M.A.A., Azeman, N.H., Aziz, T.H.T.A., Bakar, A.A.A., Zain, A.R.M., 2024. Harnessing quantum plexcitons for enhanced sensitivity and selectivity of creatinine sensor. Sens. Actuators B 412, 1–16.
Kim, D., Kang, J., Kim, T.W., Pan, Y., Park, J.H., 2021. The future of quantum information: challenges and vision. J. Inf. Process. Syst. 17 (1), 151–162.
Klerkx, L., Jakku, E., Labarthe, P., 2019. A review of social science on digital agriculture, smart farming and agriculture 4.0: new contributions and a future research agenda. NJAS-Wageningen J. Life Sci. 90, 1–16.
Knight, C., Khouakhi, A., Waine, T.W., 2024. The impact of weather patterns on inter-annual crop yield variability. Sci. Total Environ. [online] 955, 177181. https://doi.org/10.1016/j.scitotenv.2024.177181.
Kumar, N., Sharma, B., 2020. Opportunities and challenges with WSN's in smart technologies: a smart agriculture perspective. In: Bhargava, B.K., Paprzycki, M., Kaushala, N.C., Singh, P.K. (Eds.), *Handbook of Wireless Sensor Networks: Issues and Challenges in Current Scenario's*. Springer, pp. 441–463.
Kumar, P., Reddy, S.R.N., 2020. Wireless sensor networks: a review of motes, wireless technologies, routing algorithms and static deployment strategies for agriculture applications. CSI Trans. ICT 8 (3), 331–345.
Kumar, R., Mishra, R., Gupta, H.P., Dutta, T., 2021. Smart sensing for agriculture: applications, advancements, and challenges. IEEE Consum. Electron. Mag. 10 (4), 51–56.
Kutas, M., Haase, B.E., Riexinger, F., Hennig, J., Bickert, P., Pfeiffer, T., Bortz, M., Molter, D., von Freymann, G., 2022. Quantum sensing with extreme light. Adv. Quantum Technol. 5 (6), 1–28.
Lau, H.K., Clerk, A.A., 2018. Fundamental limits and non-reciprocal approaches in non-Hermitian quantum sensing. Nat. Commun. 9 (1), 1–13.
Laura, D., Urrutia, E.P., Salazar, F., Ureña, J., Moreno, R., Machado, G., Cazorla-Logroño, M., Altamirano, S., 2024. Aerial remote sensing system to control pathogens and diseases in broccoli crops with the use of artificial vision. Smart Agric. Technol. 10, 100739. https://doi.org/10.1016/j.atech.2024.100739.
Le, T., Zhang, Z., Wu, J., Shi, H., Cao, X., 2017. A fluorescent immunochromatographic strip test using a quantum dot-antibody probe for rapid and quantitative detection of 1-aminohydantoin in edible animal tissues. Anal. Bioanal. Chem. 410 (2), 565–572. https://doi.org/10.1007/s00216-017-0756-1.
Li, Y., Guo, Z., Shuang, F., Zhang, M., Li, X., 2022. Key technologies of machine vision for weeding robots: a review and benchmark. Comput. Electron. Agric. 196, 106880.
Li, W., Wu, B., 2024. Computational fluid dynamics investigation of pesticide spraying by agricultural drones. Comput. Electron. Agric. 227, 109506. https://doi.org/10.1016/j.compag.2024.109506.
Liang, L., Wong, S.C., Lisak, G., 2023. Effects of plastic-derived carbon dots on germination and growth of pea (Pisum sativum) via seed nano-priming. Chemosphere 316, 137868. https://doi.org/10.1016/j.chemosphere.2023.137868.
Liao, K., Yang, Z., Tao, D., Zhao, L., Pires, N., Dorao, C.A., Stokke, B.T., Roseng, L.E., Liu, W., Jiang, Z., 2024. Exploring the intersection of brain–computer interfaces and quantum sensing: a review of research progress and future trends. Adv. Quantum Technol. 7 (1), 1–24.
Liu, L., Yang, F., Liu, X., Du, Y., Li, X., Li, G., Chen, D., Zhu, Z., Song, Z., 2024. A review of the current status and common key technologies for agricultural field robots. Comput. Electron. Agric. 227, 109630.
Liu, B., Li, P., Wang, Y., Guo, Y., Zhang, H., Dong, S., Xiong, Y., Zhang, C., 2020. Quantum dot submicrobead–based immunochromatographic assay for the determination of parathion in agricultural products. Food Anal. Methods 13, 1736–1745.
Liu, K.S., Henning, A., Heindl, M.W., Allert, R.D., Bartl, J.D., Sharp, I.D., Rizzato, R., Bucher, D.B., 2022. Surface NMR using quantum sensors in diamond. Proc. Natl. Acad. Sci. 119 (5), 1–8.
Lyu, X., Tan, Q., Wu, L., Zhang, C., Zhang, Z., Mu, Z., Zúñiga-Pérez, J., Cai, H., Gao, W., 2022. Strain quantum sensing with spin defects in hexagonal boron nitride. Nano Lett. 22 (16), 6553–6559.
Ma, W., Wang, X., Yang, S.X., Xue, X., Li, M., Wang, R., Yu, L., Song, L., Li, Q., 2024. Autonomous inspection robot for dead laying hens in caged layer house. Comput. Electron. Agric. 227, 109595.
Mannone, M., Seidita, V., Chella, A., 2023. Modeling and designing a robotic swarm: a quantum computing approach. Swarm Evol. Comput. 79, 101297.
Maraveas, C., Piromalis, D., Arvanitis, K.G., Bartzanas, T., Loukatos, D., 2022. Applications of IoT for optimized greenhouse environment and resources management. Comput. Electron. Agric. 198, 106993.
Maraveas, C., Konar, D., Michopoulos, D.K., Arvanitis, K.G., Peppas, K.P., 2024. Harnessing quantum computing for smart agriculture: empowering sustainable crop management and yield optimization. Comput. Electron. Agric. 218, 108680.
Marciniak, C.D., Feldker, T., Pogorelov, I., Kaubruegger, R., Vasilyev, D.V., van Bijnen, R., Schindler, P., Zoller, P., Blatt, R., Monz, T., 2022. Optimal metrology with programmable quantum sensors. Nature 603 (7902), 604–609.
Matlali, L. and Fischer, A., 2023. *How quantum technology could revolutionise Africa's health, agriculture, and finance sectors*. World economic Forum. https://www.weforum.org/stories/2023/02/quantum-technology-in-africa/.
Martos, V., Ahmad, A., Cartujo, P., Ordoñez, J., 2021. Ensuring agricultural sustainability through remote sensing in the era of agriculture 5.0. Appl. Sci. 11 (13), 1–25.
Marukhyan, S.S., Hovhannisyan, V.A., Gasparyan, V.K., 2025. Urease combined with CdSe quantum dots as an enzyme sensor for quantitative detection of some metals in water. Spectrochim. Acta A Mol. Biomol. Spectrosc. 326, 125186.
Mehedi, I.M., Hanif, M.S., Bilal, M., Vellingiri, M.T., Palaniswamy, T., 2024. Remote sensing and decision support system applications in precision agriculture: challenges and possibilities. IEEE Access 12, 1–13.
Memon, R., Shaheen, I., Qureshi, A., Niazi, J.H., 2024. Enhanced detection of cardiac troponin-I using CdSe/CdS/ZnS core-shell quantum dot/TiO2 heterostructure photoelectrochemical sensor. J. Alloy. Compd. 1008, 176592.
Mirhosseini, M., Barani, F., Nezamabadi-Pour, H., 2017. QQIGSA: A quadrivalent quantum-inspired GSA and its application in optimal adaptive design of wireless sensor networks. J. Netw. Comput. Appl. 78, 231–241.
Morchid, A., El Alami, R., Raezah, A.A., Sabbar, Y., 2024. Applications of internet of things (IoT) and sensors technology to increase food security and agricultural sustainability: benefits and challenges. Ain Shams Eng. J. 15 (3), 102509.
Mukhamedieva, D.T., 2024. Innovative quantum technologies in agriculture for assessing land fertility. E3S Web of Conferences 494, 1–10.
Munawar, G., Surendro, K., 2024. Utilizing quantum algorithms to achieve carbon neutrality in urban areas: a systematic review. Alex. Eng. J. 108, 911–936.
Najdenko, E., Lorenz, F., Dittert, K., Olfs, H.W., 2024. Rapid in-field soil analysis of plant-available nutrients and pH for precision agriculture—a review. Precis. Agric. 25 (6), 3189–3218. https://doi.org/10.1007/s11119-024-10181-6.
Neo, G. and Santos, R., 2022. *Transforming food systems with farmers: a pathway for the EU.* World Economic Forum. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/consulting/us-transforming-food-systems-farmers.pdf.

Nikolidakis, S.A., Kandris, D., Vergados, D.D., Douligeris, C., 2015. Energy efficient automated control of irrigation in agriculture by using wireless sensor networks. Comput. Electron. Agric. 113, 154–163.

Nishanth , R., Nithya , shree, Patil, O.G., P, O.P. and C.S, K. (2022). A Review on Quantum Entanglement. *Research & Reviews: Journal of Physics*, [online] 11(2), pp.23–27. doi:https://doi.org/10.37591/rrjophy.v11i2.3489.

Nsibande, S.A., Forbes, P.B.C., 2016. Fluorescence detection of pesticides using quantum dot materials–a review. Anal. Chim. Acta 945, 9–22.

Oh, E., Gregoire, M.D., Black, A.T., Jeramy Hughes, K., Kunz, P.D., Larsen, M., Lautier-Gaud, J., Lee, J., Schwindt, P.D., Mouradian, S.L., Narducci, F.A., 2024. Perspective on quantum sensors from basic research to commercial applications. AIAA J. 62 (11), 4029–4053.

Ojha, T., Misra, S., Raghuwanshi, N.S., 2015. Wireless sensor networks for agriculture: the state-of-the-art in practice and future challenges. Comput. Electron. Agric. 118, 66–84.

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 Sens. (Basel) 15 (2), 1–46.

Onojeghuo, A.O., Blackburn, G.A., Huang, J., Kindred, D., Huang, W., 2018. Applications of satellite 'hyper-sensing'in Chinese agriculture: challenges and opportunities. Int. J. Appl. Earth Obs. Geoinf. 64, 62–86.

Pandiselvam, R., Imran S, S., Hegde, V., Sujithra, M., Prathibha, P.S., Prathibha, V.H. and Hebbar, K.B., 2024. Evaluation of unmanned aerial vehicle for effective spraying application in coconut plantations. *Heliyon*, **10**(19), pp.1-10. doi: 10.1016/j.heliyon.2024.e38569.

Parrish, C.H., Hebert, D., Jackson, A.J., Ramasamy, K., McDaniel, H., Giacomelli, G.A., Bergren, M.R., 2021. Optimizing spectral quality with quantum dots to enhance crop yield in controlled environments. Commun. Biol. 4 (1), 1–9. https://doi.org/10.1038/s42003-020-01646-1.

Paul, K., Chatterjee, S.S., Pai, P., Varshney, A., Juikar, S., Prasad, V., Bhadra, B., Dasgupta, S., 2022. Viable smart sensors and their application in data driven agriculture. Comput. Electron. Agric. 198, 107096.

Pawase, P.P., Nalawade, S.M., Ashok Walunj, A., Balasaheb Bhanage, G., Bhaskar Kadam, P., Durgude, A.G., Patil, M.R., 2024. Comprehensive study of on-the-go sensing and variable rate application of liquid nitrogenous fertilizer. Comput. Electron. Agric. 216, 108482. https://doi.org/10.1016/j.compag.2023.108482.

Pievanelli, E., Stefanelli, R., Trinchero, D., 2016. April. Microwave-based leaf wetness detection in agricultural wireless sensor networks. In: *2016 IEEE Sensors Applications Symposium (SAS)*. IEEE, pp. 1–4.

Pogorzelski, J., Horsthemke, L., Homrighausen, J., Stiegekötter, D., Gregor, M., Glösekötter, P., 2024. Compact and fully integrated LED quantum sensor based on NV centers in diamond. Sensors 24 (3), 743. https://doi.org/10.3390/s24030743.

Polymeni, S., Plastras, S., Skoutas, D.N., Kormentzas, G., Skianis, C., 2023. The impact of 6G-IoT technologies on the development of agriculture 5.0: a review. Electronics 12 (12), 1–24.

Pyingkodi, M., Thenmozhi, K., Nanthini, K., Karthikeyan, M., Palarimath, S., Erajavignesh, V., Kumar, G.B.A., 2022. Sensor based smart agriculture with IoT technologies: a review. In: *2022 International Conference on Computer Communication and Informatics (ICCCI)*. IEEE, pp. 1–7.

Raparthi, M., 2022. Quantum sensing technologies for biomedical applications: investigating the advancements and challenges. J. Comput. Intel. Robot. 2 (1), 21–32.

Renius, K.T., 2020. *Fundamentals of tractor design*. Springer.

Rademacher, M., Millen, J., Li, Y.L., 2020. Quantum sensing with nanoparticles for gravimetry: when bigger is better. Adv. Opt. Tech. 9 (5), 227–239.

Rahu, M.A., Karim, S., Shams, R., Soomro, A.A., Chandio, A.F., 2022. Wireless sensor networks-based smart agriculture: sensing technologies, application and future directions. Sukkur IBA J. Emerg. Tech. 5 (2), 18–32.

Rajak, P., Ganguly, A., Adhikary, S., Bhattacharya, S., 2023. Internet of Things and smart sensors in agriculture: scopes and challenges. J. Agric. Food Res. 14, 100776.

Rajasekaran, T. and Anandamurugan, S., 2019. Challenges and applications of wireless sensor networks in smart farming—a survey. In: *Advances in Big Data and Cloud Computing: Proceedings of ICBDCC18*, pp.353-361.

Ravi, P.V., Subramaniyam, V., Saravanakumar, N., Pattabiraman, A., Pichumani, M., 2023. What works and what doesn't when graphene quantum dots are functionalized for contemporary applications? Coord. Chem. Rev. 493, 215270.

Rivero-Angeles, M.E., 2021. Quantum-based wireless sensor networks: a review and open questions. Int. J. Distrib. Sens. Netw. 17 (10), 1–13.

Rosell-Polo, J.R., Cheein, F.A., Gregorio, E., Andújar, D., Puigdomènech, L., Masip, J., Escolà, A., 2015. Advances in structured light sensors applications in precision agriculture and livestock farming. Adv. Agron. 133, 71–112.

Rubino, G., Manzano, G., Brukner, Č., 2021. Quantum superposition of thermodynamic evolutions with opposing time's arrows. Commun. Phys., [Online] 4 (1). https://doi.org/10.1038/s42005-021-00759-1.

Sanchez, P.R., Zhang, H., 2022. Evaluation of a CNN-based modular precision sprayer in broadcast-seeded field. Sensors 22 (24), 9723. https://doi.org/10.3390/s22249723.

Sandeep, D.H., Krushna, B.R., Navya, N., Santhosh, D.B., Sharma, S.C., Krithika, C., Sridhar, C., Coumare, V.N., Nagabhushana, H., 2024. Sustainable fabrication of fluorescent carbon quantum dots as an optical amplifier in modern agriculture, anti-counterfeiting, food packing and intelligent pH detection. Mater. Today Sustainability 27, 100855.

Sari, C.A., Purwanto, P., Rachmawanto, E.H., Syukur, A., 2024. An integration of quantum systems using BB84 for enhanced security in aeroponic smart farming. TELKOMNIKA (Telecommunication Computing Electronics and Control) 22 (6), 1491–1501.

Schmitt, S., Gefen, T., Stürner, F.M., Unden, T., Wolff, G., Müller, C., Scheuer, J., Naydenov, B., Markham, M., Pezzagna, S., Meijer, J., 2017. Submillihertz magnetic spectroscopy performed with a nanoscale quantum sensor. Science 356 (6340), 832–837.

Schuff, J., Fiderer, L.J., Braun, D., 2020. Improving the dynamics of quantum sensors with reinforcement learning. New J. Phys. 22 (3), 1–16.

Shahzad, M.A., Younis, U., Ehsan, A., Alarfaj, A.A., Alharbi, S.A., Ansari, M.J., 2024. Impact of gibberellic acid GA3, quantum dot biochar, and rhizosphere bacteria on fenugreek plant growth and stress responses under lead stress. Sci. Rep. 14 (1), 1–11. https://doi.org/10.1038/s41598-024-81072-z.

Singh, N., Singh, A.N., 2020. Odysseys of agriculture sensors: current challenges and forthcoming prospects. Comput. Electron. Agric. 171, 105328.

Singh, P., Pandey, P.C., Petropoulos, G.P., Pavlides, A., Srivastava, P.K., Koutsias, N., Deng, K.A.K., Bao, Y., 2020. Hyperspectral remote sensing in precision agriculture: present status, challenges, and future trends. In: Pandey, P.C., Srivastava, P.K., Balzter, H., Bhattacharya, B., Petropoulos, G.P. (Eds.), *Hyperspectral Remote Sensing*. Elsevier, pp. 121–146.

Singh, R.K., Khan, A., 2023. A comparative study of quantum and classical deep learning for intelligent agriculture. J. Information Comput. Sci. 13, 185–193.

Sirohi, S., Vats, N., Kumar, S., Srivastava, V., Kumar, J., 2024. Quantum dots and its significance in sustainable agriculture: a review. African J. Bio. Sci. 6 (14), 2110–2126.

Sishodia, R.P., Ray, R.L., Singh, S.K., 2020. Applications of remote sensing in precision agriculture: a review. Remote Sens. (Basel) 12 (19), 1–31.

Soller, H., 2024. *Quantum sensing: poised to realize immense potential in many sectors*. [Online] Available at: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/tech-forward/quantum-sensing-poised-to-realize-immense-potential-in-many-sectors [Accessed 16th December 2024].

Sotoodehfar, A., Zadeh-Haghighi, H., Simon, C., 2024. Quantum theory of a potential biological magnetic field sensor: radical pair mechanism in flavin adenine dinucleotide biradicals. Comput. Struct. Biotechnol. J. 26, 70–77.

Soussi, A., Zero, E., Sacile, R., Trinchero, D., Fossa, M., 2024. Smart sensors and smart data for precision agriculture: a review. Sensors 24 (8), 1–32.

Strangfeld, A., Carraz, O., Eiden, A., Heliere, A., Silvestrin, P., 2023. Quantum sensing for Earth observation at the European Space Agency: latest developments, challenges, and future prospects. Sens., Syst., Next-Gen. Satellites XXVII 12729, 56–62.

Stray, B., Lamb, A., Kaushik, A., Vovrosh, J., Rodgers, A., Winch, J., Hayati, F., Boddice, D., Stabrawa, A., Niggebaum, A., Langlois, M., 2022. Quantum sensing for gravity cartography. Nature 602 (7898), 590–594.

Sun, L., Yang, L., Dou, J.H., Li, J., Skorupskii, G., Mardini, M., Tan, K.O., Chen, T., Sun, C., Oppenheim, J.J., Griffin, R.G., 2022. Room-temperature quantitative quantum sensing of lithium ions with a radical-embedded metal–organic framework. J. Am. Chem. Soc. 144 (41), 19008–19016.

Szigeti, S.S., Hosten, O., Haine, S.A., 2021. Improving cold-atom sensors with quantum entanglement: prospects and challenges. Appl. Phys. Lett. 118 (14).

Tahmasbi, M., Bloch, M.R., 2021. On covert quantum sensing and the benefits of entanglement. IEEE J. Select. Areas Information Theory 2 (1), 352–365.

Tan, T.L., Nulit, R., Jusoh, M., Rashid, S.A., 2023. Recent developments, applications and challenges for carbon quantum dots as a photosynthesis enhancer in agriculture. RSC Adv. 13 (36), 25093–25117.

Tan, T.L., Zulkifli, N.A., Zaman, A.S.K., binti Jusoh, M., Yaapar, M.N. and Rashid, S.A., 2021. Impact of photoluminescent carbon quantum dots on photosynthesis efficiency of rice and corn crops. *Plant Physiology and Biochemistry*, **162**, pp.737-751.

Taseer, A., Han, X., 2024. Advancements in variable rate spraying for precise spray requirements in precision agriculture using unmanned aerial spraying systems: a review. Comput. Electron. Agric. 219, 108841. https://doi.org/10.1016/j.compag.2024.108841.

Taylor, J.A., 2023. Precision agriculture. *Elsevier eBooks*, pp.710–725. doi: 10.1016/b978-0-12-822974-3.00261-5.

Thakur, D., Kumar, Y., Kumar, A., Singh, P.K., 2019. Applicability of wireless sensor networks in precision agriculture: a review. Wirel. Pers. Commun. 107, 471–512.

Tian, J., An, M., Zhao, X., Wang, Y., Hasan, M., 2023. Advances in fluorescent sensing carbon dots: an account of food analysis. ACS Omega 8 (10), 9031–9039. https://doi.org/10.1021/acsomega.2c07986.

Tong, Y., Zhang, D., Li, Z., Hu, G., Zou, Q., Xiao, L., Wu, W., Huang, L., Liang, S., Duan, H., Hu, J., 2024. PbS quantum dot image sensors derived from spent lead-acid batteries via an environmentally friendly route. Engineering.

Toselli, M., Baldi, E., Ferro, F., Rossi, S., Cillis, D., 2023. Smart farming tool for monitoring nutrients in soil and plants for precise fertilization. Horticulturae, [Online] 9 (9), 1–14. https://doi.org/10.3390/horticulturae9091011.

Toural, J.L.S., Marzoa, V., Bernardo-Gavito, R., Pau, J.L., Granados, D., 2023. Hands-on quantum sensing with NV− centers in diamonds. C – J. Carbon Res., [Online] 9 (1), 16. https://doi.org/10.3390/c9010016.

Tsukamoto, M., Ito, S., Ogawa, K., Ashida, Y., Sasaki, K., Kobayashi, K., 2022. Accurate magnetic field imaging using nanodiamond quantum sensors enhanced by machine learning. Sci. Rep. 12 (1), 1–7.

Turkanović, M., Hölbl, M., 2014. The (in) adequacy of applicative use of quantum cryptography in wireless sensor networks. Quantum Inf. Process 13, 2255–2275.

Ullo, S.L., Sinha, G.R., 2021. Advances in IoT and smart sensors for remote sensing and agriculture applications. Remote Sens. (Basel) 13 (13), 1–14.

Vanghele, N., Petre, A., Matache, A., Stanciu, M., 2020. Agriculture 5.0 – review. Ann. Univ. Craiova 51 (2), 576–583.

Wang, X., Wang, J., Hu, B., Zhang, Y., Tian, H., 2024. Rapid determination of organophosphorus insecticides residue in fruit juice by a fluorescence sensor based on carbon quantum dots. J. Food Compos. Anal. 136, 106816.

Wang, Y., Zhang, W., Chai, H., Zhang, Z., Lin, S., Qin, X., Du, J., 2025. Fully integrated quantum magnetometer based on nitrogen-vacancy centers. Phys. Rev. Appl 23 (3). https://doi.org/10.1103/physrevapplied.23.034008.
Webb, J.L., Troise, L., Hansen, N.W., Olsson, C., Wojciechowski, A.M., Achard, J., Brinza, O., Staacke, R., Kieschnick, M., Meijer, J., Thielscher, A., 2021. Detection of biological signals from a live mammalian muscle using an early stage diamond quantum sensor. Sci. Rep. 11 (1), 1–11.
Weiss, M., Jacob, F., Duveiller, G., 2020. Remote sensing for agricultural applications: a meta-review. Remote Sens. Environ. 236, 111402.
Wu, Y., Weil, T., 2022. Recent developments of nanodiamond quantum sensors for biological applications. Adv. Sci. 9 (19), 1–19.
Xiao, M., Mei, L., Qi, J., Zhu, L., Wang, F., 2024. Functionalized carbon quantum dots fluorescent sensor array assisted by a machine learning algorithm for rapid foodborne pathogens identification. Microchem. J. 201, 110701.
Xie, M., Yu, X., Rodgers, L.V., Xu, D., Chi-Durán, I., Toros, A., Quack, N., de Leon, N.P., Maurer, P.C., 2022. Biocompatible surface functionalization architecture for a diamond quantum sensor. Proc. Natl. Acad. Sci. 119 (8), 1–7.
Xing, Y., Wang, X., 2024. Precise application of water and fertilizer to crops: challenges and opportunities. Front. Plant Sci. 15, 1–17. https://doi.org/10.3389/fpls.2024.1444560.
Yan, F., Iliyasu, A.M., Li, N., Salama, A.S., Hirota, K., 2024. Quantum robotics: a review of emerging trends. Quantum Mach. Intell. 6 (2), 86.
Yang, Q., Li, Q., Li, H., Li, F., 2021. pH-response quantum dots with orange–red emission for monitoring the residue, distribution, and variation of an organophosphorus pesticide in an agricultural crop. J. Agric. Food Chem. 69 (9), 2689–2696.
Yashwanth, H.J., Naik, M.M., Dileep, M.S., Muniyappa, M., Rani, M.N., 2024. Nitrogen, phosphorous co-doped carbon quantum dots as glucose and lactate sensor. Mater. Chem. Phys. 162, 130149.
Yazdinejad, A., Zolfaghari, B., Azmoodeh, A., Dehghantanha, A., Karimipour, H., Fraser, E., Green, A.G., Russell, C., Duncan, E., 2021. A review on security of smart farming and precision agriculture: security aspects, attacks, threats and countermeasures. Appl. Sci. 11 (16), 7518. https://doi.org/10.3390/app11167518.
Yu, C.J., Von Kugelgen, S., Laorenza, D.W., Freedman, D.E., 2021. A molecular approach to quantum sensing. ACS Cent. Sci. 7 (5), 712–723.
Yu, P., Cui, J., Yang, J., Khan, M.U., Yang, L., Li, S., Li, M., Liu, S., Kong, L., Chen, Z., 2024. A novel aptamer-based photoelectrochemical sensor for zearalenone detection: integration of g-C3N4/BiOBr with in situ growth Ag2S quantum dots. Bioelectrochemistry, 108853.
Zaiser, S., Rendler, T., Jakobi, I., Wolf, T., Lee, S.Y., Wagner, S., Bergholm, V., Schulte-Herbrüggen, T., Neumann, P., Wrachtrup, J., 2016. Enhancing quantum sensing sensitivity by a quantum memory. Nat. Commun. 7 (1), 1–11.
Zhai, Y., Yue, Z., Li, L., Liu, Y., 2022. Progress and applications of quantum precision measurement based on SERF effect. Front. Phys. 10. https://doi.org/10.3389/fphy.2022.969129.
Zhang, Y., Duan, H., Liu, Y., Li, Y., Lin, J., 2023. Converge of coordinate attention boosted YOLOv5 model and quantum dot labeled fluorescent biosensing for rapid detection of the poultry disease. Comput. Electron. Agric. 206, 107702.
Zhou, J.W., Zou, X.M., Song, S.H., Chen, G.H., 2018. Quantum dots applied to methodology on detection of pesticide and veterinary drug residues. J. Agric. Food Chem. 66 (6), 1307–1319.
Zou, Z., Li, C., Wu, X., Meng, Z., Cheng, C., 2024. The effect of day-to-day temperature variability on agricultural productivity. Environ. Res. Lett. 19 (12), 124046. https://doi.org/10.1088/1748-9326/ad8ede.