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A comprehensive review on smart farming

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Abstract
Precision agriculture, sometimes referred to as "smart farming," is a revolutionary approach to farming that incorporates cutting-edge technologies like big data analytics, drones, robotics, artificial intelligence (AI), and the Internet of Things (IoT). This thorough analysis explores the developments, uses, and difficulties of smart farming with the goal of offering a broad grasp of its potential to improve resource efficiency, sustainability, and production. The study investigates the application of predictive analytics in decision-making processes as well as the usage of smart sensors for real-time soil, crop health, and weather monitoring. It also emphasises the use of unmanned aerial vehicles (UAVs) and autonomous machines for accurate pest control, watering, and planting. Now withstanding its advantages, the assessment also discusses important obstacles like expensive implementation costs, complicated technology, and data security issues. This assessment seeks to direct future breakthroughs and promote the broad adoption of smart farming methods for a sustainable agricultural future by combining recent developments and pointing out research needs.

Keywords: Smart farming, artificial intelligence, internet of things, precision agriculture

Introduction
Internet of Things, Artificial Intelligence, and Nanotechnology are emerging as some of the remarkable features of Agriculture 4.0. It has transformed the way agriculture and agriculture based enterprises have been operated to date and has also impacted its supply chain (Javaid *et al.*, 2022) [46]. The growth in crop production is also further attributable to information and communication technologies. It is during the last twenty years that we have entered into the fourth agricultural revolution because the landscape has changed so much with the advent of artificial intelligence (AI) and information communication technology (ICT) (Araújo *et al.*, 2021) [7]. Agricultural processes like harvesting or weeding have been done by using machines, fertilizers have been sprinkled by drones and monitored growth stages through them. Such innovations have mainly had the advantage of running the machines or gadgets from a distance (John & Arul Leena Rose, 2024) [49]. Technology used in precision agriculture has raised net returns and operating earnings, according to a report released by the US Department of Agriculture (USDA) (Lowenberg-DeBoer, 2019) [61]. Smart farming advances precision agriculture further by focusing management tasks primarily on location improved by context- as well as situation-awareness, driven by real-time occurrences (Javaid *et al.*, 2022) [46]. Human-caused environmental changes may result in circumstances that make it impossible for new crops to grow (Rajagopal *et al.*, 2024) [86]. Similarly, increasing urbanization raises prices, diminishes labour in regions normally used for food production, and lowers the industry's potential for productivity (Satterthwaite *et al.*, 2010) [97]. Given this, smart farming is a novel approach to farm management that makes use of methods and tools across a range of agricultural production stages and scales, allowing for the resolution of issues related to labour shortages and rising food production needs. Many application cases for smart farming exist worldwide, demonstrating the influence of this innovative approach to agricultural practice. But effective farming goes beyond just producing food. In reality, by using big data analytics to deliver insightful information regarding the whole farming process, it has revolutionized current agriculture business models and affected the entire food supply chain (Wolfert *et al.*, 2017) [125]. This is because big data analytics facilitates real-time operational decision making.

Smart farming uses smart sensors and equipment on the field to improve traditional farming methods (Mohamed *et al.*, 2021) [69]. The synergistic interaction of these sensors and equipment results in more productive farming practices and higher crop yields (Berger *et al.*, 2022) [13]. Furthermore, farming with intelligence leaves less impact on the environment. Precision agriculture technologies that apply fertilizers and insecticides sparingly or precisely to specified areas will decrease leaching issues and the release of greenhouse gases (Lieder & Schröter-Schlaack, 2021) [58]. For the farmer, agriculture can be more profitable with smart farming. Farmers will save money and labour by using less resource inputs, and hazards will be lower due to improved spatially explicit information dependability (Walter *et al.*, 2017) [118]. Cultivating crops in the best possible way will be made possible by most effective, site-specific weather forecasts, yield estimates, and likelihood maps for illnesses and calamities derived from a dense network of climate and weather information. Site-specific data also creates new insurance and economic opportunities for the whole value chain, from technology along with input suppliers to producers, distributors, and farmers in developed and developing nations (Coble *et al.*, 2016) [24]. A market analysis indicates that improved farmer training and education, knowledge exchange, simple access to funding, and rising customer demand for natural foods are the things that would help farmers embrace sustainable agricultural technology (Scoones *et al.*, 2009) [99].

The first barrier to the complete adoption of smart farming in remote regions is the digital gap, or lack of connectivity (Jerhamre *et al.*, 2022) [48]. Although dispersed coverage still needs to be taken into consideration, the introduction of 5G is expected to enhance the circumstance in rural and economically deprived regions, as recent polls conducted within EU borders have shown. Up to 53% of EU rural areas were unconnected to Next Generation Access networks at the end of 2017, making them difficult to obtain (Bacco *et al.*, 2019; Salemink *et al.*, 2017) [10, 96].

Smart farming

The application of numerous innovations and gadgets, such as the internet, cloud, and IoT devices, is known as "smart farming" (Javaid *et al.*, 2022) [46]. The population of the globe is expected to grow and reach approximately 9.7 billion people by 2050. In order to feed this enormous population, crop productivity must be increased. It is reasonable to assume that smart farming entails utilizing both software and hardware innovations to enhance farm productivity (Saiz-Rubio & Rovira-Más, 2020) [95]. The smart agriculture is an effective lever as:

1. Agro-ecological shift must be ensured for diversification and ecological processes in order to develop productive systems that are effective, feasible, and profitable (Chable *et al.*, 2020) [21];
2. Utilize techniques and instruments for phenotyping plants and animals to establish and enhance novel production systems that can adjust to intricate local environmental circumstances (Watt *et al.*, 2020) [120];
3. Connecting farm animals through individual sensor use creates a more courteous and environmentally friendly farming system (Zhang *et al.*, 2021) [124];
4. Improve agricultural consulting services by providing more individualized and focused guidance based on vast amounts of complemented data that are analysed almost instantly (Rose *et al.*, 2016) [93].

In addition to providing autonomous awareness of surroundings through a variety of sensors and built-in intelligence, smart gadgets go beyond traditional tools (such as rain gauges, tractors, and notebooks) by being able to perform autonomous activities or do so remotely (Balafoutis *et al.*, 2017) [11]. The greatest advantage of smart farming is its capacity to save valuable time. Self-steering machines automatically guide the tractor along route lines with the aid of auto guidance software (Torres-Torriti & Burgos, 2023) [114]. Therefore, smart agriculture, which will be built on a combination of creative solutions of emerging ICTs, like IoT, has the potential to create a lucrative and environmentally friendly agricultural production (Ayaz *et al.*, 2019; Dhanaraju *et al.*, 2022) [29, 126]. Smart farming changes the way agriculture is practiced and maximizes production using the highly available technology. Top technologies embrace drones for aerial photography and monitoring, precision agricultural tools utilizing GPS to determine targeted planting practices including resource use, and Internet of Things sensors used in real-time data gathering about crop status and soil conditions (Dhanaraju *et al.*, 2022; Shafi *et al.*, 2019) [29, 100].

The Internet of Things (IoT) was launched for agricultural purposes to assist connect multiple devices in order to address problems like farmers' and end users' inability to access or depend necessary functions from faraway locations, compatibility, complicated structure, challenges with adding novel technology, cost, and high energy conservation. IoT technologies also serve as an interface for anytime, anywhere accessibility to and control of devices (Dholu & Ghodinde, 2018; Khanna & Kaur, 2019) [30, 54]. Farmers are unable to personally monitor and examine every plant in order to address deficiencies in nutrients, pests, and diseases; however, Internet of Things (IoT) technology is still helpful and has helped farmers reach an important turning point in modern agriculture (Ayaz *et al.*, 2019; Khanna & Kaur, 2019) [54, 126]. According to reports, 250,000 farms and 1200 million hectares of land are home to 10 to 15% of US farmers that use IoT technologies. According to estimates, the Internet of Things might boost production in agriculture by 70% by 2050 if new techniques are developed (Elijah *et al.*, 2018; Khanna & Kaur, 2019) [54, 127]. Increasing crop yields at a lower cost is the primary benefit of using IoT. An average farm utilizing IoT, for instance, sees an increase in production of 1.75%, a decrease in energy spending of 17 to 32 dollars per hectare of land, and an 8% decrease in the use of water for irrigation. These findings are based on reports (Bizikova *et al.*, 2020; Navarro *et al.*, 2020) [15, 74].

The Internet of Things utilizes a number of supporting strategies, including embedded devices, big data, cloud computing, wireless sensing networks, security standards and architectures, protocols for communication, and web-based services (Abdul-Qawy *et al.*, 2015; Botta *et al.*, 2016) [1, 16]. In order to alert farmers, Doshi *et al.* (2019) [128] presented a device that can create messages on various platforms. By providing real-time data from the agricultural land, the device helps farmers make informed decisions that will increase crop yields while conserving resources (fertilizers and water).

Table 1: IOT technologies used in agriculture

S. No	Technology	Application	References
1	Big data analysis	More accurately process collect data and perform agricultural activities.	(Firouzi *et al.*, 2018) [36]
2	Communication protocol	Transmit all data that is related to agriculture via the network.	(Tao *et al.*, 2021)
3	Cloud computing	Obtain, preserve, analyse, and provide the data that has been provided from the remote client.	(Symeonaki *et al.*, 2019) [109]

Artificial intelligence

Artificial intelligence for smart farming offers a practical answer to the problems facing sustainability in agriculture today. Artificial Intelligence (AI) helps with the quick assessment and construction of effective remedies for dynamic and complex situations (Thilagu & Jayasudha, 2022) [113]. The three most popular types of AI and machine learning techniques are Decision Tree (DT), Neural Network (NN)-based models, and Support Vector Machine (SVM) (Bansal *et al.*, 2022) [12]. AI is often employed to monitor an animal farm's movements and locations. Artificial intelligence (AI) allowed picture recognition technologies to analyse photos captured by drones or cameras in order to assess the condition of the crops (Syeda *et al.*, 2021) [108]. If farmers are able to identify patterns connecting diseases, pests, or nutrient deficiencies, they would be able to respond to the risks in good time; as such, crop health will improve. Predictive analysis using AI makes it possible to make agricultural yield using past information and current information and makes the reliability of producing such forecasts by the consideration of a combination of factors such as historical yields, soil conditions, and even weather trends by the algorithm used in the machine learning algorithms (Farooqui *et al.*, 2024) [35]. With such information, farmers will be more competent in their decisions on the time to plant and how they should share resources. In addition, real-time artificial intelligence algorithms through computer vision can distinguish between crops and weeds. For that reason, there is lesser pesticide overuse that has to be in the designing of automatic systems to spray exclusively where there are weeds (Su, 2020; Talaviya *et al.*, 2020) [106, 110]. Moreover, combining GPS technology with AI algorithms makes precision agriculture techniques possible. Artificial intelligence-driven autonomous machinery can traverse fields with extreme precision, enhancing the effectiveness of farming tasks including planting, harvesting, even spraying. This lowers the quantity of resources consumed as well as the quantity of labour that is necessary.

Table 2: Different AI technologies in use

S No.	Technology	Use	Reference
1	Artificial neural network (ANN)	Crop analysis based on weather conditions; used in appropriate groupings for information mining and machine learning categorization	(Mishra *et al.*, 2016) [68]
2	Convolutional neural network (CNN)	Used to reduce the volume of output by utilizing the numerous weather and meteorological events, then go on to the data handling stage and perform operations such categorization, standardization, and filtration.	(Guha *et al.*, 2022) [40]
3	Recurrent neural network (RNN)	Forecasting weather patterns, transforming them step-by-step, and refining weather updates using timelines-where the quantity of concealed points contributes to the production of reliable data	(Gupta *et al.*, 2024) [41]
4	Long short term memory network (LSTM)	To predict agricultural yields in the future, analyse historical data that includes climate patterns, soil health, and previous yields.	(Reddy *et al.*, 2024) [90]
5	Support vector machine (SVM)	Utilize digital photography to forecast moisture levels in the soil; used to classify soil samples according to pH and nutritional value.	(Reshma *et al.*, 2020) [92]

Sensors

On-farm weather variations as well as modifications to soil and yield characteristics can be measured and tracked by the sensors (Bullock *et al.*, 2019) [18]. Engineered to measure the amount of water stress in plant leaves, these sensors allow researchers to look into variations in plant water stress. Some these kinds of sensors have the EM4325 UHF chip incorporated into them, which makes this method of measuring water stress in, leaves an added benefit of smart farming (Visconti *et al.*, 2020) [117]. As a result, the sensors are able to collect various data that will be utilized to analyse farm regulations and help with decision-making. These intelligent sensors track changes in the overall condition of the crops, soil, and livestock. They also help to improve the amount and quality of agricultural output (Monteiro *et al.*, 2021) [70]. Standard sensors included in smart agricultural networks include soil moisture sensors, which track changes in soil moisture, temperature of the soil sensors, which measure changes in soil temperature, air temperature sensors, soil pH value sensors, humidity sensors, N, P, and K sensors, among others (Lloret *et al.*, 2021) [59], different other types of sensors widely used in agriculture are listed below in Table 3 with their uses.

Table 3: Types of sensors and their uses

SI. No.	Type of sensor	Use	Reference
1	Soil-moisture sensor	Uses a variety of characteristics, such as the electrical resistivity of the soil and dielectric constants, to indirectly calculate the amount of water by the volume of the soil.	(Singh *et al.*, 2019) [103]
2	Temperature-humidity sensor	Provides information about both temperature along with relative humidity simultaneously.	(Mahbub, 2020) [63]
3	Light sensor	Determines the amount of ambient light present. The sensor recognizes whenever there is not enough light.	(Ramya *et al.*, 2017) [88]
4	pH sensor	Shows if the substance being studied is basic, neutral, or acidic.	(Pramanik, 2023) [83]

Cloud

Cloud computing, sometimes referred to as streaming services. computing, is a kind of web-based computing that gives computers as well as additional devices on-demand access to shared processing information and resources (Chavali, 2014; Johnraja *et al.*, 2024) [23, 50]. It can take many other forms, including as infrastructure as a service (IaaS), platform as a service (PaaS), software as a service (SaaS), data as a service (DaaS), etc. The capacity to store data on the cloud and use it for analysis is known as cloud computing. Utilizing a variety of gadgets, including radio-frequency identification (RFID), global system for mobile communications (GSM), general packet radio service (GPRS), Wi-Fi, Bluetooth, and Zigbee modules, several smart agricultural systems are built (Prakash *et al.*, 2023) [82].

The allure of cloud computing lies in its ability to provide services at any time and from any location. It also considerably lowers the price of using those services. Very little labour is needed, and those services need to be maintained. Additionally, it saves consumers money by keeping software updated and preventing the need to acquire it (Gupta, 2012; Xue & Xin, 2016) [43, 122]. Cloud companies handle all of these problems. Various models are available for cloud computing depending on the needs of the user. In other words, much like with smart farming, farmers must be aware of specifics like the type of soil, moisture content, nutritional content, and resource availability, among other things. Because of this, people are using cloud computing technology to give farmers access to the gathered and processed data online, enabling them to learn those specifics.

Unmanned aerial vehicles (UAV)
With the help of sensors with cameras installed on the UAV, deep learning algorithms have been applied to crop picture categorization, vegetation recognition & differentiation, disease, weed, and crop nutrient monitoring (Olson & Anderson, 2021) [76]. UAVs are frequently used to collect data in smart farms. By adding cameras, sensors, and GPS to the device, the UAV can collect data from as high as possible in the smart farm for a variety of uses in management and monitoring applications (Lachgar *et al.*, 2023; Radoglou-Grammatikis *et al.*, 2020) [56, 85]. Agricultural drones are highly appealing due to the combination of ultra-small micro-electromechanical systems (MEMS) sensors with UAVs used in agriculture. In difficult terrain where it is difficult for people to move around and crops are at various altitudes, some unmanned aerial vehicles (UAVs) are being utilized to efficiently sprinkle water and other pesticides. For this reason, the Massachusetts Institute of Technology classified unmanned aerial vehicles (UAVs) as a "green-tech" instrument in smart farming in 2014 (Boursianis *et al.*, 2022; Islam *et al.*, 2021) [17, 44]. Groups of drones with 3D cameras and diverse sensors can cooperate to give farmers extensive land management skills thanks to recent developments in swarm technologies and mission-based management (Mukherjee *et al.*, 2019) [72]. By drastically cutting down on working hours, these agricultural UAVs are giving farmers the capacity to supervise and oversee their farms from above, leading to improvements in stability, productivity, and measurement accuracy (Wang *et al.*, 2021) [119]. Additionally, their use has aided in the growth of numerous agricultural fields, including mapping, weed detection and elimination, fertilizer and pesticide prospecting and spraying, seed planting, and fertility evaluation (Mohamed *et al.*, 2021; Rehman *et al.*, 2022) [69, 91].

Table 4: Different areas of applications of UAV in agriculture

S. No.	Areas of application	Benefit	Reference
1	Monitoring	Keep an eye on crop characteristics like leaf area index, height of plants, leaf colour, leaf shape, and leaf size, as well as soil moisture levels and irrigation water characteristics like pH and salinity; an eye on meteorological characteristics like air pressure, temperature, wind speed, relative humidity, rainfall, and radiation.	(Almalki *et al.*, 2021) [4]
2	Mapping	Plan an agricultural land in 2D or 3D for practical usage. Economical precision agriculture chores like separating fruit quality areas, locating deforestation, and agronomically controlling homogeneous regions are all made possible with the use of these kinds of maps.	(Lottes *et al.*, 2017) [60]
3	Spraying pesticides and fertilizers	Regarded as a wide-area or rapid sprayer. Lowering the need for labour.	(Maddikunta *et al.*, 2021) [129]
4	Planting seeds	Seeds, fertilizers, as well as plant nutrients are distributed efficiently and on schedule.	(Maddikunta *et al.*, 2021) [129]
5	Detection of weeds	Using multi-spectrum sensors, hyper-spectral cameras, along with UAVs equipped with cameras, it is possible to identify weeds and other plant and agricultural infestations.	(Boursianis *et al.*, 2022) [17]

Areas of application
Smart farming allows farmers to track and monitor their activities using unprecedented levels of precision, through aerial vehicles, IoT sensors, data analytics, etc. They could be applied in crops, livestock, and precision agriculture, among others. All of these tend to focus on increasing the efficiency, sustainable performance, and profitability of agricultural ventures. The innovations address pertinent concerns of present-day agriculture such as food security, climate change, and others; aside from enabling them to make intelligent decisions.

Crop production
Steep increase in agricultural productivity Smart farming increases agricultural productivity by using the application of modern technologies such as IoT sensors, GPS, and data analytics (Yadav *et al.*, 2022) [130]. Accuracy in applying water, fertilizers, or pesticides by monitoring real-time crop wellness, moisture level, and the healthiness of the soil increases. Waste is therefore minimized, and productivity enhanced to a higher output (Kumar *et al.*, 2024) [24]. Predictive analytics also has the capacity to predict weather patterns and pest crises that enable farmers to make more informed decisions in terms of resource handling, planting, and harvesting-all these are crucial in optimizing yield. Resource efficiency and sustainability are encouraged by smart farming. Drones and automated devices help in saving costs and human errors since plantings and harvestings are streamlined labour-intensive chores (Patel, 2023) [79]. Water-scarce places hugely benefit from the smart irrigation system where the right amount of water is provided at the right time for conserving it. Techniques of remote sensing provide insightful crop health information which enables it to be treated in time (Khanal *et al.*, 2020) [53]. Smart farming is one of those avenues through which the new technologies are advanced to enable farmers worldwide to meet the increasing food demand while making minimal impacts on the environment. Crop production productivity is enhanced as well (Azadi *et al.*, 2021; Javaid *et al.*, 2022) [9, 46].

Livestock management
Wearable for managing cattle, such as smart collars and ear tags, incorporate Internet of Things technology. These gadgets keep an eye on the health, whereabouts, and activities of the animals. Real-time notifications regarding possible issues can be sent to farmers, allowing for proactive handling and animal health assurance (Neethirajan, 2017) [75]. These gadgets' battery-operated nature is a drawback. Owing to clever farming practices, animal productivity has increased dramatically. It has been reported that smart farming has made it simpler for farmers

to monitor their animals' movements both within and outside the farm, as well as to determine the animals' attitudes and behavioural patterns (Schillings *et al.*, 2021) [98]. Because smart farming techniques have been applied to aquaculture, fish producers can now monitor and control crowding across the fish farm (Føre *et al.*, 2018) [37]. Other limitations apply to the usage of Internet of Things devices on the farm that run on batteries, as these batteries can run short quickly. It is likely that the psychological effects of introducing an unusual association to the animal's body have not been taken into account by the researchers. This raises the question as to if the animals find it amusing to have so many electrical devices attached to their body.

Post-harvesting

Smart farming is vital to ensure crop quality is maintained and waste is minimized, as well as to enhance post-harvest processes. Temperature management systems and Internet of Things sensors are two examples of the technologies used in real-time state of storage monitoring (Kasera *et al.*, 2024) [51]. These help maintain proper humidity and temperature levels, thereby adding to extended shelf life by keeping those products fresh without deterioration (Dhanaraju *et al.*, 2022; Farooq *et al.*, 2019) [29, 34]. More importantly, such data can help farmers make decisions in terms of handling and storage of the harvest since it allows tracking of quality in real-time.

Robotics and automated systems significantly enhance post-harvest productivity. With automated sorting and packing systems, crops may be sorted easily and accurately based on size, quality, and maturity, ensuring that only the best food finds its way to the market (Ayaz *et al.*, 2019; Pal & Kant, 2020) [48, 126]. In addition to increasing marketability, this minimizes labour costs and the danger of handling-related injuries. Intelligent logistics solutions also maximize the route efficiency of shipping, which reduces delays and ensures that products arrive on time while remaining fresh.

One advantage of smart agricultural techniques is improved supply chain traceability. Block chain and Internet of Things technologies allow the farmer to trace their produce from the farm all the way down to the consumer while building confidence and clarity on that pathway (Chandan *et al.*, 2023) [22]. Consumers who are concerned about the provenance and security of their food are relying more and more on this traceability. Generally speaking, waste is reduced, post-harvest processes using smart farming technologies are more effective, and the final products are higher-quality as well as more competitive altogether.

Crop data management

In order to provide a feasible solution, field data is often managed using Geographic Information Systems (GIS), which are displayed on maps (Bhat *et al.*, 2011) [14]. An assortment of software tools, commonly referred to as data platforms, enable the mapping, analysis, storing, and manipulation of any type of georeferenced information. The Field-level Geographic Information System (FIS) is a specialised GIS system that was developed as a result of precision agriculture operations (Srinivasan, 2006) [105]. Agricultural software solutions support the automation of data acquisition and production, monitoring, coordinating, making judgments, sustaining, and organizing farm operations. These services are in along with basic record-keeping functions like generating crops rates (harvests and yields), revenue and loss, farm planning, weather forecasting, soil nutrients monitoring, and field mapping (Cambra Baseca *et al.*, 2019) [19]. These applications also contain sophisticated features for labour contracts, finance, and inventory management that automate field accounting operations for farms as well as agricultural enterprises (Saiz-Rubio & Rovira-Más, 2020) [95].

However, farmers that use industrialized data management systems sometimes have to supply their crop data to an external software platform held by a private corporation. This fact has led to a great deal of controversy around data ownership.

Influence of various parameters on smart farming

Using technology to maximize the production and efficiency of agricultural processes is known as smart farming, or precision agriculture. To track and regulate farming activities, it makes use of automation, machine learning, data analytics, and sensors. However, fig 1 presents several key parameters influence smart farming:

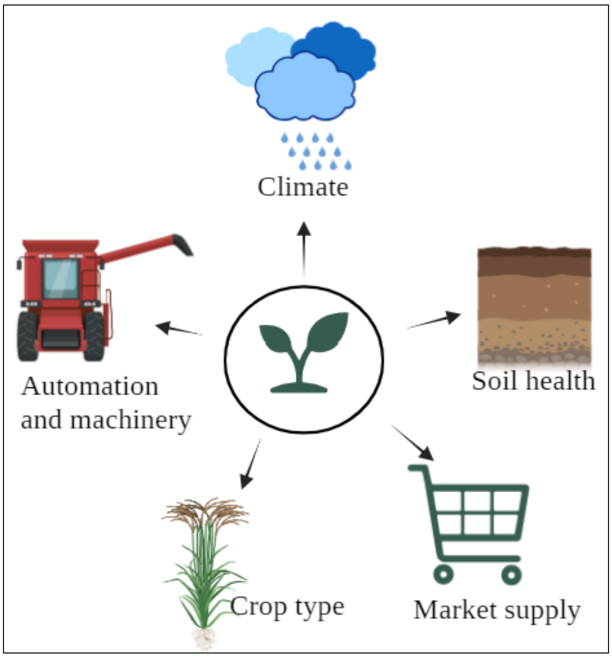

Fig 1: Factors influencing smart farming

Climate

Climate has an instantaneous impact on smart farming since it determines the temperature, humidity, rainfall, and sun radiations that crop plants require to grow healthy and wholesome (Mandal *et al.*, 2024) [66]. Smart farming optimizes agricultural practices by continually monitoring weather factors with the help of sensors, drones, and satellite imagery. For example, it can warn in early detection of temperature swings, droughts, or heavy rainfall to change irrigation schedules, plant dates, or even take precautionary measures like frost covering (Fuentes-Peñailillo *et al.*, 2024; Javaid *et al.*, 2022) [38, 46]. Accordingly, smart farming systems also include weather forecasts to assist farmers in predicting and adapting to seasonal conditions and thus reducing their exposure to extremes such as heat waves, storms, or frost (Rathore *et al.*, 2016) [89].

Climate also impacts the management of pests and diseases in that temperature and moisture create conditions that are conducive to infestations. Climate information in smart farming allows it to predict diseases breakouts and improve pest control (El-Magrous, 2020) [31]. For example, in monitoring humidity levels, the system can alert the farmer automatically to spray fungicides or even increase greenhouse aeration (Paul *et al.*,

2022) [80]. Wind patterns also influence pollination and pesticide application. With conditions from wind reducing chemical drift and optimizing the resource being used, they can be understood and utilized in response. And thus, though it has brought hardship to farmers, the latter can make real-time decisions error-free, increasing productivity and sustainability through integrating climate data into smart systems.

Soil health

Crop selection and farming practice depends on the condition of the soil. Since one knows what its soil consists of, he/she can further maximize the yield by choosing crops that are ideal for specific soil type; either it is sandy, loamy, or clay-rich in composition. Highly important elemental aspects of the soil are determining its pH and biological composition concerning its content's capacity to offer nutrients to plants for growth. These factors can be measured by technologies to allow for tailored treatments, such as adding organic matter to improve soil structure or lime application for neutralizing acidic soils (El-Ramady *et al.*, 2014; Ramesh & Rajeshkumar, 2021) [32, 87]. Monitoring biodiversity and soil microbial activity helps retain soil fertility and diminish dependence on chemical inputs. Smart farming is also consistent with sustainable goals when it leads to healthier soils with high structure and biodiversity (M. Tahat *et al.*, 2020) [62]. These soils further promote water infiltration, prevent erosion, and enhance carbon sequestration. In any case, good soils underpin any of the additional smart farming advances, including data analytics, automation, and crop health monitoring (AlZubi & Galyna, 2023; F. K. Shaikh *et al.*, 2022) [5, 101-102]. Consequently, it forms an integral part for the prosperity as well as the long-run viability of contemporary farming.

Automation and machinery

Taking revolutionary parts in smart farming, automation and mechanization revolutionize farm operations with mighty leaps in productivity to save an abundance of labour cost and ensure exactness in farming activities (Miles, 2021; Montes & Ribeiro, 2023) [67, 71]. Farming operations such as sowing, fertilizing, weeding, and harvesting can be completed with minimal human involvement due to the emergence of autonomous tractors, robotic harvesters, and drones. Because these technologies consist of GPS and sensor systems, over-application of inputs like fertilizer and water can be avoided and the production increased with precise application (Majumder *et al.*, 2021) [65]. Automation further allows farmers to handle more area through fewer assets and hence optimize their operations through real-time data obtained from the field to support decisions (Subeesh & Mehta, 2021) [107]. Drones and other aerial imaging tools enable farmers to minimize crop losses by providing comprehensive tracings of crop health, soil health, and insect infestations that allow for swift interventions (Emimi *et al.*, 2023) [33]. Automation promotes agricultural production that is environmentally friendly and resource-efficient, such as saving human labour, increasing the rate, and speed of farming operations. That increases production and supports them (Tsolakis *et al.*, 2023) [115].

Type of crop

The type of crop greatly affects the type of smart farming that will be applied because it determines what kind of technology, tools, and techniques to use in maximizing its growth. In turn, precision farming technologies are actually dependent on the specific requirements that each crop has its own required climate, soil, water, nutrients, and other factors (Shafi *et al.*, 2019) [100]. Although staple crops such as wheat or corn tend to utilize big technology in planting and harvesting, more highly valued crops like fruits and vegetables may necessitate more acute disease, pest, and nutrient level watch (Saikia *et al.*, 2020) [94]. Crop type also determines irrigation systems because some crops require much more water than others, while others require drought-resistant methods (Ahmed *et al.*, 2023) [3]. Techniques for crop rotation, being an important part of smart farming also vary with the choice of crops due to effects on nutrient replacement and soil management (Tariq *et al.*, 2019) [112]. Therefore, the design of the smart farming system will be dependent on the crop, from the sensors chosen and methods of irrigation to data analysis required to optimize productivity and efficiency.

Market and supply chain

Market and supply chain decide what, when, and how farmers should grow their crops as well as the speed and cost of getting the produce to customers in the way they like. Thus, farmers will give priority on what to cultivate given market circumstances concerning commodity prices, demand fluctuations, and preferences of customers. Thus, in the case of market data indicating increased demand or better price for a particular crop, high technology farming will make it swift and easy enough to change planting dates, optimize resource usage, and even produce according to specific demands as the situation permits (Khan *et al.*, 2021) [52]. With the support of smart farming technology and real-time market information, the farmer can make better decisions and avoid falling prey to increased over-production and saturated markets, which are thus easily at loss (Wolfert *et al.*, 2017) [125].

In terms of the supply chain, smart farming enables the improvement of efficiency and liability, as well as quality control, in transferring products from the farm to the consumer (Latino *et al.*, 2022) [57]. Besides that, data from smart agricultural systems can also be merged with logistics that control the supply chain to facilitate better cooperation between players, reduce transportation time, and shorten the cycle from harvest to the marketplace (Prause & Boevsky, 2019) [84]. Thus, in addition to profitability, the economy and supply chain dictate how long smart farming techniques will last and adjust.

Challenges and issues

Although these devices provide useful information about some of the parameters relating to physical aspects to enhance crop productivity and ways to cultivate better crops, there are still some particular challenges and limitations in smart farming-based agriculture systems. Some of the major challenges and hindrances to implement smart agriculture applications are discussed below (Fig 2.):

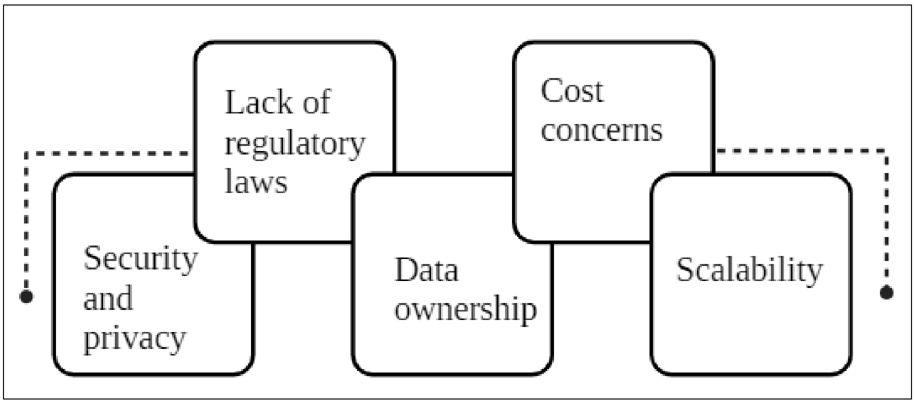

Fig 2: Major challenges in smart farming

Security and privacy

Smart farming is fuelled by the application of IoT. Because most of IoT devices are not designed with security in mind, they are vulnerable to cyber-attacks (Gupta *et al.*, 2020) [42]. A farming environment that is hazardous and unproductive can be created by remotely attacking these instruments. Integrity, privacy, secrecy, authentication, and availability are all potential targets for attacks on Internet of Things devices (Abosata *et al.*, 2021) [2]. Attacks on privacy may arise from an attempt by an attacker to get access to private information and hence jeopardize system privacy. One kind of attack that impersonates approved nodes, like Internet of Things devices, is called an attack against authentication (Nandy *et al.*, 2019) [73]. These attacks may take the shape of spoofing, masquerading, replay, impersonation, or spoofing assaults. Attacks against secrecy are those that try to eavesdrop on the network communication between Internet of Things (IoT) devices, jeopardizing secrecy and maybe influencing the wrong judgments (Omolara *et al.*, 2022) [77]. Cyber-attacks on farms have the potential to have catastrophic consequences and upend the economy of a country whose primary industry is agriculture.

Lack of regulatory laws

Farmers' challenges in implementing digital technologies are partly caused by the absence of legislative and regulatory frameworks that address the gathering, sharing, and application of agricultural data (Smidt & Jokonya, 2022) [104]. There are inconsistent laws pertaining to agricultural statistics. The worries of the farmers have been addressed, nevertheless, with the recent proposal of certain security and confidentiality principles as well as data codes of conduct. The United States' Privacy and Security Principles for Farm Data (PSPFD) were instituted in 2014 by the American Farm Bureau Federation (Amiri-Zarandi *et al.*, 2022) [6]. These guidelines address a variety of privacy issues, particularly those pertaining to data sharing procedures. Every player in the ecosystem of smart farming needs to constantly modify their agreements, services, and goods to comply with the laws and privacy policies that are in place (Van der Burg *et al.*, 2019) [116]. But given the volume of information and the complexity of legal papers, smart farming actors find that manually verifying compliance is expensive and laborious.

Data ownership

The problem of mutual trust between parties must be addressed before digital technology can completely change the food chain. The more data are combined, the more valuable they become economically. This leads to issues with legislation and regulation around the ownership of aggregated versus personalized data and user rights for both farmers and digital application developers (Wiseman *et al.*, 2019) [121]. It gets harder to specify data ownership and usage rights as the total amount of users rises. The problem of who owns or has access to agricultural data arises because farmers are more aware of its potential value as a result of the abundance of data being created. This problem might possibly make successful data interchange impossible (Jayne *et al.*, 2010) [47]. Aside from this, stakeholders are worried about the way the data is obtained and utilized because there is no government regulation in place and agricultural data contracts are inconsistent (Carbonell, 2016; Wiseman *et al.*, 2019) [20, 121]. As a result, there are now less possible benefits from using these agricultural data. The problem of data ownership is further exacerbated by the fact that agricultural data is not recognized as intellectual property by legal or regulatory frameworks worldwide (Devare *et al.*, 2023) [28].

Cost concerns

The implementation of IoT in agriculture comes with a number of costs, which are divided into two categories: hardware costs and software costs. The cost of the hardware comprises base station infrastructure, IoT devices, modules, and other items (Majumdar *et al.*, 2021) [64].

Scalability

The technology and solutions that are effective in small-scale or specialized farming settings might not be easily used in larger-scale or more varied agricultural contexts, making scalability a major problem for smart farming (Glaroudis *et al.*, 2020) [39]. In general, any one-size-fits-all strategy would prove highly difficult to implement since every farm is unique based on its composition of soil, climate, crop diversity, and accessibility of resources (Ayoub, 2023) [8]. For example, when scaling up to larger farms or different regions, the precision agriculture instruments like sensors, drones, or automated machinery may need to be modified according to local conditions, which are very expensive and complicated to set up (Delavarpour *et al.*, 2021) [27]. Often, effective smart farming implementation involves the harmonization of multiple systems, ranging from machinery to data platforms and even Internet of Things devices, across numerous operations (Debauche *et al.*, 2021) [26]. This may be challenging due to the unstandardized and non-compatible nature of various technologies sold by different vendors, thereby complicating the smooth growth of smart instruments in the use of farmers.

The infrastructural divide presents another difficulty. Thus, making the scalability of smart farming even more difficult, many rural areas still lack the power infrastructure and high-speed internet necessary for real-time data transfer and equipment functioning (Mohamed *et al.*, 2021; Tao *et al.*, 2021) [69, 111]. Smaller or resource-constrained farms in particular face financial difficulties due to the initial cost of implementing these innovations at scale and the requirement for continuous maintenance.

Conclusion
By gathering and analysing data from various farming elements, digital technologies have completely changed the agricultural industry. Digital agriculture generates enormous volumes of data on a regular basis, which has led to the widespread use of big data in practical applications. Monitoring crop health, estimation of yields, water management, and predicting demand are just a few of the ways that these data have benefited farming methods. However, using digital technologies that are globally accessible and networked creates questions about the privacy of massive data that is readily available. The privacy concerns in the agricultural sector discourage farmers from participating in data gathering efforts and impede the advancement of smart farming practices. At various phases of the data lifecycle, privacy assurance procedures should be implemented to allay these worries. In this study, we categorized the privacy requirements and concerns in this domain and presented a large data lifecycle strategy from a privacy perspective. Furthermore, we examined the cutting edge technologies now in use that have an impact on big data privacy in intelligent farming. In addition, we discussed how laws impact farmers' willingness to share data and their ability to contribute to intelligent agricultural methods. It is evident from this analysis that there are numerous ways to solve privacy concerns while allowing big data and contemporary technology to be used in this ecosystem. Smart farming has a lot of promise to strengthen agriculture worldwide.

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- Vandna Chhabra: Conceptualization, supervision, validation, visualization, writing - review and editing.

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The authors confirm that all necessary permissions for publication have been obtained.

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