Recent Trends in Internet-of-Things-Enabled Sensor Technologies for Smart Agriculture

Faisal Karim Shaikh, *Senior Member, IEEE*, Sarang Karim, Sherali Zeadally, *Senior Member, IEEE*, and Jamel Nebhen

***Abstract*—Smart agriculture integrates key information communication technologies with sensing technologies to provide effective and cost-efficient agricultural services. Smart agriculture leverages a wide range of advanced technologies, such as wireless sensor networks, Internet of Things, robotics, agricultural bots, drones, artificial intelligence, and cloud computing. The adoption of these technologies in smart agriculture enables all stakeholders in the agricultural sector to develop better managerial decisions to get more yield. We differentiate between traditional agriculture and smart agriculture based on the deployment architectures along with a focus on the various processing stages in smart agriculture. We present a comprehensive review of various types of sensors that are playing a vital role in enabling smart agriculture. We also review the integration of various sensing technologies with emerging technologies and computing infrastructures to make agriculture smarter. Finally, we discuss open research challenges that must be addressed to improve the adoption and deployment of smart agriculture in the future.**

***Index Terms*—Communication protocols, computing infrastructure, Internet of Things (IoT), sensing technologies, sensors, smart agriculture, smart farming.**

I. Introduction

AGRICULTURE is considered as one of the most ancient professions of human beings. It provides the major ingredient of food for mankind and other living organisms on earth. By 2050, it is expected that the worldwide population will be 9–10 billion resulting in increased food demand to 60%–70% [1], [2]. The "green revolution" between 1950 and the late 1960s has caused a fundamental change in agricultural systems [3]. To increase the crop yield, farmers started to adapt the use of hybrid seeds, fertilizers, and pesticides rather than relying on conventional agriculture techniques. To optimize the agriculture yield, farmers have to keep track of various factors, such as environmental (temperature, humidity, and CO_2) [4], [5], [6], [7], [8], terrestrial (insect detection and leaf chlorophyll) [9], [10], underground (soil temperature, soil humidity, and soil moisture) [2], [11], [12], [13], [14], [15], [16], and irrigation (water flow and level) [12], [17], [18], [19].

Along with open field agriculture, indoor farming is also getting attention because the environment cannot be controlled in the open field. Indoor farming generally referred to as greenhouse farming is a unique mode of growing crops under transparent shelter structures. The main purpose of greenhouses is to provide favorable growing conditions and to protect crops from unfavorable weather and various pests. Greenhouse farming also includes vertical, hydroponic, and aquaponic farming. In vertical farming, the specific crops are grown at various vertical stacked levels compared to only on single plan in an open field. In contrast, hydroponic farming does not require any soil for crop growth and relies on water and nutrients [20]. Aquaponic combines cultivating fish with hydroponics where the aquaculture water is provided to hydroponically grown plants [21]. Recent agricultural advances correspond to the synthetic technological developments in traditional agricultural systems around the world [22].

Although modern agricultural techniques have boosted food production and helped the world to cope with hunger crisis, they have also drastically increased health calamities [23]. For instance, the usage of modern pesticides reduces the antioxidant levels which may lead to neurodegeneration, cardiovascular, respiratory, renal, endocrine, cancer, and reproductive problems [24]. Thus, researchers have started to re-examine and review modern agricultural practices.

Recent advances and usage of information and communications technologies (ICTs) in the agricultural sector have brought about numerous benefits and have paved the way toward smart agriculture in both outdoor and indoor environments. ICTs can be used in the various agricultural sectors, such as cultivation, harvesting, irrigation, and farming. ICTs help in improving the production efficiency, production quality, post-harvesting processes, and monitoring of the environmental parameters that affect the agriculture ecosystem.

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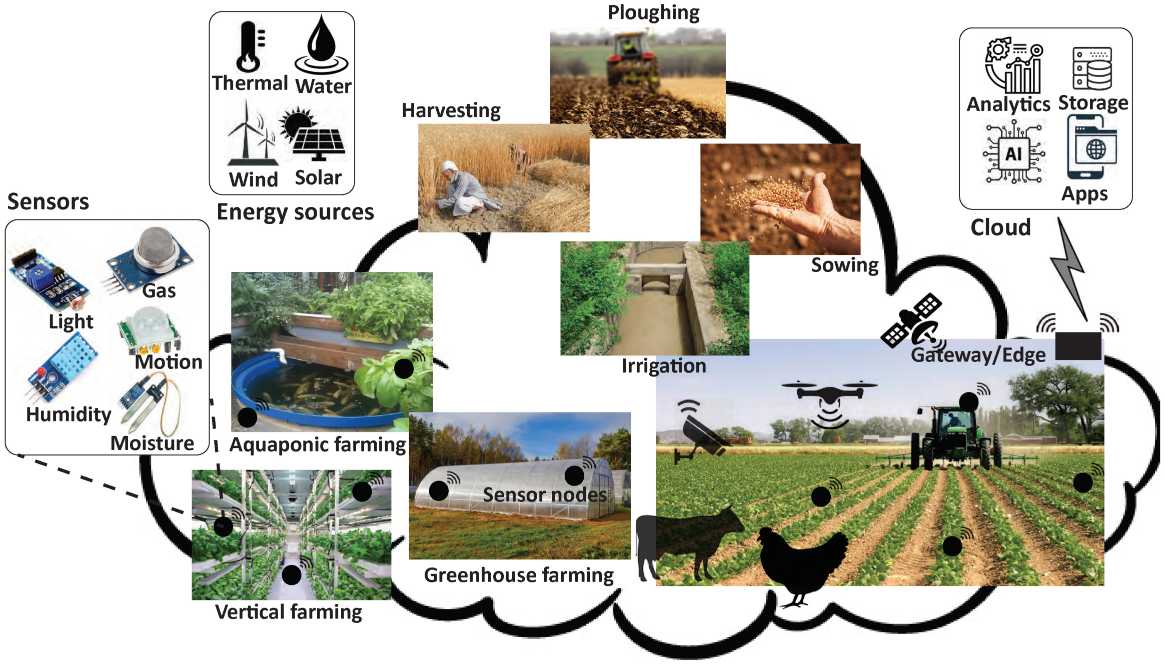

Fig. 1. Smart agriculture scenario.

Additionally, ICTs can also help in reducing the required resources needed for harvesting and post-harvest trash management [25]. Smart agriculture ensures automation in agriculture by using wireless sensor networks (WSNs) [26], [27], [28], agricultural robots (agbots) [29], [30], robots [30], [31], and drones [26], [32], [33] for measuring, monitoring, and detecting agriculture parameters. Smart agriculture supports the use of emerging technologies, such as Internet of Things (IoT) [1], [13], [14], [34], [35], [36], image processing [17], [33], [37], [38], [39], cloud computing [19], [35], [40] and fog computing [41], for up-to-date crop knowledge, efficient decision-making using artificial intelligence (AI) [42], [43], and management perceptions [27].

The smart agriculture system continuously monitors and collects information about key parameters from agricultural fields using sensors and communication devices [44]. The key parameters include soil pH, soil moisture, humidity, temperature, water-level, and so on. These parameters require different kinds of sensors to be deployed in the field. Generally, the sensor nodes are tiny in size with limited battery power [45]. To provide continuous and an uninterrupted smart agriculture system, energy harvesting mechanism can be adopted to power the sensor nodes [46], [47], [48]. At the edge of the network, the gateway node collects the information from the field and forwards it to the cloud for further processing and analysis. Fig. 1 illustrates the smart agriculture scenario with modern techniques, paradigms, and technologies that can accelerate agricultural transformations and developments.

We organize the remainder of this article as follows. Section II focuses on different aspects of smart agriculture. In Section III, we discuss various sensing technologies that enable smart agriculture. Section IV describes various emerging technologies and computing infrastructures that help make agriculture smarter. In Section V, we discuss future challenges of smart agriculture. Finally, we make some concluding remarks in Section VI.

II. Smart Agriculture

The integration of sensing, actuating, and computing technologies into traditional agriculture leads to the development of smart agriculture. The smart agriculture ecosystem consists of various stages, i.e., ploughing, sowing, irrigation, fertilizers/pesticides, crop harvesting, and livestock. By applying recent technologies, such as IoT, agbots, drones, remote sensing, and AI into the various stages of smart agriculture can solve most of the traditional cultivation concerns, i.e., drought reaction, crop optimization, environmental concerns, pest-control, over/under-irrigation, and so on.

A. *Smart Ploughing*

The examination and preparation of the soil are very much necessary before sowing the seeds of desired crops or plants. Therefore, soil analysis and examination are required to assess the nutrient status of the field and implement different crucial decisions at various stages of soil ploughing and crop management [25]. Presently, different sensing devices (Section III-A and platforms (Section III-B) are available to help farmers monitor the soil parameters and prescribe solutions to prevent deterioration of soil and crops [49]. These toolkits can determine the soil properties (e.g., moisture, texture, and soil stress) that eventually mitigate degradation, compaction, salinization, and acidification issues so that the unnecessary use of fertilizers can be avoided.

After the soil examination stage, ploughing of the field starts in order to prepare it for sowing of the seeds. Ploughing creates breathing space for the soil by loosening and overturning it and making it suitable for growth of small organisms living in the soil. Traditionally, ploughshare (cutting blade) and hoe have been used along with animals or tractors for ploughing. Recently, the use of cultivators and other machinery including laser-based levelers have been used to reduce the labor and time for ploughing the fields [50], [51], [52]. In the future, we foresee the use of smart machinery and drone that can enable better and efficient mechanisms for ploughing of the fields [53], [54]. By using drones and light detection and ranging (LiDAR) together the fields can be scanned to decide whether ploughing is needed or not. There is also a great concern over whether to plough or not as it results around 5% of total global greenhouse gas emission in EU [55]. Accordingly, greenhouse farming is becoming increasingly popular where the greenhouse emission can be controlled efficiently. Vertical farming further reduces the emissions by growing the crops vertically and using less soil. In hydroponics and aquaponics, the soil is altogether not used for crops and therefore, there is no need for ploughing the soil in this type of farming.

B. Smart Sowing

Traditionally, seed sowing is done through a funnel shaped tool. The seeds are placed in the funnel and are placed in the soil using the sharp ends of the tool. Other traditional methods include broadcasting, drilling, dibbling, and seed dropping. All these methods are manual in nature, laborious, time-consuming, and require more seeds. By taking the advantage of smart agriculture and, in particular vision-based technologies, we can precisely calculate the distance between the seeds and depth of the soil where the seeds need to be sowed [56]. Further, the use of global positioning system (GPS) technology for seed sowing has also been used [57]. In [58], a seed drill and infra-red (IR) sensor is synchronized with the GPS module in order to penetrate the soil and place the seeds at correct positions inside the soil. Lamichhane and Soltani [59] presented an in-depth review of seed sowing and seedbed management for higher yields.

Generally, because of controlled environment, sowing in greenhouses can be done anytime in a year. Seeds are sown in open seed bedding trays and can be monitored using IoT sensors, such as temperature, humidity, and moisture [60]. In hydro and aquaponics, sowing can be done in beds using pebbles or gravel. The number of seeds required in such environments is significantly less than the traditional crop sowing. However, the types of crops which can be grown in hydroponics and aquaponics are still limited.

C. Smart Irrigation

Accessible water for agriculture is often in the form of rivers, lakes, and rainwater. It is worth noting that the agricultural sector alone uses around 70% of the available water on land [61]. Given the current usage trends of water and the increasing demand by the agricultural sector, we need controlled irrigation systems to avoid over and irregular irrigation.

Several IoT-based smart irrigation systems, such as sprinkler-controlled irrigation [62], [63], drip irrigation, [64], [65] and valve-controlled irrigation [12], [66], [67] have been developed for controlled irrigation [68], [69]. Katyara *et al.* [70] developed a systematic irrigation system that uses WSN which enables the users to monitor the irrigation process by using a cellular network. Similarly, Navarro-Hellín *et al.* [71] described another WSN-based controlled irrigation framework which enables users to store the sensed data in the cloud for post-processing. In smart agriculture, the drip and sprinkler irrigation systems have shown to be high-efficiency systems resulting in significant water savings keeping the crop yields intact [72], [73]. In vertical greenhouse farming, the water usage is further reduced by using closed-loop irrigation. In contrast, hydroponics uses 13 times less water than traditional soil farming, while aquaponics uses 90% less water than traditional farming [74]. For smart irrigation systems to have real-time monitoring and actuation, data needs to be available at edge networks rather than sending the data to the cloud for further processing and analysis [75].

D. Smart Usage of Fertilizers and Pesticides

Fertilizers are the organic or biochemical materials, which can fulfill all nutrient requirements of plants, crops, and soil fertility. Crops require three main nutrients: 1) phosphorus (P) for roots, flowers, and fruits; 2) potassium (K) for stem development and water movement in plants; and 3) nitrogen (N) for crop leaves growth [76]. The fertilizer usage under smart agriculture assists farmers in providing and measuring the required nutrient dosage which eventually reduces its adverse impacts on the ecosystem. There are various emerging technologies [77], [78], variable-rate methodologies [79], [80], and unmanned vehicles [81] that enables the smart usage of fertilizers. In [82] and [83], the nutrient status of the crops is estimated by using images obtained from the field and using the normalized difference vegetation index (NDVI) (a simple graphical indicator that can be used to analyze images to determine if the image contains green vegetation). Lavanya *et al.* [84] proposed several IoT-enabled smart fertilizer models.

Similarly, pesticides are also essential in the agricultural sector for improving the crop production [85], [86]. Recently, numerous key technologies, e.g., agbots and drones provide significant solutions to cope with the pest infected crops and plants [44], [87]. These technologies precisely detect only the affected areas of the crops and spray the pesticides [57], [88] on them. Modern IoT-based pesticide management offers real-time tracking and disease prevention [89], [90]. The sensors deployed in the field capture the images of plant leaf and detect in real time whether the leaf is infected or not. Similarly, the sensors may also detect in real-time the presence of pests using infrared sensors and report to central station such that drones or agbots can be deployed to the infected site and spray the pesticides.

Due to controlled environment in greenhouses, the fertilizers and pesticides consumed are less than the open field farming. However, due to the year-round production of greenhouse crops, the amount of fertilizers and pesticides is significant [91]. Furthermore, monitoring and timely detection of pests are crucial for greenhouses because any pest attack will be highly destructive. In hydroponics, since soil is not utilized, the crops are fed with nutrients using chemicals including fertilizers. Similarly, in aquaponics, the fish waste is utilized to provide nutrients to the crops for growth.

E. Smart Crop Harvesting

Crop harvesting is the final stage during which farmers are able to get yield or production from their cultivated fields. The harvesting time of the crop can be estimated based on the analysis of plant/crop height, size, form, color, and the most notable factor is the fruit maturation stage [57]. Harvesting at the appropriate calendar not only leads to optimizing the crop quantity, quality, and yield but also enables the planning of an efficient strategy to reap and haul the crops. Farmers must know when these plants are truly ready for harvesting in order to maximize the profit from the crops. On the other hand, for greenhouses (vertical, hydroponics, and aquaponics) the production is all year round. For any specific crop, the environment may be recreated to cultivate and harvest it.

In [92], the authors developed a yield monitoring device to assist farmers in getting real-time visual harvesting data via a mobile application which is then uploaded to the cloud. Measuring the growth of fruits can be very useful in predicting the expected volume of the production and yield quality [93]. Robots are also being used in harvesting processes with the following objectives: 1) to check the fruit and its ripeness and b) to pluck the fruit carefully without damaging it [94]. Generally, for fruit/crop ripeness remote sensing and visual/image processing techniques are used [37], [95], [96]. To protect the crops and to increase the yield the pests and rodents in fields and greenhouses are monitored, tracked, and trapped using visual, motion, and pest detector sensors mounted on ground or on drones [97], [98].

F. Smart Livestock

Although, livestock seems a hobby for some people living in the countryside, but it is a big economic activity as well. In many parts of the world, livestock is an important source for the provision of foods, such as milk, eggs, and meat. Further, in some regions, farmers use the draught animals to plow their fields and for transportation purposes. As a result of mechanization of agriculture, we have seen a steady reduction in such activities. Also, farmers have been using animal dung and manure for fertilization and for producing the biomass gas [99].

There are various cattle and livestock sensing devices that are used to monitor animal behavior. These sensing devices can be implanted or attached at the collar of the animals. A wearable livestock sensing device allows the farmers to monitor the behavior, activities, and health of their animals. Akhigbe *et al.* [100] presented a more in-depth review of IoT-enabled livestock management.

III. Sensing Technologies for Smart Agriculture

Information collection and subsequent actions pose interesting challenges in the traditional agriculture scenario. Data collection from a large field or crop requires extensive time and efforts. The analysis of soil, crop, and environment requires regular field trips. Advances in sensing technologies are making the monitoring of crops easier. Generally, sensors are deployed and embedded in open fields and greenhouses to monitor and control the ploughing, sowing, irrigation, use of fertilizer and pesticides, harvesting, and livestock. In many cases, the various sensors are integrated to form an efficient platform to support smart agriculture, e.g., to determine if the field is good for ploughing. The sensors that are used to record the temperature, humidity, moisture, and nitrogen level of the soil can be deployed on a single platform which can be placed in the field. The collected data are then transferred to some centralized location using various technologies as Section IV describes.

A. Smart Agriculture Sensors

Smart agriculture requires sensors to improve agricultural practices and increase the production rate of crops. Various types of sensors can be deployed to collect physical and environmental data from the farms. There are several sensors that have been used to improve various aspects of smart agriculture. To support smart ploughing, sowing, irrigation, use of fertilizer and pesticides, harvesting, and livestock, we classify the agricultural sensors (as Fig. 2 shows) into following groups: 1) soil; 2) weather; 3) irrigation; 4) crop; and 5) livestock.

Soil, weather, and crop sensors can support smart ploughing, sowing, and harvesting tasks. Soil temperature, moisture, salinity, conductivity, and permittivity can be monitored using various sensors to take proper decisions from filed ploughing to crop harvesting. Recently, computed tomography (CT) is being used for various tasks, such as analysis of soil samples [101], plant stress detection [102], and the detection of pest-infested fruits [103]. The environmental parameters can be monitored using temperature, humidity, wind, rain gauge, and gas sensors. By monitoring environmental parameters, quick and timely decisions regarding open field and greenhouse crops can be taken which is essential for crop yield. Crop sensors can be used to help with harvesting by monitoring the growth of plants. The crop sensors can also determine when to spray pesticides by examining the images of crop/plants or by using pest detector sensors to overcome possible diseases. Satellite imagery can be used to obtain nitrogen variable rate maps to identify the areas where nitrogen balance is low and accordingly efficient utilization of fertilizers can be achieved. Image processing techniques can be applied on captured images from camera sensors in the field to identify and predict crop/plant diseases [104]. Infrared and motion sensors can be used to detect the animals and pests inside the fields. To monitor the health of plants, photosynthetically active radiation (PAR) sensor measures photosynthetic light levels in both the air and the water to correlate the photosynthesis process in the plants.

Irrigation sensors support efficient decision-making for smart irrigation and analyze the water requirement for crops. To ensure right amount of water flow and level sensors can be

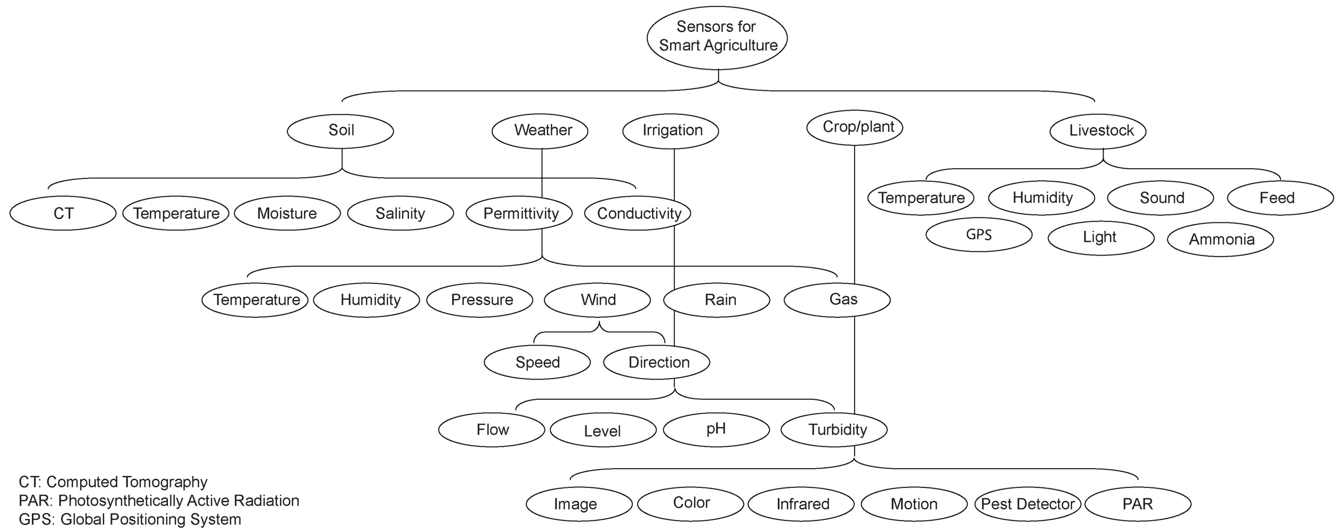

Fig. 2. Classification of sensors used for smart agriculture.

used. For good water supply for the crops, pH and turbidity sensors can be utilized.

For monitoring the movement of the livestock, the collar sensors use GPS technology can be used. Furthermore, humidity, light, temperature, and sound sensors can be used to determine the proper habitat for healthy livestock. Feed and ammonia sensors are utilized for proper feeding of the livestock in the vacinity of the indoor and outdoor farms.

Unmanned vehicles with sensing technologies can be utilized for performing various agricultural tasks autonomously [25]. Recently, drones, equipped with high resolution cameras and sensors, are being extensively used in smart agriculture [105]. The task of monitoring is extremely important in all agricultural applications because often, we need to monitor large areas [106]. Thus, the unmanned vehicles and drones embedded with various sensors (such as camera) facilitate pest detection and crop imaging (images can be used to identify diseases, growth of plants, crop yield, and so on). Multiple agbots [29], [30] have been developed to minimize the workload of farmers and speed-up the cultivation by using innovative techniques for smart farming. For example, weeding agbots are used to inspect crop rows and identify and remove weeds quickly compared to traditional methods.

Table I presents the specific sensors that are used to support smart agriculture (based on our classification of sensors used in the agricultural sector).

TABLE I
SENSORS USED IN SMART AGRICULTURE

Sensor model	Sensor type	Manufacturer/vendor	Ref.
Soil			
S-Soil MTEC-02B	Soil sensor	Seeed studio	[107]
Parallax 28092	Soil moisture	Parallax	[108]
XH-M214	Soil moisture	ICStation	[109]
MP406	Soil moisture	ICTInternational	[110]
FSG15N1A	Soil compaction	Honeywell	[111]
STP01	Soil temperature	Hukseflux	[112]
THERM200	Soil temperature	Vegetronix	[113]
STH-4 Code 5029	Soil pH and solids	Envco	[114]
5000L10	Soil salinity	Envco	[115]
SoilVUE10	Soil permittivity	Campbell Scientific Inc	[116]
EJK 14.01 EC-PROBE	Soil conductivity	Envco	[117]
Phoenix Nanotom 180NF	Computed tomography	GE	[118]
Weather			
ECRN-100 High-REC	Rain gauge sensor	Decagon	[119]
ECRN-50 low-REC	Rain gauge sensor	Decagon	[120]
SenseCAP ONE S500	Weather Sensors	Seeed Studio	[121]
CM-100	Terrestrial sensors	Stevens Water	[122]
Model 03002/03102	Wind flow and directions	R.M. Young	[123]
AQM 65	Air quality sensors	Aeroqual	[124]
Sense H2	Gas sensor	NTM Sensors	[125]
Irrigation			
ARAD	Water flow sensor	Netafim	[126]
Octave	Water flow sensor	Netafim	[127]
PB fertilizer meter	Fertilizer flow sensor	Netafim	[128]
CS477-L	Water level sensor	Campbell Scientific	[129]
CX-RLM-071	Water level sensor	Shanghai Cixi Inst. Co.	[130]
WQ201	pH sensor	Global Water	[131]
WQ730	Turbidity sensor	Global Water	[132]
Crop/plant			
DEX70	Fruit/stem size	Dynamax	[133]
FI-MM	Fruit/stem size	Phyto Sensor	[134]
CI-340	Multiple leaf sensors	CID Bio-Science, Inc.	[135]
SONY TCD-D10	Sound recorder	Sony	[136]
RE 200B	PIR (motion) sensor	Nippon Seramic	[137]
RedEye and BioCam	Camera-integrated traps	iDefigo/Mi5 Security, NZ	[138]
NJG115xP	GPS / Location	New Japan Radio	[139]
SQ-520	PAR sensor	Apogee instruments	[140]
EI sensor	Pest detector	IOSTrees	[141]
Livestock			
GPS ear tags	Cattle tracking	mOOvement Co.	[142]
Quantified AG tag	Movement, temperature	Postscapes	[143]
Cowlar	Movement, temperature	Cowlar Inc.	[144]
AfiCollar	Neck collar	Afimilk Ltd	[145]
AfiAct II	Leg sensor	Afimilk Ltd	[146]
DOL 53	Ammonia sensor	dol sensor	[147]
iDOL 46R ATEX	Feed sensor	dol sensor	[148]

B. Hardware Platforms Used in Smart Agriculture

In the last decade, we have witnessed a significant increase in the use of sensing technologies and applications in the agricultural sector. Recently, various technological firms and entrepreneurs have been focusing on smart agriculture.

Fig. 3 depicts the agricultural sensing products that are currently available on the market and Table II summarizes the different agricultural sensing products used for open field and greenhouses.

Libelium (a Spanish company) has developed a smart agriculture toolkit called Libelium Smart Agriculture Xtreme [149] has developed several solar-powered sensors. These sensors include temperature, humidity, pressure, soil oxygen level, solar radiation, conductivity, weather station,

Fig. 3. Selected hardware platforms for smart agriculture. (a) Libelium smart agriculture [149]. (b) Tertill [150]. (c) Arable Mark [151]. (d) Grofit [152]. (e) GreenIQ [153]. (f) MeteoHelix [154]. (g) Edyn garden sensor [155]. (h) CropX [156]. (i) Pycno: TERRA sensors [157]. (j) SKY weather station [158]. (k) Loup monitors [159]. (l) Growlink controller [160]. (m) Topcon crop canopy [161]. (n) mOOvement tag [162]. (o) Calving sensor [163]. (p) Farm sense pest controlling device [164].

and many more. These sensors support various communication protocols, e.g., long-range (LoRa) wide area networks (LoRaWANs), wireless fidelity (Wi-Fi), ZigBee, Sigfox, and 4G. The sensors can be utilized for various smart agriculture applications based on IoT, e.g., precision farming, greenhouses, weather station, and irrigation. The Xtreme toolkit can be used both in open fields and in greenhouses.

A solar powered weeding robot is developed by Tertill [150]. The robot prevents weeds from growing using especially designed wheels. However, if weeds grow, the robot cuts them using a built-in trimmer. This robot is useful for small gardens in an open field.

Arable Company provides an irrigation management Mark 2 tool for smart agriculture [151]. It provides over forty climate and plant related measurements that include precipitation, temperature, humidity, pressure, and radiometry and spectrometry sensors. Mark 2 also uses solar panels for energy harvesting making it sustainable. For connectivity, it relies on cellular communication, i.e., 2G, long-term evolution (LTE)-M, and narrowband-IoT (NB-IOT). Farmers can use this tool to monitor irrigation, soil moisture, crop water scarcity, and precipitation in order to provide the required amount of water to crops. The tool helps avoid over- and under-irrigation problems for open field smart agriculture.

TABLE II
HARDWARE PRODUCTS AND COMPANIES INVOLVED IN SMART AGRICULTURE

Sensing technology	Reference	Sensing parameters	Application
Libelium Smart Agriculture Xtreme	[149]	Temperature, humidity, pressure, conductivity, solar	Soil, weather, irrigation
Tertill	[150]	Plant height, weed	Plant
The Arable Mark	[151]	Soil moisture and rainfall	Soil, weather, irrigation
Grofit climate monitoring system	[152]	Air humidity, temperature and solar radiation	Weather
GreenIQ	[153]	Sprinkler controller	Irrigation
MeteoHelix IoT Pro	[154]	Radiation, pressure, humidity, rain, pollution, temperature	Soil, weather
Edyn garden sensor	[155]	Nutrition, temperature, humidity, moisture, light	Soil, irrigation
CropX-Soil Temperature	[156]	Soil moisture	Soil
Pycno: TERRA Sensors	[157]	Soil and ambient	Soil, irrigation
SKY-LoRa Weather Station : Pycno	[158]	Rain, wind	Weather
Loup electronics	[159]	Optical sensor, moisture content	Plant/crop
Growlink	[160]	Temperature, humidity, CO_2, pH, conductivity, flow	Weather, irrigation
mOOvement	[162]	GPS	Livestock
Moocall	[163]	Motion	Livestock
Topcon	[161]	Multiple	Soil, plant/crop
Grownetics	[165]	Multiple	Soil, weather, irrigation, plant
ICT International	[166]	Multiple	Soil, weather, plant
John Deere	[167]	Multiple	Soil, plant
Bio Instruments	[168]	Multiple	Plant
CID Bio-science	[169]	Multiple	Plant

Grofit Company [152] developed a system for greenhouses that monitors irrigation, agricultural climate, and the soil using remote sensing and AI. The system can measure air temperature, humidity, soil moisture, and solar radiation. It offers a Bluetooth for node communication with a base station and cellular communication for the base station.

The GreenIQ [153] smart garden hub is used to control the irrigation system of the garden in an intelligent way. It minimizes wastage of water. The device controls various types of irrigation valves and sprinklers based on timers and the past/future weather conditions. It can be easily integrated with other home automation sensors. For communication purposes it uses Wi-Fi.

The MeteoHelix IoT Pro [154] toolkit is especially designed for open field agricultural environmental monitoring based on IoT. It supports a wide range of sensing parameters, such as solar radiation, rain gauge, pressure, pollution, dewpoint, frostpoint, humidity, and temperature. Currently, it only supports Sigfox and LoRaWAN for communication and data transfers.

The Edyn smart garden system [155] tracks light, nutrition, moisture, humidity, and temperature of an open field garden. The sensor gathers and analyzes data about changing weather and soil conditions. It is Wi-Fi enabled and sends notifications to the phone using the Edyn application to maximize the plant's health. Additionally, the Edyn Water Valve uses the collected data to smartly control the watering system.

CropX technologies have developed a platform for open field smart agriculture [156]. It includes moisture, temperature, and conductivity sensor to monitor the soil. The CropX platform integrates weather, aerial imagery information from publicly available data to create topography maps, soil mapping, crop, and hydraulic models to enable farmers to monitor the crops and achieve a high yield.

Pycno Inc. developed an IoT-based TERRA sensor [157] along with a sustainable solar energy harvester for monitoring the soil and irrigation in an open field. TERRA monitors: 1) solar radiation; 2) air temperature and humidity; 3) soil temperature; and 4) soil moisture to enable smart agriculture. The soil moisture sensors are daisy chained with a distance of 15 cm and can monitor moisture up to 1.2 m under the soil. The kit supports direct cellular connection or Internet connectivity via a master node using Wi-Fi. Optionally, the GPS module can be integrated to get the location information periodically. The kit is well suited for small-scale fields, such as gardens and greenhouses. Pycno also developed a weather station called SKY WIND [158] which monitors wind speed, ultraviolet (UV) index, temperature, and humidity to support smart agriculture.

Loup electronics [159] provide various types of monitors and sensors for smart ploughing, smart sowing, and smart crop harvesting in open field agriculture. It includes drill, planter, optical yield, and moisture sensors/monitors which can be installed on vehicles, such as tractors, thrashers, and so on. Farmers can use these sensor/monitors to collect information (such as the number of seeds sowed and the nitrogen contents of the soil) from the field, which helps in field mapping and yield optimization.

Growlink [160] manufactures various types of sensors and controllers to support mostly greenhouse-based smart agriculture. The various types of sensors can measure temperature, humidity, CO2, pH, conductivity, flow, tank, and light levels. Based on the atmospheric conditions, the controllers developed by Growlink can control the devices and put them in an on-and-off state. Wi-Fi is used for communication between sensors and the controllers.

Topcon [161] has been manufacturing open field smart agriculture products for a long time. The products from Topcon facilitate soil preparation, seeding, crop care, and harvesting using various sensors, e.g., a yield monitoring system using optical sensors and moisture sensors calculates the yield while harvesting the crop.

To keep track of livestock, a company called mOOvement developed the GPS-based ear tags [162]. It uses LoRa networks to get the data from the GPS ear tags. The tag sends the cattle's location and provides actionable insights and alerts. Tags use batteries and built-in solar panel to operate.

The Moocall Calving Sensor [163] is a device that predicts when a cow is going to give birth. The device is mounted on the tail of the pregnant cow to monitor the movements of the tail to predict the time of birth. All communications are done over a cellular network.

FarmSense developed a FlightSensor [164] which is a real-time, cloud-based insect monitoring platform which detects, quantifies, and classifies the insects using machine learning algorithms. To detect the insects, optical sensors are used. On one side of the tunnel is a light source and on the other the optical sensor. The insects are drawn into a tunnel by using attractants (such as plant volatiles, flower oils, sugars, and proteins) and the FlightSensor uses shadows to identify the insects. The sensor measures how much light is occluded when an insect flies inside. The communication is done using cellular networks.

Additionally, there are many companies which are providing sensor solutions for the smart agriculture. Grownetics [165] provides hardware and software solutions to support soil, weather, irrigation, and plant growth monitoring. Grownetics products can be used both in open fields and greenhouses. ICT International [166] provides a wide range of products for soil, plant, and environmental monitoring for open field agriculture. John Deere [167] offers comprehensive solutions for smart open field agriculture and forests. The solutions include smart displays, data acquisition from sensors, data management, and remote connectivity. Bio Instruments [168] provides noninvasive monitoring of growing plants, such as leaf carbon dioxide exchange, crop growth monitoring, sap flow sensor, leaf temperature sensor, and so on. CID Bio-science [169] runs business in plant science tools. The tools include leaf area measurement, leaf area index, photosynthesis measurement, root measurement, and leaf spectroscopy.

IV. Integration of Sensing Technologies With Other Emerging Technologies

Smart agriculture is currently leveraging various emerging technologies that are playing a vital role in the modernization of agricultural practices. Fig. 4 presents the integration of various technologies and computing infrastructures in the proposed smart agriculture architecture.

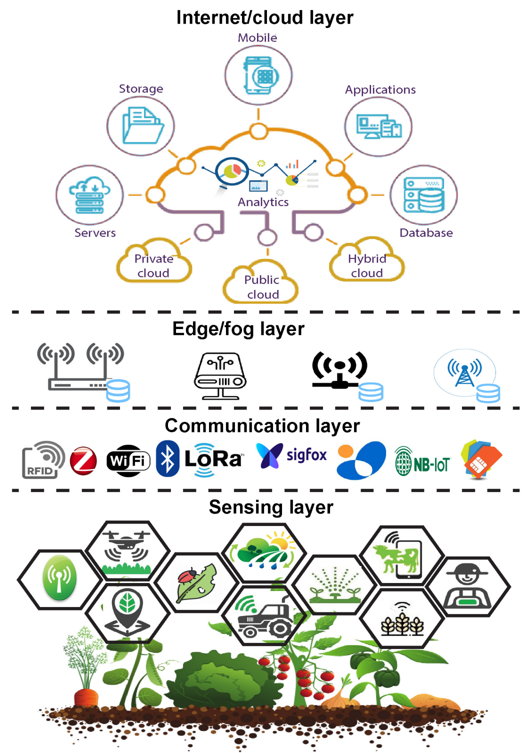

Fig. 4. Integration of various technologies and computing infrastructures in the proposed smart agriculture architecture.

The proposed smart agriculture architecture comprises the sensing layer, communication layer, edge/fog layer, and cloud layer. Each layer consists of various technologies which must be integrated efficiently to support the various smart agriculture domains. The sensing layer includes various types of sensors as Section III discusses. Next, we discuss the various technologies available at each layer.

A. Smart Agriculture Communication Layer

IoT ecosystem connects different devices and sensors to the Internet to support real-time processing and actions, such as crop monitoring, controlled irrigation, and cattle rearing, and implement weather stations and greenhouses. IoT technology is extensively deployed to manage and control agricultural services [170]. Wireless communication technologies play an important role in IoT-based smart agriculture in transferring the collected information to the relevant stakeholders. The communication network needs to be reliable, accurate, and secure for information transfer. There are many wireless communication technologies that are widely used in smart agriculture systems [25], [34], [44], [171], [172] and these include: 1) radio frequency identification (RFID); 2) Bluetooth; 3) ZigBee; 4) Wi-Fi; 5) LoRa; 6) Sigfox; 7) worldwide interoperability for microwave access (WiMAX); 8) NB-IoT; and 9) cellular networks. Table III mentions the standard, frequency, range, and data rate of these wireless technologies.

1) RFID: To record details (such as identification number and type of object) about each object individually, the RFID technology [173] is often used. RFID objects are equipped

TABLE III
COMMUNICATION TECHNOLOGIES FOR SMART AGRICULTURE

Protocol	Standard	Frequency	Range	Data rate
RFID	ISO 18000-6c	860 / 960 MHz	<5 m	40–160 Kbps
Bluetooth	IEEE 802.15.1	2.4 GHz	>8 m	1–24 Mbps
ZigBee	IEEE 802.15.4	2.4 GHz	<100 m	20–250 Kbps
Wi-Fi	IEEE 802.11 b/d/g/n	5–60 GHz	20–100 m	1 Mbps - 7 Gbps
LoRa	LoRaWAN R1.0	868 / 915 MHz	>10 Km	0.3–50 Kbps
SigFox	SigFox	868 or 902 MHz	30–50 Km	100–600 Kbps
WiMAX	IEEE 802.16	2–66 GHz	20–80 Km	>70 Mbps
NB-IoT	3GPP	2.14GHz	<10 Km	50 Kbps
Cellular	2G, 3G, 4G, 5G	450MHz to 52.6GHz	>10 Km - few feets	Kbps-Gbps

with tags which come in various sizes and types, i.e., active and passive tags. RFID readers are used to gather data from RFID tags using radio waves. Tags can store a small of data including special identification numbers. For smart agriculture, tags may store some identification data of the soil, crop, or location [174]. Wasson *et al.* [175] had integrated RFID in IoT-based systems for monitoring crops.

2) Bluetooth: Bluetooth and its variant Bluetooth low energy (BLE) is a low-powered and low-capacity-based adhoc network suitable for short-range communications. In Bluetooth, the communication is carried between nodes and the base station. In [105], a Bluetooth enabled system is integrated with an aerial vehicle to perform agricultural services, such as fertilizing the crops and spraying the pesticides. In addition, that system was also used in livestock monitoring applications.

3) ZigBee: ZigBee Alliance introduced the ZigBee wireless protocol based on the IEEE 802.15.4 standard. ZigBee can be used for different network topologies, such as a star, tree, and bus [176]. Cheng and Deng [177] developed an IoT-based agricultural monitoring system where the sensed data are transferred toward these base station using the ZigBee protocol.

4) Wi-Fi: The Institute of Electrical and Electronic Engineering (IEEE) developed the 802.11 standard for wireless local area networks (WLANs). The IEEE 802.11 standard is further divided into other standards, such as 802.11 a/b/g/c/ac each supporting different network bandwidths [178]. WLAN is well-known as Wi-Fi. The Wi-Fi communication network is widely adopted for indoor or short-range applications, such as schools, hospitals, universities, community centers, and so on. In a smart agriculture application scenario, a Wi-Fi enabled IoT-based system is used to communicate between nodes and a base station.

5) LoRa: LoRa wireless communication is widely used in low data rate IoT-based applications [179]. Due to its wide range capability and low energy consumption, it provides a low power wide area networks (LPWANs) interface between the sensing devices and the cloud. Queté *et al.* [180] described the design of a smart irrigation system, that utilizes the LoRaWAN for wireless communications. Dos Santos *et al.* [181] described another agricultural monitoring system based on the LoRa technology.

6) SigFox: SigFox offers very low data rate and an ultranarrowband for wireless connectivity to low-powered IoT devices and objects [182]. In [183], a SigFox network-based system was employed in livestock to track the animal activities and location. Llaria *et al.* [184] developed another system for cattle monitoring based on the SigFox networking technology which enable farmers to increase their livestock productivity.

7) WiMAX: WiMAX offers a very high data rate(up to 74 Mbits/s) compared to other communication technologies. WiMAX offers multiaccess wired or wireless broadband connectivity which includes fixed, mobile, and nomadic communications. Ferdoush *et al.* [185] have used WiMAX to transfer the data from a farm to the central cloud.

8) Narrowband IoT: NB-IoT technology is a low-power narrowband WAN technology based on a cellular network with wide-range radio transmission. The third-generation partnership project (3GPP) has launched and standardized the NB-IoT technology [186]. Valecce *et al.* [187] developed an NB-IoT-based agricultural field monitoring system. The underlying system architecture fetches agricultural data, such as temperature, humidity, and light from the field. Similarly, Yao and Bian [188] described an integrated cloud computing and NB-IoT-based smart agricultural system.

9) Cellular: Cellular communication comprises different communication standards from 2G to 5G and beyond. It includes global system for mobile (GSM), general packet radio service (GPRS), enhanced data rates for GSM evolution (EDGE), universal mobile telecommunications system (UMTS), high-speed downlink packet access (HSDPA), LTE, and 5G. The cellular system is suitable for large-scale fields and farms due to its wide range and high data rate support. By using cellular communication in farming, temporal variations in the fields, crop monitoring, soil monitoring, and temperature conditions can be monitored [189], [190].

B. Smart Agriculture Edge/Fog Layer

The integration of agricultural sensing technologies (as discussed in Section III) together with computing infrastructures offers real-time, wide access to the essential data via the Internet. Both edge and fog computing technologies play a crucial role in addressing numerous agricultural needs and diverse agricultural applications' requirements (such as delay, throughput, and so on) using shared resources close to the network [191]. The computing infrastructure of edge/fog helps in performing agricultural tasks that often require more computation or more precision. Fog computing facilitates the remote users by providing them with the necessary agricultural sensed data for analysis. Guillén *et al.* [192] proposed an IoT integrated edge-based design for smart agriculture. Khumalo *et al.* [41] conducted a smart agriculture-based case study which analyzes fog computing resources that provide cost-effective solutions in underdeveloped areas and good services to users that satisfy critical performance demands. Security and privacy are two main challenges for edge/fog layer [193]. To address these challenges, recently, we have seen the usage of blockchain technology integrated with edge/fog layer [194]. Blockchain can provide a traceable, privacy preserving, and unaltered archive for sharing edge knowledge to farmers and the relevant stakeholders [195]. By implementing blockchain at the edge or fog layers will help in tracking the provenance of food quickly which leads to trustworthy food supply chains. Furthermore, if smart contracts are employed, it allows timely payments between farmers and stakeholders that can be generated by data changes in the blockchain [196]. Alzoubi *et al.* [195] and Zhang *et al.* [197] provided a recent overview of blockchain solutions for fog and edge layer approaches, respectively.

C. Smart Agriculture Internet/Cloud Layer

Cloud computing provides sharing of resources cost-effectively and offer services, such as Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). Given that huge amounts of data (resulting in big data) are often generated in smart agriculture, the sensing and edge/fog layer sends such data to the Internet/cloud layer for further analysis and processing. Big data analysis in smart agriculture enables an in-depth understanding of the data collected from various sources [198], [199] such as recommending the right crop protection mechanism after processing data collected from weather, irrigation, and plant/crop sensors. Kamilaris *et al.* [200] presented a comprehensive review of big data in the agricultural domain. AI-based approaches are used on big data at the Internet/cloud layer for data analytics. Shadrin *et al.* [42] designed an AI-based system which analyzes the growth of plants using recurrent neural networks (RNNs). Deep learning (DL) techniques are widely used in precision farming to assist farmer to enable them to efficiently detect insects/pests [201] and monitor the crops [38]. Image processing also enables data processing technologies to better predict rainfall, perform irrigation control, and select appropriate field nutrients. Huang *et al.* [37] applied a Mask region-based convolutional neural network (R-CNN) model on different images for checking the status of ripeness of tomatoes in order to prevent early harvesting. We have presented a good review of AI best practices in smart agriculture in [202].

V. Open Research Challenges

Smart agriculture has shown numerous benefits over traditional agriculture. However, there are several challenges which must be addressed in the future in order to achieve its full potential.

A. Disparity Between Developed and Developing Countries

Agriculture today is vastly different in developed countries compared with developing countries. In developed nations, many farmers themselves have business and agronomy degrees. They are educated, trained, and have access to a wide range of tools to be successful in the agriculture sector. In these countries, digital agriculture techniques integrate advanced technologies with agricultural practices. These innovative techniques make farming more cost-efficient while maximizing productivity. In contrast, many developing countries still use traditional agricultural techniques which are labor intensive and result in lower production of agricultural products. We highlight some of these disparities between developed and developing countries in terms of different agricultural practices.

Farming: In developed countries, it is performed by applying modern and digital techniques, such as tractors enabled with sensors and thrashers which can calculate yield in real-time. In developing countries, it is often performed by adopting traditional manual methods and conventional tools.

Land Preparation: In developed countries, smart tractors are used for land preparation and ploughing the field. This is quite different in many developing nations today where animals, such as bullocks and oxen or normal tractors are used for ploughing the fields.

Cultivation: Developed countries use high-yielding variety (HYV) of seeds [203] and they use multiple cropping techniques such that different crop types can be cultivated from the same land to augment the yield production. However, in developing countries this practice is almost nonexistent.

Soil Fertility: Advanced countries use chemical fertilizers to increase the yield, but it gradually declines the soil fertility. Soil fertility is generally not affected in developing countries which use natural fertilizers, such as animal dung and manure.

Irrigation: Developed countries use controlled and drip irrigation systems to avoid over-irrigation. In contrast, developing countries use flooded or canal irrigation systems, which increases the chances of over-irrigation and wastage of water.

Crop Monitoring: Developed countries use multiple types of sensors, such as passive IR (PIR) sensor, sound sensors, and motion sensor to protect the crop from granivorous (seedeater) birds. But developing countries use bird scarers, nonlethal methods, and predators to protect their crops.

B. Smart Agriculture Standardization

For smart agriculture adaption over a large scale, there is a strong need for standardization at various stages of smart agriculture similar to Industry 4.0. Current agricultural and farming practices do not follow any standardized formats for devices, the data, and the processes. Interoperability issues among the devices, products, systems, and applications can be addressed with standardization in smart agriculture. Standards should emerge and play a fundamental role in Smart Agriculture 5.0 in the future.

C. Energy Scavenging

Sensors rely on an energy source, i.e., battery for sensing and communication purposes. Due to an increase in the number of devices (especially with emergence of IoT), batteries are not a reliable and sustainable solution because changing batteries for a large number of nodes is not viable. Renewable energy sources, such as solar, wind, water, and RF [204] energy harvesting schemes, need to be incorporated in the design of smart agriculture products right from the beginning. Some products have already started looking into adopting harvesting systems based on solar energy. However, we need to explore other cost-efficient energy sources for energy harvesting in the agricultural domain in the future.

D. Crop Safety

Generally, farmers care most about the health and yield of crops. Using smart agriculture and sensors can prevent crops from physical threats, i.e., from insects, animals, and so on. We need to develop more accurate identification and classification techniques of pests and weeds such that early steps can be taken to eradicate them. Optical sensors, along with advances in imaging and thermal sensors, have also gained lot of attention in recent years and can be utilized to identify the very small pathogens harmful for the crops. Acoustic and gas sensors can also be exploited for pest detection in the fields and greenhouses. By accurately identifying the pests and rodents the farmers can target areas that are affected by bugs and spray pesticides on the identified areas only. This will significantly improve the use of pesticides and minimize the chances of crop intoxication and environmental pollution.

E. Smart Agbots and Drones

In different countries, the crop productivity level has greatly increased whereas farming costs have decreased with implementation of agricultural robots (also referred to agbots) [205]. Today, we are witnessing a significant increase in robotic applications which are enabling smart farming [206]. The use of robotic technologies is alleviating the labor shortages and long-term diminishing profitability in the agricultural sector. However, expanding the capabilities of robots from the lab and greenhouse environment to outdoor areas subjected to real-life conditions remains a challenge. At present, current robotic technologies are limited to performing only specific, repetitive tasks whereas the scalability to various tasks, different fields, crops, or environments remains a challenge. Furthermore, interoperability and standardization of agbots and drones is another major challenge that still needs to be addressed when they are adopted and deployed in the fields. Moreover, expensive technologies and the required infrastructures needed to deploy agbots and drones in the field may be a barrier to their adoption in developing countries.

F. Artificial Intelligence

AI advances are increasingly playing an important role in smart agriculture. Rapid advances in energy-aware hardware and technologies will enable researchers to start focusing on distributed AI rather than applying centralized AI approaches, i.e., using the cloud. Edge networks as well as IoT nodes can exploit AI capabilities to provide timely, robust, and fine-grained predictions regarding weather forecast, plant/crop growth, and so on. We need to investigate and develop more advanced AI techniques which can make accurate forecasting of water requirements for crops, plant diseases, and localized weather with less data and computational resources for various smart agriculture domains. Associated deep-learning-based approaches, such as transfer learning or capsule networks can be explored for future decision-making systems as they require less data for learning. In the future, we foresee that supervised learning techniques would be replaced by reinforcement learning approaches to interpret the predictions from a learned environment. Generative adversarial networks (GANs) will also play an important role in addressing the problem of data scarcity in various agricultural domains in the future. The synthetic data created by GANs can be utilized by CNN to optimize the prediction capability and accuracy which so far has been restricted by the limited size of data sets. Furthermore, the swarm intelligence-based machine learning and DL algorithms can be used to effectively forecast the various parameters used in smart agriculture. Natural language processing (NLP)-based expert systems or robots or chatbots may be built to train farmers for better productivity with safe and accurate data analysis. The digital twin technology may also be integrated with other technologies to develop hybrid algorithms in the agri-food industry for sustainability and green energy initiatives.

G. Security

The agricultural sector is witnessing the wide acceptance of IoT and smart agriculture applications and devices. Thus, smart agriculture is expected to deal with a large amount of sensitive data produced by various sensors deployed in the fields and greenhouses. We must identify and analyze security requirements and privacy concerns for various types of data generated by different smart agricultural applications in conjunction with the deployment of smart agriculture systems in the fields and greenhouses. For farmer to customer communication and contracts, blockchain approaches must be exploited to have transparency in the smart agriculture ecosystem.

VI. Conclusion

We have described the smart agriculture ecosystem which consists of: 1) ploughing; 2) sowing; 3) irrigation; 4) fertilizers/pesticides; 5) crop harvesting; and 6) livestock in detail. We have discussed the sensing technologies and platforms that underpin smart agriculture both in open fields and greenhouses along with the various types of sensors and applications used. We have described the integration of different technologies (such as edge, fog, and cloud computing) at the various layers of the proposed smart agriculture architecture. Finally, we have identified a few open challenges associated with smart agriculture that must be addressed in the future. These include: 1) the adoption of smart agriculture in developed countries and developing countries; 2) standardization; 3) energy harvesting; 4) the implementation and deployment of agbots and drones; 5) the use of AI; and 6) security in smart agriculture.

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