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Internet-of-Things (IoT)-Based Smart Agriculture: Toward Making the Fields Talk

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ABSTRACT Despite the perception people may have regarding the agricultural process, the reality is that today's agriculture industry is data-centered, precise, and smarter than ever. The rapid emergence of the Internet-of-Things (IoT) based technologies redesigned almost every industry including ‘‘smart agriculture’’ which moved the industry from statistical to quantitative approaches. Such revolutionary changes are shaking the existing agriculture methods and creating new opportunities along a range of challenges. This article highlights the potential of wireless sensors and IoT in agriculture, as well as the challenges expected to be faced when integrating this technology with the traditional farming practices. IoT devices and communication techniques associated with wireless sensors encountered in agriculture applications are analyzed in detail. What sensors are available for specific agriculture application, like soil preparation, crop status, irrigation, insect and pest detection are listed. How this technology helping the growers throughout the crop stages, from sowing until harvesting, packing and transportation is explained. Furthermore, the use of unmanned aerial vehicles for crop surveillance and other favorable applications such as optimizing crop yield is considered in this article. State-of-the-art IoT-based architectures and platforms used in agriculture are also highlighted wherever suitable. Finally, based on this thorough review, we identify current and future trends of IoT in agriculture and highlight potential research challenges.

INDEX TERMS Food quality and quantity, Internet-of-Things (IoTs), smart agriculture, advanced agriculture practices, urban farming, agriculture robots, automation, future food expectation.

I. INTRODUCTION

To improve the agricultural yield with fewer resources and labor efforts, substantial innovations have been made throughout human history. Nevertheless, the high population rate never let the demand and supply match during all these times. According to the forecasted figures, in 2050, the world population is expected to touch 9.8 billion, an increase of approximately 25% from the current figure [1]. Almost the entire mentioned rise of population is forecasted to occur among the developing countries [2]. On the other side, the trend of urbanization is forecasted to continue at an accelerated pace, with about 70% of the world's population predicted to be urban until 2050 (currently 49%) [3]. Furthermore, income levels will be multiples of what they are now, which will drive the food demand further, especially in developing countries. As a result, these nations will be more careful about their diet and food quality; hence, consumer preferences can move from wheat and grains to legumes and, later, to meat. In order to feed this larger, more urban, and richer population, food production should double by 2050 [4], [5]. Particularly, the current figure of 2.1 billion tons of annual cereal production should touch approximately 3 billion tons, and the annual meat production should increase by more than 200 million tons to fulfill the demand of 470 million tons [6], [7].

Not only for food, but crop production is becoming equally critical for industry; indeed crops like cotton, rubber, and gum

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are playing important roles in the economies of many nations. Furthermore, the food-crops-based bioenergy market started to increase recently. Even before a decade, only the production of ethanol utilized 110 million tons of coarse grains (approximately 10% of the world production) [7], [8]. Due to the rising utilization of food crops for bio-fuel production, bio-energy, and other industrial usages, food security is at stake. These demands are resulting in a further increase of the pressure on already scarce agricultural resources.

Unfortunately, only a limited portion of the earth's surface is suitable for agriculture uses due to various limitations, like temperature, climate, topography, and soil quality, and even most of the suitable areas are not homogenous. When zooming the versatilities of landscapes and plant types, many new differences start to emerge that can be difficult to quantify. Moreover, the available agricultural land is further shaped by political and economic factors, like land and climate patterns and population density, while rapid urbanization is constantly posing threats to the availability of arable land. Over the past decades, the total agriculture land utilized for food production has experienced a decline [9]. In 1991, the total arable area for food production was 19.5 million square miles (39.47% of the world's land area), which was reduced to approximately 18.6 million square miles (37.73% of the world's land area) in 2013 [10]. As such, the gap between demand and supply of food is becoming more significant and alarming with the passage of time.

Further examination showed that every crop field has different characteristics that can be measured separately in terms of both quality and quantity. Critical characteristics, like soil type, nutrient presence, flow of irrigation, pest resistance, etc., define its suitability and capability for a specific crop. In most of situations, the differentiations of characteristics can exist within a single crop field, even if the same crop is being cultivated in entire farm; hence, site-specific analyses are required for optimal yield production. Further, adding the dimension of time, specific crops in the same field rotate season-to-season and biologically reach different stages of their cycle within a year in areas where locational and temporal differences result in specific growth requirements to optimize the crop production. To respond to these demands with a range of issues, farmers need new technology-based methods to produce more from less land and with fewer hands.

Considering the standard farming procedures, farmers need to visit the agriculture sites frequently throughout the crop life to have a better idea about the crop conditions. For this, the need of smart agriculture arises, as 70% of farming time is spent monitoring and understanding the crop states instead of doing actual field work [11]. Considering the vastness of the agriculture industry, it incredibly demands for technological and precise solutions with the aim of sustainability while leaving minimum environmental impact. Recent sensing and communication technologies provide a true remote "eye in the field" ability in which farmers can observe happenings in the field without being in the field. Wireless sensors are facilitating the monitoring of crops constantly with higher accuracy and are able to, most importantly, detect early stages of unwanted state. This is the reason why modern agriculture involves the usage of smart tools and kits, from sowing to crop harvesting and even during storage and transportation. Timely reporting using a range of sensors makes the entire operation not only smart but also cost effective due to its precise monitoring capabilities. Variety of autonomous tractors, harvesters, robotic weeders, drones, and satellites currently complement agriculture equipment. Sensors can be installed and start collecting data in a short time, which is then available online for further analyses nearly immediately. Sensor technology offers crop and site-specific agriculture, as it supports precise data collection of every site.

Recently, the Internet-of-Things (IoT) is beginning to impact a wide array of sectors and industries, ranging from manufacturing, health, communications, and energy to the agriculture industry, in order to reduce inefficiencies and improve the performance across all markets [12]–[16]. If looking closely, one feels that the current applications are only scratching the surface and that the real impact of IoT and its uses are not yet witnessed. Still, considering this progress, especially in the near past, we can predict that IoT technologies are going to play a key role in various applications of the agriculture sector. This is because of the capabilities offered by IoT, including the basic communication infrastructure (used to connect the smart objects—from sensors, vehicles, to user mobile devices—using the Internet) and range of services, such as local or remote data acquisition, cloud-based intelligent information analysis and decision making, user interfacing, and agriculture operation automation. Such capabilities can revolutionize the agriculture industry which probably one of most inefficient sectors of our economic value chain today. To summarize this discussion, figure 1 provides the main drivers of technology, while figure 2 highlights

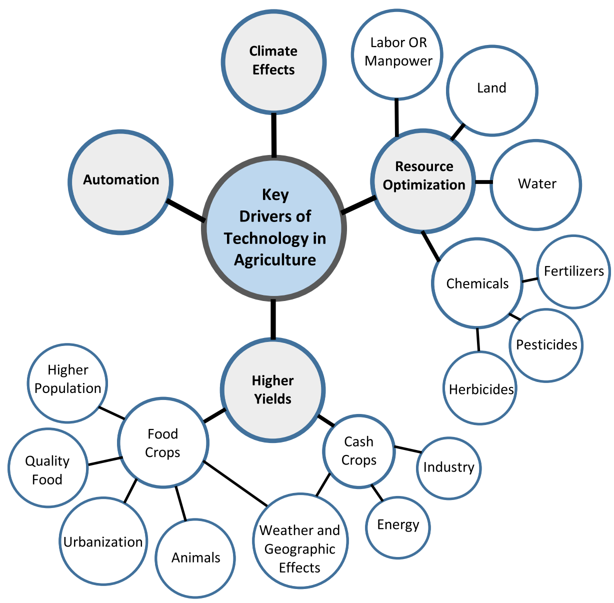

FIGURE 1. Key drivers of technology in agriculture industry.

FIGURE 2. Major hurdle's in technology implementation for smart agriculture.

the major hurdles of technology implementation in smart agriculture.

Researchers and engineers around the globe are proposing different methods and architectures and based on that suggesting a variety of equipment to monitor and fetch the information regarding crop status during different stages, considering numerous crop and field types. Focusing on the market demand, many leading manufactures are providing a range of sensors, unmanned aerial vehicles (UAVs), robots, communication devices, and other heavy machinery to deliver the sensed data. In addition, various commissions, food and agriculture organizations, and government bodies are developing polices and guidelines to observe and regulate the use of these technologies in order to maintain food and environment safety [17]–[20].

There are reasonable efforts that highlight the role of the IoT in the agriculture industry, but most of the published work focuses only on applications [10], [21], [22]. Most of the existing articles either provide no insight or show limited focus on the various IoT-based architectures, prototypes, advanced methods, the use of IoT for food quality, and other future issues considering the latest facts and figures. This manuscript examines the trends in IoT-based agriculture research and reveals numerous key issues that must be addressed in order to transform the agriculture industry by utilizing the recent IoT developments. The major contribution of this article is to provide real insight regarding:

- Expectations of the world from the agriculture industry
- Very recent developments in IoT, both scholarly and in industry are highlighted and how these developments are helping to provide solutions to the agriculture industry.
- Limitations, the agriculture industry is facing.
- Role of IoT to cope these limitations and other issues like resources shortage and their precise use, food spoilage, climate changes, environmental pollution, and urbanization.
- Strategies and policies that need to be considered when implementing IoT-based technologies
- Critical issues that are left to solve and possible solutions that are further required, while suggestions are provided considering these challenges.

This article is a compendium of knowledge that can help the researchers and agriculture engineers implementing the IoT-based technologies to achieve the desired smart agriculture. The rest of this document is organized as follows. Section II provides a deep overview of major applications of IoT in agriculture and what we can achieve by utilizing these technologies. Section III gives insight regarding the role of IoT in advanced agriculture practices, like vertical farming (VF), hydroponics, and phenotyping, to manage the issues of increased urban population. Section IV highlights various technologies and equipment, like sensors, robots, tractors, and communication devices, being used to implement IoT in this industry. Accepting the worth of UAVs in precision agriculture, Section V caters application achievements that are not possible even using other latest technologies. Food safety and transportation are other critical areas requiring focus to overcome the hunger issues which did not get the attention of researchers as it deserves. Section VI supplies the role of the IoT to ensure food quality for longer periods and to deliver to remote areas. Section VII identifies current and future trends of this technology in the crop industry by highlighting potential research challenges. Finally, Section VIII concludes this article.

II. MAJOR APPLICATIONS

By implementing the latest sensing and IoT technologies in agriculture practices, every aspect of traditional farming methods can be fundamentally changed. Currently, seamless integration of wireless sensors and the IoT in smart agriculture can raise agriculture to levels which were previously unimaginable. By following the practices of smart agriculture, IoT can help to improve the solutions of many traditional farming issues, like drought response, yield optimization, land suitability, irrigation, and pest control. Figure 3 lists a hierarchy of major applications, services and wireless sensors being used for smart agriculture applications. While, major instances in which the advanced technologies are helping at various stages to enhance overall efficiency are discussed below.

A. SOIL SAMPLING AND MAPPING

Soil is the ''stomach'' of plants, and its sampling is the first step of examination to obtain field-specific information, which is then further used to make various critical decisions at different stages. The main objective of soil analysis is to determine the nutrient status of a field so that measures can be taken accordingly when nutrient deficiencies are found. Comprehensive soil tests are recommended on an annual basis, ideally in Spring; however, based on soil conditions and

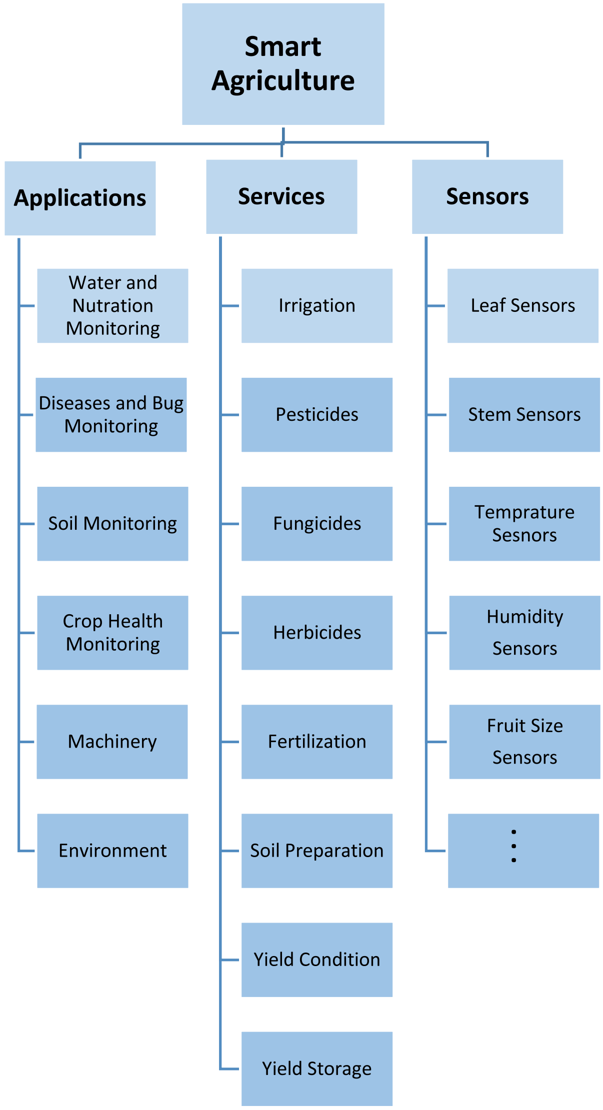

FIGURE 3. General hierarchy of possible applications, services and sensors for smart agriculture.

weather consents, it may be done in in Fall or Winter [23]. The factors that are critical to analyze the soil nutrient levels include soil type, cropping history, fertilizer application, irrigation level, topography, etc. These factors give insight regarding the chemical, physical, and biological statuses of a soil to identify the limiting factors such that the crops can be dealt accordingly. Soil mapping opens the door to sowing different crop varieties in a specific field to better match soil properties accordingly, like seed suitability, time to sow, and even the planting depth, as some are deep-rooted and others less. Furthermore, growing multiple crops together could also lead to smarter use of agriculture, simply making the best use of resources.

Currently, manufacturers are providing a wide range of toolkits and sensors that can assist farmers to track the soil quality and, based on this data, recommend remedies to avoid its degradation. These systems allow for the monitoring of soil properties, such as texture, water-holding capacity, and absorption rate, which ultimately help to minimize erosion, densification, salinization, acidification, and pollution (by avoiding excessive use of fertilizer). Lab-in-a-Box, a soil testing tool kit developed by AgroCares, is considered a complete laboratory in itself based on its offered services [24]. By using this, any farmer, without having any lab experience, can analyze up to 100 samples per day (overall, more than 22,000 nutrient samples a year) without visiting any lab.

Drought is a major concern which limits the productivity of crop yield. Most of the regions around the globe face this issue with various intensities. To deal with this issue, especially in very rural areas, remote sensing is being used to obtain frequent soil moisture data which helps to analyze the agricultural drought in far regions. For this purpose, the Soil Moisture and Ocean Salinity (SMOS) satellite was launched in 2009 which provides global soil moisture maps every, one to two days. Authors in [25] used SMOS L2 to calculate the Soil Water Deficit Index (SWDI) in Spain in 2014. In this effort, they followed different approaches to obtain the soil water parameters in order to compare with the SWDI acquired from in situ data. In [26], authors used the moderate resolution imaging spectroradiometer (MODIS) sensor to map various soil functional properties to estimate the land degradation risk for sub-Saharan Africa. The soil maps and field survey data, which covered all major climate zones on the continent, were used to develop the prediction models.

Sensors and vision based technologies are helpful to decide the distance and depth for sowing the seed efficiently. Like in [27], sensor and vision based autonomous robot called Agribot is developed for sowing seeds. The robot can perform on any agricultural lands on which the self-awareness of the robot's placement is ascertained through the global and local maps generated from Global Positioning System (GPS) while the on-board vision system is paired with a personal computer. Advancing further, various non-contact sensing methods are proposed to determine the seed flow rate as in [28] where the sensors are equipped with LEDs; consist of infrared, visible light and laser-LED as well as an element as a radiation receiver. The output voltage varies based on the movement of the seeds through the sensor and band of light rays, and falling of shades on the elements of receiver. The signal information, linked to the passing seeds, is used to measure the seed flow rate.

B. IRRIGATION

About 97% of Earth's water is salt-water held by oceans and seas, and only the remaining 3% is fresh water—more than two-third of which is frozen in the forms of glaciers and polar ice caps [29], [30]. Only 0.5% of the unfrozen fresh water is above the ground or in the air, as the rest lies underground [31]. In short, humanity relies on this 0.5% to fulfill all its requirements and to maintain the ecosystem, as enough fresh water must be kept in rivers, lakes, and other similar reservoirs to sustain it. It is worth mentioning that solely the agriculture industry uses approximately 70% of this accessible fresh water [32], [33]. In many countries, situation rises to 75% e.g. Brazil, further in some underdeveloped countries, even it exceeds 80% [34]. The main reason for this high water consumption is the monitoring procedure as even in 2013, crops visual inspection for irrigation decision-making was very common, as nearly 80% of farms in United States were observed by this [10], [35]. According to the UN Convention to Combat Desertification (UNCCD) estimates in 2013 show that there were 168 countries affected by desertification and by 2030, almost half of the world population will be living in areas with high water shortages [36]. Considering the figures of water crises around the globe, same time its increasing demands in agriculture and many other industries, it should be provided to places only where it is needed, most importantly, in required quantities. For this purpose, increased awareness has been implemented to conserve the existing under-stress water resources by employing more efficient irrigation systems.

Various controlled irrigation methods, like drip irrigation and sprinkler irrigation, are being promoted to tackle the water wastage issues, which were also found in traditional methods like flood irrigation and furrow irrigation. Both the crop quality and quantity are badly affected when facing water shortage, as irregular irrigation, even excess, leads to reduced soil nutrients and provokes different microbial infections. It is not a simple task to accurately estimate the water demand of crops, where factors like crop type, irrigation method, soil type, precipitation, crop needs, and soil moisture retention are involved. Considering this fact, a precise soil and air moisture control system using the wireless sensors not only makes an optimal use of water but also leads to better crop health.

The current situation of irrigation methods is expected to be changed by adopting the emerging IoT technologies. A significant increase in crop efficiency is expected with the use of IoT based techniques, such as crop water stress index (CWSI)-based irrigation management [10], [35]. For this, attaining crop canopy at different periods and air temperature are needed for the calculation of CWSI. A wireless sensors based monitoring system where all the field sensors are connected to collect the mentioned measurements, further transmit to processing center where corresponding intelligent software applications are used to analyze the farm data. Not only this but information from other sources including weather data and satellite imaging is applied to CWSI models for water need assessment, and finally specific irrigation index value is produced for each site. A prominent example is VRI (Variable Rate Irrigation) optimization by CropMetrics [37], which works according to topography or soil variability, ultimately improves the water use efficiency.

C. FERTILIZER

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A fertilizer is a natural or chemical substance that can provide important nutrients for the growth and fertility of plants. Plants mainly need three key macronutrients: nitrogen (N) for leaf growth; phosphorus (P) for root, flowers, and fruit development; potassium (K) for stem growth and water movement [38]. Any sort of nutrients deficiency or applying them improperly can be seriously harmful for the plant health. More importantly, excessive use of fertilizer not only results in financial losses but also creates harmful impacts to the soil and environment by depleting the soil quality, poisoning ground water, and contributing to global climate changes. Overall, crops absorb less than half the nitrogen applied as fertilizer, while remaining either emitted to the atmosphere or lost as run off. Unbalanced use of fertilizer leads to an imbalance in both soil nutrient levels and global climate as, reportedly, around 80% of the world's deforestation has occurred due to agricultural practices alone [39].

Fertilization under smart agriculture helps to precisely estimate the required dose of nutrients, ultimately minimize their negative effects on the environment. Fertilization requires site-specific soil nutrient level measurements based on various factors, such as crop type, soil type, soil absorption capability, product yield, fertility type and utilization rate, weather condition, etc. The reason is that the measurement of soil nutrient level is not only expensive but also time consuming, as, typically, investigations of soil samples at each location are required. To better depict this discussion, figure 4, summarizes the major inputs, processes and resultant outputs of smart agriculture.

New IoT-based fertilizing approaches help to estimate the spatial patterns of nutrients requirements with a higher accuracy and minimum labor requirements [40], [41]. For example, the Normalized Difference Vegetation Index (NDVI) uses aerial/satellite images to monitor crop nutrient status [42], [43]. Basically, NDVI is based on the reflection of visible and near-infrared light from vegetation and is used to estimate the crop health, vegetation vigor, and density, further contributing to assess the soil nutrient level. Such precise implementation can significantly improve the fertilizer efficiency, simultaneously reducing the side effects to the environment. Many recent enabling technologies, like GPS accuracy [44], geo mapping [45], Variable Rate Technology (VRT) [46], [47], and autonomous vehicles [48], are strongly contributing to IoT-based smart fertilization.

Other than precision fertilization, fertigation [49] and chemigation [50], [51] are other benefits of IoT. In these methods, water-soluble matters, such as fertilizers, soil amendments, and pesticides, can be applied through the irrigation system. Although, these methods are not new to agriculture and have been applied over last three decades, their precise use with real results has been witnessed only with IoT integration [52], [53]. Based on recent outcomes, fertigation is considered as the best management practice to improve the effectiveness of many agriculture matters; most importantly, it can be integrated with IoT-based smart farming infrastructure seamlessly.

D. CROP DISEASE AND PEST MANAGEMENT

The Great Famine, also known as the Irish Potato Famine, in which approximately one million Irish people died around 1950, resulted due to crop failure and yield

FIGURE 4. Some key inputs, processes involved and possible outputs of smart farming.

reduction caused by "potato blight" disease [54]. Even today, corn growers in the US and southern Canada are facing an economic loss of approximately one billion USD due to "southern corn leaf blight" disease [55]. The Food and Agriculture Organization (FAO) estimates that 20–40% of global crop yields are lost annually due to pests and diseases [56]. To control such vast production losses, pesticides and other agrochemicals became an important component of the agriculture industry during the last century. It is estimated that, in each year, around half a million tons of pesticide are used in the US alone, while more than two-million tons are used globally [57]. Most of these pesticides are harmful to human and animal health, leaving severe, even irreversible, impact to the environment, ultimately causing significant contamination to entire ecosystems [58], [59].

Recent IoT based intelligent devices, such as wireless sensors, robots and drones are allowing the growers to slash pesticide uses significantly by precisely spotting crop enemies. Compared to traditional calendar or prescription based pest control procedures, modern IoT-based pest management provides real-time monitoring, modeling, disease forecasting, hence proving more effective [60], [61].

Generally, the reliability of crop disease monitoring and pest management depends on three aspects: sensing, evaluating, and treatment. The advanced disease and pest recognition approaches are based on image processing in which raw images are acquired throughout the crop area using field sensors, UAVs, or remote sensing satellites. Usually, remote sensing imagery covers large areas and, hence, offers higher efficiency with lower cost. On the other hand, field sensors are capable to support more functions in collecting data, like environment sampling, plant health, and pest situations, in every corner throughout the crop cycle. For example, IoT-based automated traps [62], [63] can capture, count, and even characterize insect types, further uploading data to the Cloud for detailed analysis, which is not possible through remote sensing.

Approaches like vehicle precise spray and automatic VRT chemigation [64], commonly used under smart fertilization, can also be utilized for disease treatment and other pesticide applications. Moreover, the advancement of robotic technology offers new solutions. When equipping an agricultural robot with multispectral sensing devices and precision spraying nozzles, it can locate and deal with pest problems more precisely under the manipulation of a remote IoT disease management system. This IoT-based pest management system has many advantages, as it can reduce the overall expenditures while, at the same time, support the restoration of the natural climate. For example, recently, it has been found that yields of many crop types are facing severe threat due to the lack of pollination [65], [66]. In fact, the pollination is being affected due to bee colony collapse disorder resulting from the uncontrolled pesticides.

E. YIELD MONITORING, FORECASTING, AND HARVESTING

Yield monitoring is the mechanism used to analyze various aspects corresponding to agricultural yield, like grain mass flow, moisture content, and harvested grain quantity. It helps to accurately assess by recording the crop yield and moisture level to estimate, how well the crop performed and what to do next. Yield monitoring is considered an essential part of precision farming not only at the time of harvest but even before that, as monitoring the yield quality plays a crucial role. Yield quality depends on many factors, e.g. sufficient pollination with good quality pollen especially when predicting seed yields under changing environmental conditions [67]–[69]. Currently, when we are dealing with more open markets, buyers around the world become more particular about fruit quality; hence, effective production depends on the right fruit size to the right market at the right time [13].

Crop forecasting is an art to predict the yield and production (tons/ha) before the harvest takes place. This forecasting helps the farmer for near-future planning and decision making. Furthermore, analyzing the yield quality and its maturity is another critical factor which enables the determination of the right time for harvesting. This monitoring covers various development stages and uses fruit conditions like its color, size, etc., for this purpose. Predicting the right harvesting time not only helps to maximize the crop quality and production but also provides an opportunity to adjust the management strategy. Although, harvesting is the last stage of this process, proper scheduling can make a clear difference. To obtain the real benefits from crops, farmers need to know when these crops are actually ready to harvest. Figure 5 represents a snapshot of a farm area network (FAN) that can portrait the whole farm to the farmer in real time.

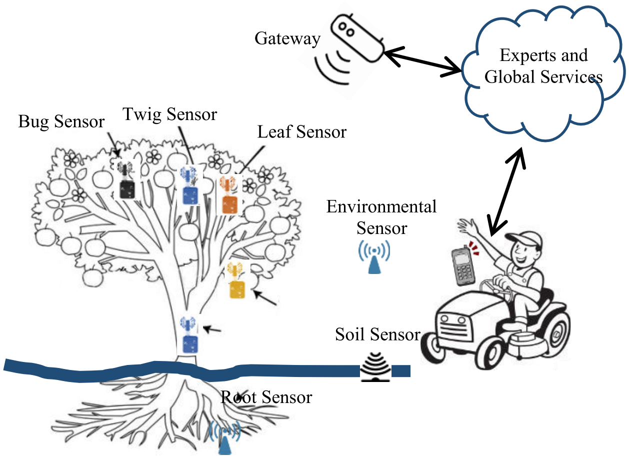

FIGURE 5. **An IoT based farm area network (FAN).**

A yield monitor, developed in [70], can be installed on any harvester combine and linked with the mobile app FarmRTX, which displays live harvest data and uploads it automatically to the manufacturer's web-based platform. This app has the ability to generate high-quality yield maps and share these maps with an agronomist, and the farmer also has the option to export to other farm management software to analyze them. To estimate the production and quality of yield precisely, the measurement of fruit growth can be highly beneficial. This idea is used in [71], where authors considered the fruit growth as the most basic and relevant parameter to estimate that how well the crop is progressing. Satellite images can be a good option to monitor the yield of crops with vast areas. This method is utilized in [72], where authors used Sentinel-1A Interferometric images to map the rice crop yield and intensity in Myanmar. As we mentioned earlier in this section, fruit size always plays a critical role to estimate its maturation, making decisions regarding harvesting, and targeting the right market, for this purpose, color (RGB) depth images are used in [73] to track the different fruit conditions in mango farms. Similarly, multiple optical sensors are used in [74] to monitor the shrinking of papayas, especially during drying conditions.

III. ADVANCED AGRICULTURAL PRACTICES

Adopting the novel methods to enhance the quality and quantity of food is not something new, as humans have been doing this for centuries. Initially, we tried to enhance the crop production by focusing on seed variety, fertilizers, and pesticides. Soon it was realized that these conventional ways were not adequate enough to fit this demand gap; hence, agriculture scientists have begun thinking of other alternatives, like bioengineered (BE) foods. BE foods, also known as genetically modified (GM) or genetically engineered (GE) foods, are foods produced by introducing changes into their DNA using the methods of genetic engineering. However, several studies highlight their serious effects on human health, including infertility, disruption in immune system, accelerated aging, faulty insulin regulations, etc. [75], [76]. All these and many other similar technologies did not receive much popularity and acceptance in society because people prefer bio and organic food. In this regards, massive research has been conducted for decades in which sensors and IoT-based technologies are helping to improve conventional agriculture processes to enhance yield production without, or with minimum, effect on its originality. For this purpose, new sophisticated and more controlled environments are projected to tackle the above-mentioned issues. The importance and involvement of new technologies is more critical, as we are moving toward more cultured and urban farming. In fact, it would not be incorrect for one to say that the success of these advanced practices is in doubt without using sensor-based technologies.

A. GREENHOUSE FARMING

Greenhouse farming is considered the oldest method of smart farming. Although, the idea of growing plants in controlled environment is not new as found since Roman times but it gained popularity in 19th century where largest greenhouses were built in France, Netherlands and Italy. Further, the practice was accelerated in the mid-20th century and highly promoted in countries that facing harsh weather conditions [77]. Crops grown indoors are very less affected by environment; most importantly, they are not limited to receiving light only during the daytime. As a result, the crops that traditionally could only be grown under suitable conditions or in certain parts of the world are now being growing anytime and anywhere. This was the actual time in which sensors and communication devices started to support various agriculture applications genuinely.

The success and production of various crops under such controlled environment depend on many factors, like accuracy of monitoring parameters, structure of shed, covering material to control wind effects, ventilation system, decision support system, etc. A detailed analysis is provided in [78], where all these factors, their impacts, and how wireless sensors can help for all this are considered. Precise monitoring of environment parameters is the most critical task in modern greenhouses, where several measurement points of various parameters are required to control and ensure the local climate. In [79], an IoT-based prototype is proposed to monitor the greenhouses where MicaZ nodes are used to measure the inside parameters like humidity, temperature, light, and pressure.

B. VERTICAL FARMING

The world needs more farmable lands to fulfill increased food demands, but reality is that one-third arable land was lost during the last four decades due to erosion and pollution [80], [81]. Unfortunately, current agricultural practices based on industrial farming are damaging the soil quality far faster than nature can rebuild it. Overall, it is estimated that erosion rates from cultivated fields is 10 to 40 times greater than the soil formation rates [82]. Considering the reduction of arable land issues, it could be a disaster for food production in the near future with current agriculture practices. Further, as we mentioned, 70% of fresh water is only used for agriculture purpose, which can increase the burden on existing limited water reservoirs. Vertical Farming (VF) is an answer to meet the challenges of land and water shortages.

VF in the form of urban agriculture offers an opportunity to stack the plants in a more controlled environment resulting in, most importantly, significant reduction in resource consumption. By following this method, we can increase the production multiple times, as only a fraction of ground surface is required (depending on the number of stacks) as compared to traditional agriculture practices. Not only for ground surface, this system is highly efficient in terms of other resources, as well. For example, according to Mirai, a Japan based indoor farm developer presented the figures regarding a Japanese farm comprised of 25,000 square meters. The figures are highly encouraging, as it is producing 10,000 heads of lettuce per day (double the production when compared with traditional methods) and is, most importantly, consuming 40% less energy and up to 99% reduced water consumption compared to outdoor fields [83]. Aerofarms, a leader in VF, growing agricultural products with upto 390 times higher yields while utilizing 95% less water at Newark [84].

Under this farming method, many parameters are important, but CO_2 measurements are most critical; hence, non-dispersive infrared (NDIR) CO_2 sensors play a critical role to track and control the conditions in vertical farms. Boxed Gascard, developed by Edinburgh Sensors [85], is especially designed by considering such an environment, which employs a pseudo dual beam NDIR measurement system to enhance the stability and reduced optical complexity. Human hands are not required to touch the crops at any stage when following the IoT-connected vertical farm; this is the claim made by Mint Controls [86] developers who offer a wide range of solutions, like waste containers and sensors and their integration for various VF applications.

C. HYDROPONIC

In order to enhance the benefits of greenhouse farming, agriculture experts moved forward another step and provided the idea of hydroponic, a subset of hydroculture in which plants are grown without soil. Hydroponic is based on an irrigation system in which balanced nutrients are dissolved in water and crop roots stay in that solution; in some cases, roots can be supported by medium like perlite or gravel. When combining hydroponics with VF, a farm of 100 sq. meters can produce the crop equivalent to 1 acre of traditional farm, most importantly upto 95% less water and fertilizers utilization and without pesticides/herbicides [87]. Currently, available systems and sensors e.g. [88], [89] are not only used to monitor a range of parameters and take readings at predefined intervals but, also, the measurements are stored so that can be used to analyze and diagnostic purpose later on.

Under this application, the precision of nutrient measurements is crucial, as such, a highly reliable wireless control system for tomato hydroponics is proposed in [90] in which they focused on various communication standards that are least effected by plants' presence and their growth. The monitoring of solution contents and their precision is most critical under this method; for this purpose, many systems are offered to check the presence of contents considering the plant demands. In [91] a wireless-sensor-based prototype is proposed to deliver a turn-key solution for the hydroponic cultivation which offers real-time measurements for soilless indoor growing. Further, a compact sensor module is presented in [92], which uses oscillator circuits to measure the presence and concentrations of various nutrients and water levels.

D. PHENOTYPING

The previously discussed smart methods look more promising for the future of agriculture, as they are already being used to produce different crop products under precise environments. Other than these, a few advanced techniques are under experiment to further enhance the crop capabilities by controlling their limitations with the help of advanced sensing and communication technologies. Among these methods, the more prominent is phenotyping, which is based on emerging crop engineering, which links plant genomics with its ecophysiology and agronomy, as shows in Figure 6. The progress in molecular and genetic tools for various crop breeding was significant in the last decade. However, a quantitative analysis of the crop behavior, e.g. grain weight, pathogen resistance, etc., was limited due to the lack of efficient techniques and technologies that we can now enjoy.

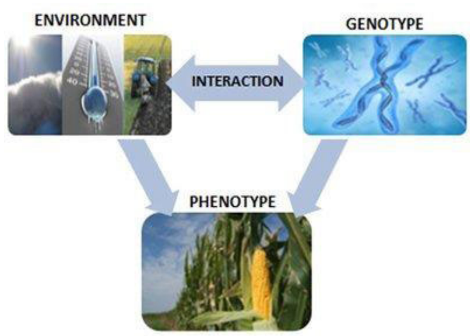

FIGURE 6. The process of phenotyping [96].

Research investigations, completed in [93], conclude that plant phenotyping can be highly beneficial to investigate the quantitative characteristics, such as those are responsible for its growth, yield quality and quantity, and resistance capabilities to handle various stresses. Similarly, the role of sensing technologies and image-based phenotyping are highlighted in [94] and describes how these solutions can help to boost the progress not only for screening numerous biostimulants but also their role in understanding the mode of actions. Furthermore, an IoT-based phenotyping platform, CropQuant, is designed to monitor the crop and relevant trait measurements that can provide facility for crop breeding and digital agriculture [95]. Here, an automatic in-field control system was developed to process the data generated by platform. The provided trait analyses algorithms and machine-learning modeling help to explore the relation among the genotypes, phenotypes, and environment where it grows.

IV. MAJOR EQUIPMENT AND TECHNOLOGIES

Different from ancient farming, most of the tasks in modern, large-scale agriculture are being done by heavy and urbane equipment, such as tractors, harvesters, and other robots which are fully or partially supported by remote sensing and other communication technologies. In precision agriculture, when tasks like sowing, fertilizing, irrigation, and harvesting are being performed, the operating vehicles are equipped with GPS and GIS facilities so that they can work precisely, site-specifically, and autonomously. In fact, the idea of site-specific crop management is not possible without involving the recent advanced technologies. The success of precision agriculture is based on the accuracy of collected data, which is usually done in two ways [10]. The first entails the usage of multifunctional imaginary devices equipped with remote sensing platforms, such as satellites, agriculture airplanes, balloons, and UAVs; the second is from various types of sensors—those that are mostly deployed for specific purpose across various sites of our interest. The gathered data is identified with the precise location information by using GPS devices so that the site-specific treatment can be provided afterwards.

Agriculture has transformed during the last few decades from small/medium farming operations to highly industrialized and commercial farming. This transition allows the leading corporations to treat agriculture like other industries, e.g., manufacturing where the measurements, data, and control are very important to provide a balance between costs and production in order to boost the profits. Accordingly, every aspect of agriculture that can be automated, digitally planned, and managed will benefit from IoT technologies and solutions. Based on this fact, efforts are being focused to offer more sophisticated tools such as agricultural robots to perform a range of activities, like planting, watering, weeding, picking, thinning, fertilizing, spraying, packing and transporting. This revolution is being driven not only due to the advancement of technology, but is also a result of factors like fear of losing the low-cost labor, most importantly need for better and cheaper food.

Based on these facts, during the period of 2017 to 2022, the global smart farming market is predicted to rise at a growth rate of 19.3% per year to touch $23.14 billion in 2022 [97]. Here it is worth mentioning that UAV/drones are generating and further expected to generate the highest revenue amongst all agricultural robots utilized in smart farming (UAVs are discussed in Section V). Evergreen demand for higher crop yield, increased incorporation of information and communication technology (ICT) in farming and the rapid global climatic changes are some of the major drivers resulting to such high market growth.

Manufacturers in the market offer a variety of products and solutions, mostly based on sensors and efficient communication for a range of applications; a few are shown in figure 7. The key technologies and equipment's that are currently available for this purpose are discussed in following.

FIGURE 7. Selected IoT based products and prototypes for smart agriculture.

A. WIRELESS SENSORS

Among all the equipment for smart farming currently available in the market, wireless sensors are the most crucial and play a key role when it comes to collecting the crop conditions and other information. Wireless sensors are being used standalone wherever required, further integrated with almost every portion of advanced agricultural tools and heavy machinery, depending on application requirements. In the following, major sensor types are discussed according to their working procedure and purpose and the benefits they offer.

1) ACOUSTIC SENSORS

Acoustic sensors offer a miscellaneous appliance in farm management, including soil cultivation, weeding, fruit harvesting, etc.; the main benefit of this technology is its low-cost solutions with fast response, especially when considering portable equipment. It functions by measuring the change in the noise level as the tool interacts with other materials, e.g., soil particles [98]. Acoustic sensors are commonly used for pest monitoring and detection [99] and classifying the seed varieties according to their sound absorption spectra [100].

2) FIELD-PROGRAMMABLE GATE ARRAY (FPGA)-BASED SENSORS

FPGA based sensors are starting to be used in agriculture recently due to their flexibility of reconfiguration. The major options where these can be employed include measuring real-time plant transpiration, irrigation, and humidity [101], [102]. However, their utilization in agriculture is in the early stages due to their limitations, such as size, cost, and power consumption. These sensors require more power; hence, they are not suitable for continuous monitoring, further high in cost even compromising on performance [103]. By overcoming these issues, FPGA-based sensors can offer satisfactory solutions according to specific application requirements.

3) OPTICAL SENSORS

These sensors use light reflectance phenomena and help to measure soil organic substances, soil moisture and color, presence of minerals and their composition, clay content, etc. [104], [105]. These sensors test the soil's ability to reflect light based on different parts of the electromagnetic spectrum. The changes occurred in wave reflections help to indicate the changes in soil density and other parameters. Fluorescence-based optical sensors are used for basic plant assessment, especially to supervise the fruit maturation [106]. Further, when integrating optical sensors with microwave scattering, it can be used for characterizing grove canopies, like olives and other similar crops [107].

4) ULTRASONIC RANGING SENSORS

Sensors of this category are considered a good choice being low cost, potential to operate in a variety of applications, and ease of use and adjustability, such as the sampling rate. Common uses are tank monitoring, spray distance measurement (e.g., boom height and width control in order to perform uniform spray coverage, object detection, and collision avoidance), and monitoring crop canopy [108], [109]. When combined with a camera, these sensors can then be used for the weed detection [110], where the heights of plants are identified using the ultrasonic sensors and the camera determines the weed and crop coverage.

5) OPTOELECTRONIC SENSORS

Optoelectronic sensors can differentiate plant type; hence, they help to detect weeds, herbicides, and other unwanted plants, especially in wide-row crops [111]. When combining, an optoelectronic sensor and location information, it can map the weed distribution and resolution [112]. Optoelectronic sensors are also capable of differentiating between vegetation and soil from their reflection spectra.

6) AIRFLOW SENSORS

These sensors are capable of measuring soil air permeability and percentage of moisture and identifying soil structure to distinguish different types of soils. Measurements can be made at singular locations or dynamically while in motion, e.g., can be used on a fixed position or in mobile mode. The desired output is the pressure required to push a predetermined amount of air into the ground at a prescribed depth. It follows the procedure of various soil properties, including compaction, structure, and moisture levels, producing unique identifying signatures [113].

7) ELECTROCHEMICAL SENSORS

These are mostly used to assess the significant soil characteristics to analyze the soil nutrient levels, such as pH [114]. The standard chemical soil analysis, which are mostly expensive and time consuming, can be easily substituted with these sensors. To be more precise, the macro and micro nutrients in the soil, salinity and pH [115], are measured using sensors of this nature.

8) ELECTROMAGNETIC SENSORS

Electromagnetic sensors are used to record electrical conductivity and transient electromagnetic response, identify electrical response, and adjust variable rate applications in the actual situation. Sensors based on this technology use electric circuits to measure the capability of soil particles to conduct or accumulate electrical charge, which is mostly done by the following two methods: contact or non-contact [116]. Residual nitrates and organic matter in the soil can also be measured using the electromagnetic sensors, as done in [117].

9) MECHANICAL SENSORS

Mechanical sensors assess the soil mechanical resistance (compaction) to indicate the variable level of compaction. The mechanical sensors enter or cut through the soil and record the force assessed by strain gauges or load cells [118]. A pressure unit is used to measure the soil's mechanical resistance, which is actually the ratio of the force needed to go into the soil medium using the frontal part of the tool, actually engaged with the soil.

10) MASS FLOW SENSORS

Category of this sensors are used for yield monitoring, as it provides the yield information by measuring the amount of grain flow, e.g., when passing through the combine harvester. Sensing the mass flow of grain to determine the crop yield is not new, as it has been performed the last two decades [119]. The mass flow sensor is the most critical component, but, overall, the yield monitoring system consists of several other modules, like the grain moisture sensor, data storage device, and an internal software to analyze the data,, which are within the interface provided in the John Deere tractors [120].

11) EDDY COVARIANCE-BASED SENSORS

This type of sensors can be used for quantifying exchanges of carbon dioxide, water vapor, methane or other gases, and energy between the surface of the earth and the atmosphere. This method offers an accurate way to measure surface-atmosphere fluxes of energy and trace gas fluxes over a variety of ecosystems for, most importantly, agricultural applications [121]. Currently, the sensors based on this technology are preferred over other similar options, like the close chamber, due to high precision and its ability to measuring continuous flux over large areas [122].

12) SOFT WATER LEVEL-BASED (SWLB) SENSORS

SWLB sensors are being utilized in agriculture catchments to characterize hydrological behaviors, such as water level and flow, at adjustable time-step acquisitions. This is done by measuring rainfalls, stream flows, and other water presence options [11], [123].

13) LIGHT DETECTION AND RANGING (LIDAR)

This technology is widely used in a range of agriculture applications, such as land mapping and segmentation, determining soil type, farm 3D modelling, monitoring erosion and soil loss, and yield forecasting [124]–[126]. LiDAR is also commonly used to obtain dynamic measurement information regarding fruit-tree leaf area, and, when combined with GPS, it can produce a 3D map [127]. Moreover, this technology is often used when estimating the biomass of various crops and trees [128].

14) TELEMATICS SENSORS

Telematics sensors support telecommunication between two places—more precisely, among two vehicles when considering the agriculture-based applications. Telemetry sensors are used to collect data from remote locations (especially inaccessible points), operations of machines that report on how the components are working, and record location and travel routes to avoid visiting the same patch [129]. These services enable farm managers to record and store all information related to farm operations automatically, which maximizes the utilization of environmental benefits, further can minimize threats like farm equipment theft as utilized in [130], [131].

15) REMOTE SENSING

Sensors belong to this category are used to capture and store the geographic information, further analyze, manipulate, manage and present all types of spatial or geographical data. Similar to LiDAR, these sensors also found significant use in agriculture applications including crop assessment, forecasting yield dates, yield modelling and forecasting, identification of plants and pests, land cover and degradation mapping etc [132]–[134]. Argos sensor is one of leading example, a satellite-based sensor system used to collect, process and disseminates environmental data from fixed and mobile platforms worldwide [135]. Moreover, automatic packet reporting system (APRS) is being integrated to report telemetry data through satellite communication [136].

Table 1 lists a few sensors to provide the idea about their possible uses and the environment where they can be placed.

TABLE 1. Some selected sensors and their possible uses in IoT based agriculture.

Sensor/ System	Target/Placed				Considered Purpose/Parameters							
	Plant	Equipment	Soil	Weather	Yield	Temp	Moisture	Location/Tracking	Wind	Pollution /Co2	Water	Fruit/ Stem Size
Loup 8000i [137]		✓			✓		✓					
XH-M214 [138]			✓				✓					
Ag Premium Weather [139]		✓		✓		✓		✓	✓			
FI-MM [140]	✓											✓
PYCNO [141]			✓	✓		✓	✓				✓	
MP406 [142]			✓			✓	✓					
DEERE 2630 [143]		✓			✓		✓					
Sol Chip Com (SCC) [144]				✓						✓	✓	
SenseH2TM [145]	✓								✓	✓		
DEX70 [146]	✓											✓
Piccolo ATX [147]		✓						✓				
CI-340 [148]	✓						✓			✓		
Wind Sentry 03002 [149]				✓					✓			
AQM-65 [150]				✓						✓		
POGO Portable [151]			✓			✓	✓				✓	
SF-4/5 [152]	✓											✓
Met Station One [153]				✓					✓			
SD-6P [154]	✓											✓
B-102 [155]		✓						✓				
YieldTrakk [156]		✓			✓		✓	✓				

B. IOT BASED TRACTORS

As rural labor resources have started to come under stress due to the expansion of the crop industry, tractors and other automatic heavy machinery started to enter the agriculture sector. Where available, an average size tractor can work 40 times faster with significantly less expenses than traditional farm labor [157]. To fulfill the continuously increasing demands, agricultural-based equipment manufacturers, like John Deere, Hello Tractors, Case IH and CNH (New Holland), have started to provide better solutions focusing on the grower's requirements. With the advancement of technology, most of these manufacturers are offering tractors with automatic-driven and even Cloud-computing capabilities. This technology is not new, as self-driving tractors have been in the market even before semi-autonomous cars. One of the main advantages of self-driving tractors is their ability to avoid revisiting the same area or row by reducing the overlap even less than an inch. In addition, they can make very precise turns without a driver's physical presence. This facility offers better precision with reduced errors, especially when spraying insecticide or targeting weeds; those are mostly unavoidable when a human controls the machinery.

Although, at the moment, no fully autonomous tractor is available in market, many researchers and manufactures are hardly working to mature the technology. Based on current progress and future demands of high-tech tractors, it is predicated that around 700,000 tractors equipped with facilities like autosteer or tractor guidance will be sold in 2028 [158], while the same study expects that around 40,000 unmanned, fully-autonomous (level 5) tractors will be sold in 2038 [159].

When talking about such cultured machines, most farmers can't afford to own them while most of the tractor service providers and manufacturers operate well below their potential. Considering the challenge, Hello Tractor has developed a solution to sort these issues. The company has developed a low-cost monitoring device that can be placed on any tractor, provides powerful software and analytics tools [160]. The benefits of this device are twofold- on one side it ensures that overall cost of tractor remains affordable for the most of growers while at the same time it monitors the condition of the tractor and reports if any problems occur. The software connects tractor's owner to farmers in need of tractor services, just like Uber for tractors. Another major example is Case IH's Magnum series [161] tractor which uses on board video cameras and LiDAR sensors for object detection and collision avoidance. Recently, Case IH used this tractor to plant soybeans by following the concept of autonomous tractors. In another development made by standards group ETSI where world's first tractor connected to a car in France, using IoT [162] to control the accidents due to farm vehicles.

After collecting all the important crop data, the next step is pushing computing from the Cloud to the edge, as John Deere [163] wants. In their proposed system, an analytics engine works locally on the farmer's tractor rather than in the Cloud in order to adjust the local inputs. For this purpose, they considered all the existing analytics and recommendations to modify the current data in real time depending on the field conditions. Based on this phenomenon, the manufacturer is bringing their tractors to next level by connecting their machine to the Internet and creating a method to display the information wherever farmer wants to see it.

C. HARVESTING ROBOTS

Harvesting is the most critical stage during the production process, as this last phase dictates the crop's output and, ultimately, its success. In some crops, this is done a single time while, in some others, performed several times, even on a daily basis, as crop reaches a certain stage. Harvesting the crop at the right time is very critical, as doing so either early or late can affect the production significantly. When talking about the labor, it is estimated that the US faces a \$3.1 billion decline in crop production on a yearly basis due to labor shortage [164]. Not only this, but, according to a study conducted by the United States Department of Agriculture, overall 14 % of farm costs go to wages and labor costs, while it can be upto 39% in some labor intensive farms [165]. Considering the worth of this stage and labor issues, farm experts expect that involvement of agriculture robotics may not only ease the labor pressure but also provide the flexibility to harvest whenever needed.

In order to automate the harvesting process and make it more precise, the role of robots has been increasing over the recent decades. Considering the robot services, many researchers have done intensive research in order to mature the sensitivity of fruit detection, its shape, size, color, and localization [166]–[169]. Automatic harvesting of fruits requires deep investigation of sophisticated sensors that are capable of collecting precise and unambiguous information of that particular crop and fruit. The task of detecting the right target in natural scenes is not simple since most of the fruits are occluded partially—sometimes even fully—under the leaves and branches or are overlapped with other fruits [170]. Here, most of the prominent studies found in regard to this purpose are deeply based on computer vision, image processing, and machine learning techniques. This process needs very specialized and sophisticated tools to differentiate the fruit conditions, as there are more than sixty shapes, sizes, and colors for a pepper alone when it is ready to harvest. Considering such complexity, many robots are being developed for specific crops. Some of the leading robots being used for crop harvesting include SW 6010 [171] and Octinion [172] for strawberries, SWEEPER robot [173] for peppers, and FFRobot [174] for tree-based fruits like apples which can pick up to 10,000 fruits per hour.

Strawberries are one of the most consumed fruits, available mostly throughout the year while labor is the major contributor to the high cost of this fruit, especially during harvesting and packaging stages [175]. As the strawberry farms are grown mostly under greenhouse systems hence the harvesting robots are designed to move on defined paths like rails where the translational motion is restricted and robots can move backward and forward only. Robots developed by Agrobot are able to collect strawberries along the side of strawberry plant rows in the field, further packed by human operators [176]. For example, SW6010 by Agrobot is a specialized and semi-automatic robot towards the specific task of strawberry harvesting [177]. Tektu T-100 is an all-electric rechargeable strawberry harvester run silently with zero emission inside the poly-tunnels [178]. The installed pickers are able to position over the crop rows and gather the fruit quickly and efficiently, directly into punnets.

D. COMMUNICATION IN AGRICULTURE

Communication and reporting the information on a timely basis are considered the backbone of precision agriculture. The real purpose cannot be achieved unless a firm, reliable, and secure connection among various participating objects is provided. To achieve communication reliability, telecom operators can play a crucial role in the agricultural sector. If we truly want to implement IoT on a large scale in the agriculture industry, we have to provide a suitably large architecture. Here, the factors like cost, coverage, energy consumption, and reliability are critical and have to be considered before choosing the mean of communication. Low-energy networks can provide connectivity only on one site and mostly do not offer services in remote areas where sensed data need to be transmitted to the farm management system (FMS). Depending on availability, scalability and application requirements, various communication modes and technologies are being used for this purpose, most common are discussed here,

1) CELLULAR COMMUNICATION

Cellular communication modes from 2G to 4G can be suitable, depending on the purpose and bandwidth requirement; however, the reliability, and even availability, of a cellular network in rural areas is a major concern. To tackle this, data transmission via satellite is another option, but, here, the cost of this communication mode is very high, which makes it not suitable for small- and medium-sized farms. The choice of communication mode also depends on application requirements, such as some farms required sensors that can operate with low data rate but need to work for long periods hence demand long battery life. For such scenarios, a new range of Low Power Wide Area Network (LPWAN) is considered a better solution for cellular connectivity, not only in terms of long battery life but also a larger connectivity range with affordable rates (2 to 15 USD per year) [179]. Currently, crop and pasture management are two of the main applications where LPWAN networks are highly suitable, and, further considering its success, it can be utilized in many other farming-related uses.

Besides WAN connectivity option, many short range and medium level communications are being used in mesh networks [180]. For example, a mesh-network of sensor nodes collects data and transmits it to the gateway which is located somewhere in the same area. The gateway further sends this data to the farm management system using the WAN network. The communication technologies used within the mesh networks vary e.g. Bluetooth and Zigbee can be used to provide connectivity for peer-to-peer wireless communications. From here, the sensed data forwarded to the FMS, which gathers and analyses the information about all the activities happening at different parts even the historical data regarding the weather and climate updates, economic, products being used and their specifications etc, in short making it decision farming. It is important to mention that, the communication technology has its own worth but the FMS also plays a critical role which must be custom designed considering the specific application requirements. Generally, based on communication data rates and power consumption, wireless sensors for agriculture applications are divided in three broad categories as shown in table 2.

TABLE 2. Data and power specifications of wireless sensors commonly used for agriculture applications.

Communication/ Data type	Possible application	Expected Data size	Power consumption (active mode)
Small sized data and low power consumption	(1) Air temperature/ humidity/ direction / speed (2) Soil temperature/ humidity (3) Leaf thickness/color (chlorophyll) (4) Trunk thickness/flux flow (5) Fruit size	100s of bytes	Less than a mA (Fractions of mA)
Medium sized data and medium power consumption	(1) Still picture camera (2) Multi or hyper spectral camera (3) Acoustic sensors	10s of Mb	10s of mA
Large sized data and large power consumption	Video streaming cameras	10s of Mb per minute	50 A

2) ZIGBEE

Zigbee is primarily designed for a wide range of applications especially to replace existing non-standard technologies. Depending on the application requirements, the devices based on this protocol can be one of three types including Coordinator, Router and End User. Further, three different topologies are supported by Zigbee networks named, Start, Cluster Tree and Mesh [34]. Based on these characteristics, and further considering the agriculture application requirements, Zigbee can play vital role especially targeting the greenhouse environment where usually short range communications are required. During monitoring the various parameters, the real time data from the sensor node is transferred through Zigbee to end server. For the applications like, irrigation and fertilization, Zigbee modules are networked for communication, e.g. in drip irrigation used to monitor soil contents like moisture. Further, SMS is forwarded to the farmer to update about the field data where GSM is required at long distance or Bluetooth module can help at the shorter distances.

3) BLUETOOTH

Bluetooth is a wireless communication standard that connects small-head devices together over shorter distances usually cooperating in a close proximity. Due to its advantages of low power requirements, easy to use and low cost, this technology is being utilized in many smart farming applications. Further, Bluetooth making advancements in many IoT systems with the release of Bluetooth Low Energy (BLE) or commonly known as Bluetooth Smart. The study conducted in [181] which tests Bluetooth and PLC (programmable logic controller) with ICS (integrated control strategy), timer control and soil moisture control approach for smart irrigation. The target of this study is to find an optimum utilization of water and energy consumption for various greenhouse or field applications. A moisture and temperature sensor based on BLE is developed in [182] especially focusing on the agriculture environments and weather conditions of crop fields. Here the reason of choosing BLE for communication purpose is due to its inherent support for smart phone accessibility. Further, a similar effort is done in [183] where a new sensor node is designed to monitor ambient light and temperature employing BLE communication protocol preferable for IoT based agriculture applications. Other than short range, WiFi is utilized whenever LAN communications are required in smart agriculture. Along short range connectivity, WiFi is utilized whenever LAN communications are required in smart agriculture. Study presented in [184] investigates a remote monitoring system using WiFi, where the sensor nodes were based on WSN802G modules. The deployed nodes communicate wirelessly with a central server, which is responsible to collect and store the monitored data and further allow displaying the information after required analysis.

4) LORA

LoRa wireless technology is a long-range, low-power platform used extensively in IoT applications. Being low in power consumption, it offers LPWAN connectivity between the wireless sensors and the Cloud. It has proved itself much more effective and reliable than Bluetooth, Wi-Fi, etc. especially in restaurants or kitchen environments. Sensors based on LoRa can be installed in smaller devices for reliable monitoring. Most importantly, LoRa signals can penetrate thick and insulated objects, even buildings, and can, hence, cover a larger network area.

Overall, LoRa-based networks perform higher in terms of lifespan and, at the same time, pose reduced maintenance and upkeep burden [185]. Considering the advantages, many researchers tested this communication method in kitchens, storage rooms, and transport systems. In [186], a test was conducted in a warehouse with a capacity to store 40 tons of apples, and results show that it provided full coverage, where the temperature and airflow readings transferred successfully with a packet rate of more the 96%. Similarly, [187] presents a system to achieve information traceability in the grain transport system to ensure the food quality by monitoring the temperature and humidity levels.

5) SIGFOX

Sigfox is also used to provide network connectivity services to low-powered objects as "things" required. It is based on narrowband or ultra-narrowband technology; hence, it takes very narrow chunks of spectrum and changes the phase of the carrier radio wave to encode the data. Based on these characteristics, it offers high level performance, even if 100 sensors need to transmit data at the same time, as experiments done in [188].

Figure 8 gives an idea that how end-to-end communication possibilities can be divided in various layers to interact with each other in order to provide the services for smart agriculture.

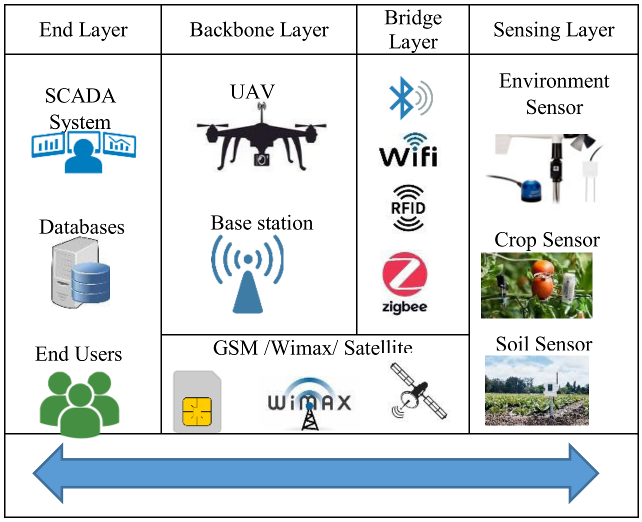

FIGURE 8. End to end communication for smart farming.

E. SMARTPHONES

Despite its availability concerns for remote fields, cellular communication is the major technology in rural areas; mobile phones are a very common source and primary mode of communication whenever the need arises to contact or update most of the farming community. Recent advancements in the smartphone industry have resulted in sharp price decreases, making this industry more attractive, especially to the small-holder growers in remote areas. The rapid spread of cellular networks in developing countries offers the opportunity to reach remote and dispersed farms with improved services. Mobile-phone-based agriculture services (m-services) are far from their assumed potential; according to an analysis done by GSM Association, only at 8 per cent [189]. However, the flexibility and functionality, such as the camera, GPS, microphone accelerometer, proximity, and gyroscope, attract the IT experts, and they are developing more appealing mobile apps that consider the farmer's various needs [190], [191]. The conclusion of FAO's 10-year investigations states that "solid information is needed regarding the impact of previous initiatives, including lessons learned, in order to inform the design and approach of future efforts" [192]. Interestingly, the smartphone is the first device that comes to mind when planning how to achieve this goal, especially considering the often dispersed and poorly serviced areas.

Recent years have seen rapid expansion of research, with researchers conducting a growing number of studies and developing various models to highlight the scope of smartphone crop applications. These researchers mostly belong to developing nations, as proposed systems are based primarily in countries like Kenya [193], [194], Ghana [195], [196], Nigeria [197], [198], Mali [199], Uganda [200], and Zimbabwe [201], [202]. Although, the scope of smartphone utilization in agriculture has been more commonly observed in Africa, experiments in countries like Cameroon [203], China [204], [205], Turkey [206], [207], and India [208], [209] are also increasing. Analysing the success of m-services depends on many factors. One of the most comprehensive studies regarding the use of mobile phones for various agriculture applications was conducted to review all the important factors [210]. This study concludes that the service will be of no effect if the developer of the application does not truly understand the farmer needs.

Obviously, the most important factor for such applications is that the farmer should access and use them. In other words, an easy-to-use, free or low-cost app that supports various languages could attract the farmer's attention. In addition, developers should study and consider the relevant factors before making their suggestions. For example, market prices are of great interest to farmers, but would be of no use in cases of bad roads and unavailability of proper transport vehicles. The developers should target the problems of the wider community instead of focusing only on farmers, considering the transporters, brokers, and other agriculture experts as well. Unfortunately, most of the applications are developed on growers' perceptions, instead of using independent and verified market data. For this purpose, the developer should not only focus on the data retrieved by independent investigators but also assess it under various usage patterns covering longer durations.

Table 3 lists smartphone based sensors that are attracting the researchers to utilize them for various agriculture purposes. While, last column provide some of the references where these sensors have been used. Further, Table 4 includes some of the important mobile apps developed for various agriculture applications along their features and achievements.

TABLE 3. Smartphone based sensors that being used in various agriculture applications.

Smartphone Sensor(s)	Purpose	Common Agriculture uses	Used In Literature
Image Sensors (Camera)	Take pictures of any object, focuses lens	Disease detection, Chlorophyll status, Fruit ripeness , Leaf Area Index (LAI), Harvest Readiness, Soil erosion and other analysis	[211-216]
GPS	Provides location, measuring the latitude and longitude of device.	Location information is attached to generate alerts. Mostly used for machine driving and tracking, land management, crop mapping	[217-219]
Microphone	Detects usual/ unusual sound and convert to electrical signals	Machine maintenance, bug detection, to make audio queries.	[220, 221]
Accelerometer	Measures acceleration forces that used to observe the tilting motion and orientation of object.	Precise movement or rotation of camera during use. Detect worker or machine activities	[222-224]
Gyroscope	Senses the angular velocity to track the object rotation or twist	Equipment movement, canopy structure measurement	[217, 220, 225]
Barometer	Measures air pressure as an altimeter. Mostly used in correcting altitude measurements by the GPS	Measures the elevation height in hilly agriculture.	[226]
Inertial Sensor	Uses accelerometer and gyro to determine the object altitude in relation to the inertial system	Precise distance of plant, leave or any other object is measured from camera.	[221, 225]

F. CLOUD COMPUTING

Precision agriculture is showing its potential and benefits by improving agricultural operations through better data-driven decision making. However, to continue this success, precision agriculture not only requires better technology and tools to process data efficiently but also at a reasonable cost such that the received data can be used to make field decisions efficiently. For this purpose, farmers can use Cloud services to access information from predictive analysis institutes so that they can choose the right product available according to their specific requirements. Cloud computing offers an edge to farmers to use knowledge-based repositories that contain a treasure of information and experiences related to farming practices as well as on equipment options available in the market with the necessary details. In most cases, all this comes along with expert advice from a wide range of sources (for example, on farming and the processing of agricultural products). To make it more effective, the scenario can be extended further to include access to consumer databases, supply chains, and billing systems.

Surely, moving towards Cloud-based services offer opportunities to explore advancements, but it comes with new challenges, as well. First, a vast range of sensors are being developed and used in precision agriculture, each of which has its own data format and semantics. Secondly, most of the decision-support systems are application-specific while, on the other hand, a farmer can be in the need of accessing various systems for a specific application, e.g., soil monitoring. Considering both of these cases, the Cloud-based decision-support system not only needs to handle the diversity of data and their formats but also must be able to configure these formats for different applications.

An open Cloud-based system has been established by AgJunction [243] which gathers and disseminates the data on

TABLE 4. Selected important smartphone applications for various agriculture applications.

Mobile Apps	Application	Features/Achievements
PocketLAI [223]	Irrigation	This app estimates leaf area index (LAI), a key factor to determine a plant's water requirements. It uses the mobile camera and accelerometer sensor to acquire images at 57.5° below the canopy, while the user keeps rotating the device along its main axis.
LandPKS [227]	Soil Assessment	Land management has long-term potential depending on climate, topography and relatively static soil properties (like soil texture, depth, and mineralogy). This app helps to improve farmers' understating of the land's potential, as well as climate change adaptation and mitigation activities.
PETEFA [228]	GIS	It provides information about the Normalized Difference Vegetation Index (NDVI) of various crops at different stages of the lifecycle. Furthermore, it provides a geo-referenced soil analysis organized by parcels.
AMACA [229]	Machinery/ Tools	Equipment costs are a major chunk of crop expenditures. This app is very helpful to estimate the cost of machinery and its implementation in various field operations. A customer-driven quality function deployment (QFD) approach is followed to link the user's expectations with the design characteristics of the app.
Ecofert [230]	Fertilizer Management	Ecofert helps to manage fertilizer to achieve its optimum use. It calculates the best combination of fertilizers based on the required nutrient solution and considers the needs of various crops. Furthermore, it takes account the cost of fertilizer based on current market prices.
eFarm [205]	GIS	eFarm is a crowdsourcing and human sensing tool that collects geotagged agricultural land information at the land parcel level. It is highly suitable for sensing, mapping, and modeling of agriculture land system studies.
AgriMaps [231]	Land Management	This app follows an evidence-based, site-specific approach to make crop and land management recommendations. It provides a platform for spatial data visualization with a greater range of geo-spatial information compared to other, similar applications.
SnapCard [232]	Spraying Applications	The SnapCard app was developed for in-field analysis of spray collectors based on imaging analyses. It uses various mobile phone sensors and follows five imaging techniques to quantify droplet deposition and size.
SWApp [233]	Irrigation	The developer of this app targets dry land areas specifically, as irrigation issues are more common in these areas. The app provides a robust, reliable and economic solution for monitoring soil water moisture, and even takes into account the weather history.
Weedsmart [234]	Weed Management	This tool is capable of enhancing weed management for a specific paddock. Based on the answers given for nine questions about a paddock's farming system, the app assesses herbicide resistance and weed seed bank risk.
VillageTree [235]	Pest Management	VillageTree offers intelligent pest management solutions by gathering pest incidence reports from farmers. It uses a crowdsourcing approach and sends the images along the location information to alert other farmers that may be affected.
WISE [236]	Irrigation	WISE is a cloud-based irrigation scheduling tool that uses the soil water balance method and allows users to quickly view their soil moisture deficit and weather measurements, as well as enables users to input applied irrigation amounts.
SafReg [237]	Forestry Management	This app supports the timber production and its natural regeneration management in agroforestry systems. For this purpose, developers targeted 20 farms from Costa Rica, Nicaragua and Honduras. Overall, this app helps to save time and money on data processing.
EVAPO [238]	Irrigation	EVAPO was developed to estimate the potential evapotranspuration (PET) in real time using the climate grid data from NASA-POWER. This app can be used for any location in the world to improve irrigation efficiency via water conservation information.
AgroDecisor EFC [239]	Fungicide	Basically, this app presents a scoring system (SS) based on weather, disease pressure, and other factors those are useful to estimate the probability of expected net return on fungicide treatment. Overall, it helps farmers to reduce the number of fungicide applications by providing scoring levels for the proper application of fungicide.
BioLeaf [240]	Health Monitoring	This app helps monitor crop foliar status. It detects leaf damage, especially as a result of insects. Based on imaging methods, two techniques (Otsu segmentation and Bezier curves) are used to estimate the foliar loss in leaves with or without border damage.
cFertigUAL [241]	Fertigation	The app calculates the amount of fertilizer and water needed for the major crop types based on various crop growing systems and the variety of fertigation technologies. Farmers can achieve the precise application of water and other nutrients in greenhouse farming.
WheatCam [242]	Crop Insurance	Based on idea of Picture-Based Insurance (PBI) which helps to improve the quality and affordability of crop insurance. Smartphone camera is used to take picture pre and post damaged insured areas. Overall, it minimizes the asymmetric information and costs of claims verification compared to indemnity insurance methods.

a form from different precise agriculture controllers, leading to a decrease in costs and environmental impacts. Furthermore, "Akisai" Cloud [244], proposed by Fujitsu, focuses on food and agricultural industries and incorporates information communication technology for increasing the food supply in the coming years.

Similarly, SourceTrace developed and offering Cloud-based mobile applications to provide visibility and relations between farms and markets, further tracking the value chain at the source, e.g., 'eService Everywhere' [245]. An important note about their applications is that, during the development, they considered the farms' remoteness and low bandwidth environments.

Figure 9 presents possible infrastructure and relationship scenario of fluid computing including Edge, Mist and Fog for smart agriculture.

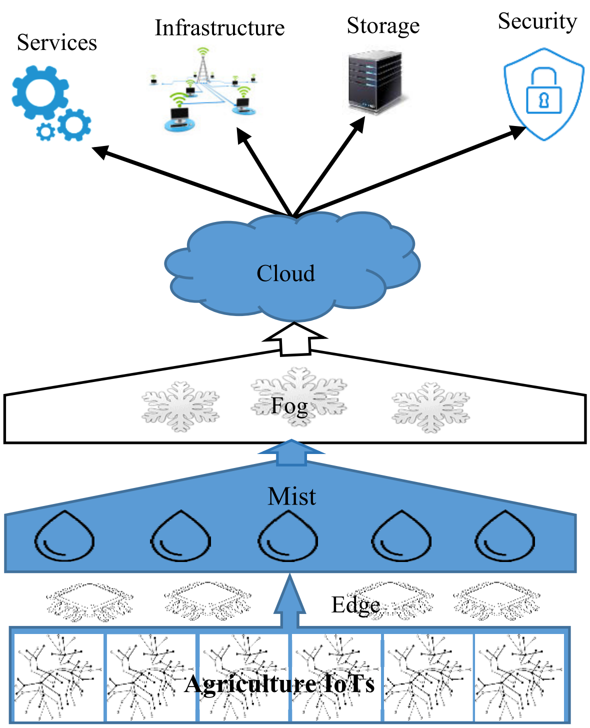

FIGURE 9. Fluid computing infrastructure for smart farming.

V. UAVs IN AGRICULTURE

Recently, the IoT has made remarkable progress in many industries, including farming sectors like poultry, fishing, etc. but when we talk about agriculture, the communication facilities like base stations or Wi-Fi are very limited, which prevents the growth of the IoT in this sector. Such communication infrastructure and related facilities are even worst in developing counties and rural areas, which is one of the major hurdles when introducing the IoT in the agriculture industry. The data acquired through the wireless sensors cannot be transmitted in the absence of reliable communication infrastructure. In such a scenario, UAVs offer an alternative, as they visit and communicate with the wireless sensors spread over large areas in order to harvest data for further processing and analysis. Furthermore, UAVs, better known as drones, fitted with high-resolution cameras and precise sensors, can be flown over thousands of hectares of farms.

The role of surveillance in all agriculture applications is highly critical, especially in forestry and crop monitoring due to the need to cover large areas [246]. Therefore, a fast, low-cost, real-time, and large-scale surveillance supported with an accurate data acquisition and transmission facility is crucial for agriculture production. Currently, mostly two options are used to obtain aerial images of a field area: satellite and airplanes. Both of them are good for a macro view of a landscape, but they face serious issues in terms of quality when it comes to micro views. These macro-view images are not good in resolution and cannot offer the image quality which is required during the analyses and decision making. Secondly, not only the resolution but visiting frequency also matters and, through both of these, it is not simple to take and collect images frequently (on average, four times a month [247]). Another serous issue is that these operate above the cloud level where there is a strong possibility that both are obstructed in bad weather.

When we talk about UAVs that provide an "eye in sky", we can overcome— or even eliminate— the above mentioned issues when we consider the micro views. The quality of images taken through UAVs depends on the attached camera's resolution—normally dozens of times better than satellite images—and, most importantly, we can adjust according to application requirements. More specifically, UAVs supports faster and better NDVI to assess crop conditions, like weed mapping, leaf assessments, etc., and provide immediate feedback so that farmers can take timely actions. Similarly, UAVs are better in terms of frequency, even if requires multiple times in a single day, and are also the option least affected by weather conditions, unless it is raining. Due to the mentioned advantages, UAVs are considered the future of precision agriculture, and this is the reason they are generating the highest revenue amongst all agricultural robots developed for precision agriculture. According to quoted figures by a report published by FAO in 2018, it is estimated that the agriculture drone-related market to be worth USD 32.4 billion [248].

The current condition of the entire field is one of the most valuable pieces of information to obtain in the precision program. With the help of this collected data, a farmer can spot problems early and rapidly; hence, appropriate interventions can be applied. Agricultural drones represent a new way to collect field-level data; the results are on-demand whenever and wherever needed, as the drone can be easily and quickly deployed. Most importantly, it is not all about their hardware but the convenience, quality, and utility they are offering, as the drone-enabled surveillance offers the real facility to have an idea of what is happening in the farm fields at that moment.

The UAVs, used for agricultural applications usually fall into two categories: fixed-wing and multi-rotor drones [249] (figure 10). Although both are available in various ranges

a) Fixed wing

b) Multi-rotor

FIGURE 10. Types of agricultural drones.

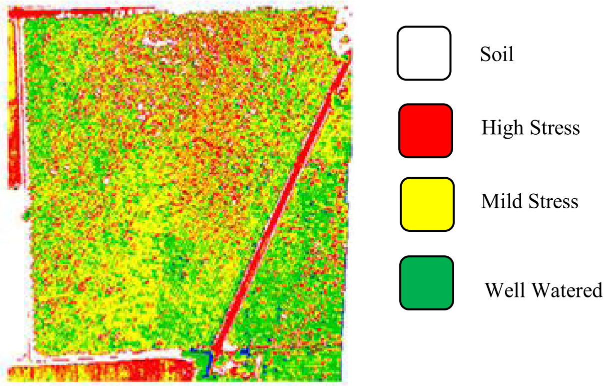

FIGURE 11. NDVI based water stress map of 160 acre walnut orchard [258].

in terms of cost, payload capacity and mostly distinguished based on hardware differences. For example, when it is required to cover a large area, fixed-wing drones are suggested due to their long-range flight capacity, most importantly they are crash tolerant e.g senseFly's eBee SQ [250] and DATAhawk [251]. On the other hand, multi-rotor drones are more common due to their easy and faster set up as can take off and land vertically. Multi-rotors actually have many advantages over the fixed wings as they are easier to operate, require no advance wind planning and have the ability to fly more precisely. Moreover, in scenarios where low altitude flight is required in order to capture extremely detailed images, which is more common in agriculture applications then the multi-rotor are considered the better choice, some major examples belongs to this type are DJI Matrice 200 [252] and Introducing Scout by American Robotics [253] which considered a fully autonomous drone for daily agriculture scouting.

Generally, drones collect information through the light reflected by the ground it is maneuvering, over, either from soil or plants. For agricultural applications, specific cameras and sensors are used, depending on the grower's interest—most commonly mentioned are thermal and hyper-spectral. Thermal sensors can help to recognize the water quantity, as leaves of plants with more water access appear cooler in an image. The same phenomenon is used in near-infrared (NIR) sensors; commonly used to note the difference between the NIR reflectance and the visible reflectance, such as NDVI [254]. The resultant NDVI-based images help to distinguish the water stress areas, as shown in figure 11. Hyper-spectral based sensors or cameras record the wavelengths of both visible and invisible lights, are able to identify the specific type of plant by measuring the color of reflected light. This reflected light is used to distinguish various plant types, ultimately helping to detect the unwanted herbicide and weeds [255]. The idea is used in [256], where authors used the multispectral images to classify various weeds.

Due to their nature and flexibility, UAVs are being used in a range of agricultural applications, including crop health monitoring, planting, plant counting, spraying, agriculture photography, and many other variable rate applications. After being equipped with automation and GPS capabilities, they are ready to take the agriculture sector to a further-modernized level. With every passing day, drones are becoming more inexpensive and reliable, hence, making themselves an ideal choice for new farming applications. Focusing on the success of this technology, SAP (Systems, Applications, and Products), one of the largest vendors of enterprise resource planning, has brought three of its major technologies together in order to make the information harvested through UAVs more effective [257]. The technologies include the HANA, a Cloud database which supports speedy data capture, retrieval, and analytics; the Leonardo IoT suite to connect and exchange information over any protocol; and the Connected Agriculture suite to provide a GUI-based, graphical-use interface to the farmers.

While it depends on the situation, in most cases, few hours delays doesn't leave serious impact in most of the agriculture applications but flight time is more important as need to cover larger areas due field vastness.

Not only vastness, but in some applications of pesticide and fertilizer, UAVs need to carry heavy payloads. In such situations, optimum battery utilization becomes crucial to extend the flight time. For this purpose, many factors can be considered to increase the drone efficiency. Firstly, when flying, choose right conditions e.g. weather or air direction. Next, try to include optimum payload and place it appropriately. For this situation, it can be helpful to attach the payload near the field, better in smaller quantities and the refilling again instead of putting heavy quantities. Further, depending on area size and visiting frequency, optimum path selection plays a critical role. For this purpose, many routing schemes like [259], [260] are proposed especially for the UAVs so choosing and implementing the right scheme can provide clear difference. Considering the application of pesticide and UAV based irrigation where drone need to fly with heavy payloads then new procedures like tethering system can be helpful. In UAV tethering, a connection that provide power through the long cable, is provided so that it can fly as long as you have power backup on the ground, most importantly it doesn't require to lift heavy batteries.

Currently, agriculture is being considered one of the most favorable fields where UAVs can offer solutions to resolve many dominant and long-lasting issues. Some of key areas in which drones are already playing key roles to assist farmers throughout the crop cycle are highlighted below.

A. SOIL AND FIELD ANALYSIS

Drones are able to produce precise information to analyze the soil before sowing the crop, which helps to determine the most suitable crop for specific land; furthermore, it suggests the seed type and its planting patterns. In [261] authors shared their experimental results using Sirius I, a fixed-wing aircraft, affixed with a Lumix GF1 digital camera by Panasonic to capture images from different sites to monitor the soil erosion issues in Morocco. Similarly, authors in [262] targeted the issues of soil analyses where they used Lumix DMC-LX 3 to take the images and Pix4UAV for mapping the results.

B. PLANTING

Millions of acres of land are currently under-utilized due to being human inaccessible or lack of suitable workers. Safety concerns of rough terrain are main reason not to utilize these areas for forestry or agriculture purpose. For this purpose, drone based planting systems are being developed that decrease planting costs upto 85 percent [263]. Not only cost, but within shorter time as some recently developed drones can plant 100,000 trees in a single day [264]. These systems shoot pods which include the seeds and necessary nutrients required to grow the plant. This method is found very effective for rough terrain; most importantly the success rate is more than 75% [265]. Due to the success and flexibility they offer, UAVs are being considered the best candidate for plantation all over the world, from NASA engineer [266] to countries like Pakistan [267] and India [268].

C. CROP MONITORING

Crop monitoring is one of tough jobs and facing low efficiency due to covering large area. Drones are offering the solutions by allowing real-time monitoring of far farms, more accurately and cost-effectively comparing with previously used satellite imagery. The Microdrones +m [269] is an accessory toolkit which provides aerial imaging facility to observe the crop nutrients, moisture levels and monitoring of other necessary parameters. A study conducted in [270] where authors used UAVs along digital camera to monitor the crop conditions. The purpose of the study was to find the relationship between the crop spectral characteristics and effect of fertilizer availability for plant health. Further, [271] presents an innovative procedure to compute and map the 3-dimensional geometric characteristics of trees and tree-rows. The generated maps can be helpful to understand the relation between the trees' growth and field related factors like its geometry and nutrients ultimately help to optimize the crop management operations.

D. IRRIGATION

Use of drones for irrigation applications is, again, two-fold. On one side, equipping UAVs with a variety of sensors and cameras can help to identify areas that are under water stress and conclude what irrigation changes are required. At the same time, they can be used for sprinkling water and pesticides on the crops precisely, especially in emergency cases, which would save both time and wastage. In [272], multispectral images of citrus crops were acquired using the fixed-wing UAV, where the retrieved data was used to assess and detect structural and physiological changes in the targeted crop. Further, [273], [274] are similar efforts in which UAVs were used to estimate the crop water stress. Furthermore, UAVs are not only used to analyze the irrigation properties but also provide solutions by sprinkling water precisely over the water stress areas as in [275]. Due to this application of UAVs, they are being considered the newest water-saving tool, while their use is helping not only to increase watering efficiency but also detect possible pooling or leaks in irrigation. Examples like 'JT20L-606' [276] and 'AGRASMG-1' [277] are specialized drones that were developed and are being used for this purpose.

E. PLANT COUNTING AND GAP DETECTION

Precision agriculture critically needs the spatial data on crop density when making decisions during various applications. The quantity and plant numbering not only reflects the field emergence but allows better and more precise assessment of the yield production, in fact, determining the crop fate. Again, UAVs are offering flexible solutions for this purpose. In [278], authors performed digital counting of Maize plants with the help of UAVs. Further, in [279], authors proposed a method in which they used UAVs to estimate the density of wheat plants at the emergence stage while a Sony ILCE α5100L RGB camera was used to take the images.

F. SPRAYING THE PESTICIDES/HERBICIDES

Similar to irrigation, UAVs can be used to spray herbicides/pesticides on crops, but their use for these applications is more critical. Spraying application would be highly efficient compared to current procedures; herbicides/pesticides are usually sprayed over the entire farm, which is not required in most cases. If using an UAV to spray herbicide, it can spray directly on the unwanted weeds or can target the affected areas only. Furthermore, as spraying using drones would be highly targeted, the drone would figure out and spray as per requirements, helping to reduce the overall expenditures. Handling the sudden environment changes like wind direction or speed is another issue for an UAV especially when being used for spraying applications. For this purpose, [280] proposed a computer based system that autonomously adopt the UAV control rules to keep precise pesticide deposition.

G. HEALTH ASSESSMENT

Scanning crops with visible and Infrared (IR) light sensors fitted on drones can identify which plants may be infected by bacteria or fungus. Using UAVs, this can be done frequently and with flexibility. The early detection of any such issues helps to prevent the disease being spread to other plants or crop areas. Multispectral images can help to detect the disease or sickness at early stages even before reaching the level in which it is possible to detect with the human eye. Experiments done in [280] present the data collection campaign performed over a sorghum crop which was severely damaged by white grubs. Further, in [281], UAVs are used to collect data from ground-based sensors, including a chlorophyll meter, water potential meter, and spectroradiometer, and the collected information was used to evaluate the plant health and crop condition, ultimately reflecting the ground truth.

H. DETECTION/RECOGNITION OF PLANT SPECIES

Recently, UAVs are being started to detect and recognize the plant species, especially those are considered extinct or remains only few on our Earth. An UAV is a best candidate to perform this task as it can go in very remote locations those are almost inaccessible to humans. As National Tropical Botanical Garden (NTBG) stated that, Hibiscadelphus woodi, a Hawaiian flower, which thought to be extinct in 2009, is discovered on a vertical cliff face using the drone [282]. Similarly, using the special cameras that can detect the forest biomass and fuel, forest fuel estimation is possible through UAVs which is mostly being done from radars and satellites [283], [284].

VI. FOOD SAFETY AND TRANSPORTATION

With the increasing population, we have to feed around 25% more mouths until 2050, as compared to 2010, which appears to be a monumental task when considering the vast hunger issues that the world is currently facing. The numbers are shocking, as more than one-quarter of the planet's population suffers from malnutrition [285] and nearly one billion people are chronically hungry [286]. Considering this current hunger scenario, it could be big ask to feed the new billions of mouths in the future. In order to handle the situation, some believe the solution lies simply in growing more food. This has also been reinforced by a latest research, published in the journal Bioscience, which concludes that from the present time until 2050, the rise in total food production should be in the bracket of 25-70%. [287]. However, what if someone tells you that there's already enough food currently grown on farms to feed 10 billion people? [288].

Yes, the good news is that we are already producing enough food for that many people; however, it is a crucial matter to figure out that how to distribute this food while maintaining its quality. Considering this fact, one can say that increasing the food production is also important, but transporting the existing available food safely and efficiently to more people is the real subject of issue of the food industry [289].

A comprehensive report regarding the future food requirements published by World Resources Institutes (WRI) in 2018, highlights that we need sustainable food industry to feed 10 billion people by 2050. The report suggests a five-course menu of solutions to tackle the future food issues where "reduction in food losses and waste" is declared as the first and most important course [290]. Further it conclude that, reducing the food loss and waste only by 25% can help to reduce the food gap by 12%, the land gap by 27% and greenhouse gas mitigation gap by 15%. To have better idea, detailed figures about the food loss are highlighted in figure 12 based on various geographical locations and considering the stages along food supply chain where these losses are occurring.

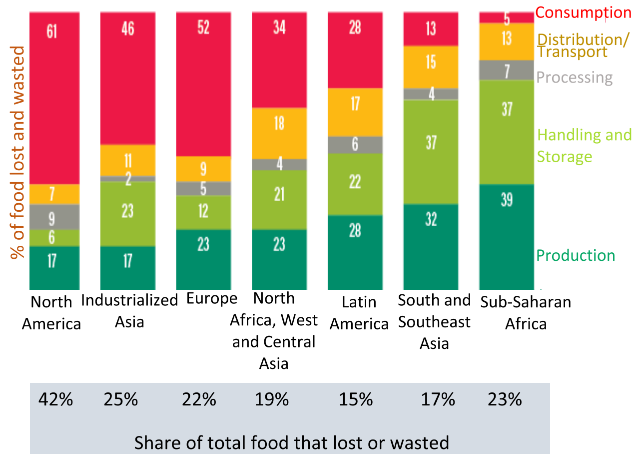

FIGURE 12. **Food losses occurring along food supply chain [290].**

Other than WRI, the figures released by United Nations' FAO are also shocking as it is estimated that one-third of all the global food produced for human use, valued at $1 trillion, is lost or wasted each year [291]. The US food waste alone represents 1.3% of its total GDP [292]. Based on these scary figures, it can be concluded that food waste is massive market inefficiency—the kind of which does not persist in other industries [293]. Although, the loss of $1 trillion has its own worth, but, more crucially, environmental implications of these losses are real, such as the water wasted to produce the food that is never eaten being equal to the water that can fulfill the needs of all of Africa [285]. Furthermore the CO_2 emissions that resulted during the growing process of this food are equivalent to removing every car off the road across the world [290]. Moreover, according to another study conducted by FAO, if you consider food waste as a source of greenhouse gas emissions, it would be the third biggest emitter in the world behind only China and the United States [294]. In addition, when food waste goes to the landfill, where it mostly ends up, it decomposes in the absence of oxygen and produces methane, which is 23 times more potent than carbon dioxide in terms of negative effects. In short, every which way you look at it; food waste is a major culprit in destroying our planet.

Among all perishable food produced in the world today, only 10% is preserved properly [295]. When we talk about most of the developed countries, a robust food cold chain is maintained where essential quality checks are followed, entailing temperature-regulated refrigerated warehouses to refrigerated trucks to ensure that food gets from farm to market safely. On the other hand, many developing countries lack such proper cold chain infrastructure, simply resulting the majority of food spoiling when being transported to the end-user. Considering this fact, there is a huge opportunity to cut food waste and improve food distribution by simply implementing a controlled-temperature transportation system. Based on the facts, one can conclude that increasing food production is not sufficient to achieve food security, but, rather, some practical actions are required to find skillful ways for efficient distribution of the already available food.

There are different ways to monitor and control food temperature. The manual method of checking a thermometer and recording the temperature has many drawbacks, where someone must actually do it and, most importantly, take the readings correctly. On other side, implementing an automatic method that uses wireless sensors to electronically measure and record temperatures can substantially improve food safety. This method allows for a continuous data stream of temperatures simply—24 hours a day, 7 days a week. By doing so, temperatures can be recorded consistently and on time, leaving little room for interpretation; in short, the entire process is based on facts and nothing more. Further, utilizing the recent technologies, the recorded data can be stored in the Cloud and accessed via any type of internet-connected device. Notifications can be established that will send real-time alerts if the temperature strays outside preset limits, allowing for immediate action to remedy the situation. Further, IoT offers predictive maintenance and indicate when the monitoring equipment itself is going to end its useful life so it can be replaced before it fails and compromises product quality. These are only couple of scenarios, now if we consider the figures presented in figure 12, IoT has the potential to monitor and keep the food quality at every stage of the supply chain, from production to consumption.

A research study conducted by Indian School of Business in which students worked with a local grower to transport fruits and vegetables in refrigerated trucks from Punjab to Bangalore, a distance of more than 2,500 km through rough roads under high temperatures. The results were highly encouraging to implement the cold chain to transport the agriculture products. The out of conducted study brought benefits in three ways: (1) increased food shelf-life from one week to two months; (2) an up to 23% higher profit for everyone linked in the supply chain was observed; (3) a 76% reduction of food wastage (post-harvest). Besides all this, another critical factor is the emission of greenhouse gases was observed to be reduced by 16% [296].

To provide the recommended environment, a device with supported technology can be installed at the storage site, even in transport trucks. Further, it is linked to an online dashboard that can be configured to send alerts in the event of abnormal temperature levels to trigger swift remedial action. Some of key technologies available for this purpose and their use cases are mentioned here.

A. COMPLIANCEMATE

Compliance with hazard analysis and critical control points (HACCP) offers a food safety and quality monitoring program which collects temperature data inside coolers and other kitchen equipment continuously. For example, its integration with Touchblock is used to capture temperatures in coolers and prep rooms at every minute [297].

B. LAIRD'S SENTRIUS

A battery-powered and long-range integrated sensor platform that leverages the benefits of LoRaWAN and Bluetooth Low Energy (BLE) connectivity. It provides LoRaWAN options at 868/915 MHz, based on the Semtech SX1272 and Nordic nRF51 silicon. Further, it offers high RF performance in a precise temperature and humidity. Two major series, including RS1xx and RG1xx (multi-wireless gateways), work together in order to provide Cloud-based services. Most importantly, it requires an inexpensive endpoint radio and a more sophisticated base station to manage the network. As compared to LoRa, Sigfox communication tends to be better if it is headed up from the endpoint to the base station. Although it supports the bidirectional functionality, its capacity going from the base station back to the endpoint is constrained, as it provides less link width going down than going up.

C. CCP SMART TAG (RC4)

CCP claims to be a complete monitoring solution for the food service and food retail industry [298]. It is capable to automate the temperature environment which meets the food safety regulations suggested for various food items.

Further, temperature and other data are interpreted and viewed on a service provider Cloud platform via web and mobile applications.

D. TEMPREPORTER

In compliance with HACCP (Hazard Analysis and Critical Control Points), it is used to monitor temperatures 24/7. Further, it logs the readings automatically. Reports are auto-filled by considering HACCP & HPRA (Health Products Regulatory Authority) recommendations regarding temperature monitoring.

According to Finistere Ventures report, as of 2018, around $2 billion has been invested globally in AgTech. Several investments are expected to cross these figures in 2019. Considering the future needs of IoT in agriculture applications, almost all leading technological giants are supporting this progress in their own way. Table 5 provides a list of several of the leading global organizations who have proposed

TABLE 5. Current status and future vision of major technological giants regarding the iot in agriculture industry.

Organization	Initiatives and Vision
Microsoft	Microsoft has begun investing in smart agriculture. The company launched a 5-year, $50-million initiative in 2018 called "AI for Earth" [300]. In this program, Microsoft targets four critical areas for building a suitable future: climate, agriculture, biodiversity and water. According to the company's DNA, the basic purpose of this move is to leverage their expertise in cloud computing, AI (Artificial Intelligence) and IoT to solve agricultural problems. FarmBeats [301] is their main project, and it aims to provide unique solutions to democratizing AI services for farmers around the world.
Google	To offer healthier food systems, Google and MIT Media Lab Open Agriculture Initiative (OpenAg^{TM}) have suggested a vision for the future of crops and agriculture [302]. To provide the latest cloud-based services in agriculture, this program includes Food Computer^{TM} devices, and various open source technologies in enclosed and climate controlled environments. They have also suggested various initiatives, such as their Climate Recipes plan, which proposes solutions based on cross linking plant phenotypic responses to environmental, biologic, and other genetic variables. Furthermore, the aim of this program is to define the resources required for this purpose.
Watson, IBM	Watson Decision, an AI-based service, provides an agriculture platform that aims to improve harvests, sustainability, and quality of smart agriculture using modern technology and IoT [303]. In this way, IBM leverages its experience, data and AI services to help the farmers make better decisions throughout the crop stages. This new innovate agriculture platform utilizes IBM's most advanced facilities and capabilities in AI, IoT, and cloud computing to create a high-tech resource that targets the complete ecosystem, from farm to fork.
Intel	Infiswift [304] is an IoT platform based on high performance Intel architecture that seeks to increase the efficiency of agriculture operations by providing connected services across the agriculture ecosystem. Its basic purpose is to help the farming industry in order to build connected and data-rich solutions to securely collect, transmit, analyze and act on key data. Infiswift works closely with growers, manufactures, and service providers to identify and build IoT hardware and software solutions based on the most recent smart agriculture challenges and requirements.
Jasper, CISCO	Jasper, which is part of the CISCO corporation, provides a cloud-based software platform for the IoT in Agribusiness, which is rapidly embracing IoT services to capitalize on automation, real-time visibility and remote diagnostics to achieve smart agriculture [305]. Products like Topcon, Motech, Observant and Semios are the best examples that bring the power of communications, sensor technology and cloud computing to the agriculture industry to enhance productivity and efficiency.
Dell	Dell has started to introduce agricultural robots and machines equipped with the latest machine learning and AI capabilities. Recently, the company has joined with Aerofarms (a vertical farming force) to accelerate IoT and data science services for smart agriculture [306]. AeroFarms, a vertical farm in Newark, is 130 to 390 times more productive than a traditional farm as a result of the help it receives from Dell's IoT team; it utilizes 95% less water. AeroFarms has further stated that the success of vertical farming would be impossible without Dell's edge to core to cloud IoT architecture.
HPE	Purdue University has begun using IoT and wireless innovations to revolutionize agricultural research: terabytes of data are being captured on a daily basis via various sensors, cameras and types of human input, all of which are processed and analyzed in real time. To efficiently produce quality food and fuel, Purdue is partnering with HPE to blend research, innovations and technologies (like IoT and cloud computing) to transform the current practices in digital agriculture. To process such huge volumes of data using an HPE supercomputer, the university is utilizing a combination of wireless sensors and edge computing technologies, provided by HPE and Aruba Networks (an HPE company) [307].
Hello Tractors	Hello Tractors and IBM Research have built an AI and blockchain-based platform that especially focuses on Africa's farmers [308]. The technology giants are jointly going to pilot the product this year, which is co-financed by IBM. The cloud-based service, named Dubbed Digital Wallet, aims to support Hello Tractor's business, which focuses on providing small-scale farmers with technological equipment and data analytics to create a smart agriculture environment.
Qualcomm	Qualcomm Ventures (QV) has been one of the leading wireless tech players over the last 15 years, and now QV considers AgTech to be one of the major investment areas for future projects. Their recent global partnerships with Strider (a Brazilian farm management platform) [309], Ninjacart (an Indian agribusiness marketplace) [310], FarmEasy (a Chinese farm data platform) [311] and especially their partnerships in Latin-America (LatAm) [312] reveal the value they place on smart agriculture.

TABLE 5. *(Continued.)* **Current status and future vision of major technological giants regarding the iot in agriculture industry.**

	Furthermore, QV invested $15 million in the AgTech start-up Prospera, which taps data analytics, computer vision and AI services to support farmers.
Farm2050	To face the global challenge of a 70% increase in food production to feed the global population of 10 billion by 2050, the "Farm2050" initiative has been proposed [313]. It is considered a significant move for the future of AgTech as more than 25 of the world's leading organizations, including Microsoft, Google, Pepsi, Bayer and John Deere, are partnering with this organization. Its basic goal is to utilize technology to advance the future of food by supporting AgTech entrepreneurs and startups.

and are proposing initiatives in AgTech, especially in regard to IoT-based agriculture solutions.

VII. CURRENT CHALLENGES AND FUTURE EXPECTATIONS

According to a plan announced in 2015 under "The 2030 Agenda for Sustainable Development", the UN and international community set a target to end hunger by 2030. However, recent figures released by WHO (World Health Organization) do not look encouraging enough to support the agenda, as more than 800 million people worldwide are facing the food shortage—one out of every nine people [313]. Although these figures are quite alarming on their own, what is more shocking is the quality of food. Other than availability, the quality of food is becoming another serious issue and even more critical.

According to a research supported by the Bill & Melinda Gates Foundation published in "The Lancet", either shortage or poor diets are diverting 11 million people to an early grave annually, making it more deadly than smoking [314]. The research, which reflects the effect of poor diet on health, was conducted in 195 countries from 1990 to 2017 and concluded that one out of five deaths per year could be prevented by providing better diet. The report summarizes that, globally, a diet lower in whole grains was the most common and leading risk factor for deaths. Other than the basic food needs, per capita incomes of most of the countries in 2050 are expected to be a multiple as compared to today's levels [315]. Such an increase in income will result in a more health-conscious population that expects quality food that is rich in fiber and other minerals. Trends, like increased population where the world needs to feed one third more mouths with increased demand of quality food, show that food demands continue to grow rapidly.

In response to all this, overall crop production needs to increase not only for food but cash-crops are also required to grow in order to fulfill the demands of industry, like cotton and rubber, and, most importantly, increasing demands for bioenergy like ethanol.

Figure 13 presents a snapshot of major challenges that future agriculture expected to face in 2050. This diagram, basically presents three major issues: how to feed around 10 billion people; without using more land and; by reducing the emission of greenhouse gasses by more than 60%. However, when we look closely then these three challenges lead to many new, including smaller rural labor, continuously shrinking arable land, water scarcity, harsh weather

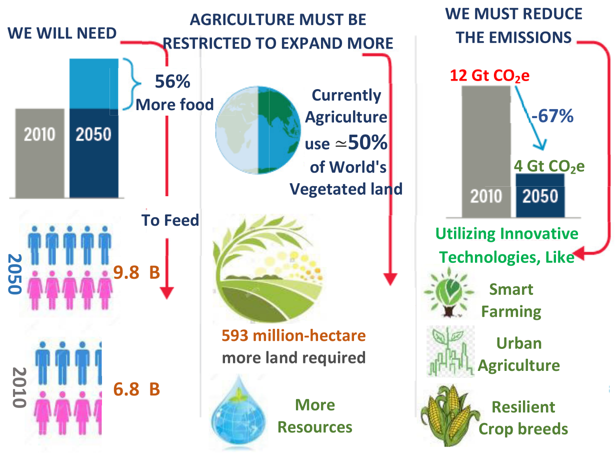

FIGURE 13. Major challenges for sustainable future agriculture.

conditions, and many more. As the world moves toward urbanization, the rural populations are not only shrinking but are rapidly aging; hence, fewer and younger growers need to step up to take the responsibility. Such population imbalance and generation shift can create serious implications, not only for the remaining workforce but also for production patterns and land tenure. Furthermore, on one side, arable land is shrinking while, among the remaining regions, many are only suitable for specific crops due to certain geographic and environmental limitations. Moreover, harsh climate changes are starting to affect almost every aspect of crop production. These changes are expected to enhance the intensity of many of the existing long-term environmental issues, like droughts, floods, groundwater depletion, soil degradation, etc.

During the 20^{th} century, in most regions, growers kept following the traditional agricultural methods while trying to meet the food demands by greater utilizing fertilizers and pesticides. Implementation of such chemicals is facing two issues: these can help to increase the production to only a certain level and, at the same time, their blind use is creating irreversible implications to the environment. Furthermore, implementation of any resource, like water, seed, fertilizers, and pesticides, uniformly across an entire field is not going to solve the problem. Rather than dealing with every farm and crop in same way, farmers need to use these resources according to the requirement of specific areas, even if they have to consider the requirement of every plant.

Focusing on the above discussion, one can feel that the farms and relevant crop operations need to be run differently than the past practices. One of the major reasons is the advancements in technology, including sensors, communication methods, machines, and even robots. In fact, technology has proved this already, as, in most developing countries; more than 50% of the population is somehow engaged in the agriculture industry yet are far behind in providing both the quantity and quality when compared with the developed countries, where less than 2% of the population is performing much better. The difference is clear, as countries like Australia, the US, and most of Europe are pioneers to employ the advanced tools and methods multiplying the crop yields during the last five decades. These comparisons show that recent technologies and advanced methods are making the farms not only highly profitable but safe and environmentally friendly.

Considering this scenario, future agriculture is expected to evolve as a high-tech industry where interconnected systems will enjoy the luxury of artificial intelligence and Big Data facilities. The resultant systems will converge into a single unit where farm machinery and management, starting from seeding to production forecasting, are combined. By involving the advanced technologies like agricultural robots, Big Data, and cloud-computing artificial intelligence, agriculture can create a new era of superfusion. Following are some of the key technologies and methods that need to apply; focusing to achieve sustainable future agriculture.

A. WIRELESS SENSORS AND THE IOT

Wireless sensors placed strategically around fields are providing farmers with up-to-date information in real time, allowing them to adapt the care that the crops need, which results in higher food production with less waste. Wireless sensor networks (WSNs) are also being used to inform farmers about nearly all aspects of their crop growth as well as about the readiness state of the farm's machinery, thus, helping in preventing loss of crop as well as enhancing the readiness of the equipment which cultivates it. WSNs with GPS capability are helping tractors in compensating for uneven terrain and optimizing land preparation for growing crops. Recently, advances in image recognition and digital signal processing gave even more capabilities to WSN to accurately determine crop quality and health.

In order to make agriculture sustainable, the use of the IoT will be at the center and forefront in agricultural operations. This includes everything from water and power usage, crop transportation, farm machinery operation and maintenance alerts, and market price updates. The IoT has the capability to make these tasks streamlined and more predictable by recognizing the crop's needs at every stage. It has already proved a breakthrough and is further going to change the way we look at various agriculture activities by providing the farmer control over their land and assets in an unprecedented way, thus, maximizing their effectiveness and efficiency. Further, the future of the IoT can be shaped by the phenomenal advances in WSNs and the fifth generation (5G) of cellular mobile communication technologies to provide farmers with real-time data and information anytime and everywhere their land is. Based on recent success, it is estimated that more than 75 million IoT-based devices will be operating in the agriculture industry by 2020. Further, the average farm is expecting to generate 4.1 million data points on a daily bases by 2050 [316].

B. COMMUNICATION

Real success of IoT in agriculture largely depends on advances in connectivity. From telecom's perspective, providing mainly connectivity and other value-added services has an immense potential and can influence the entire chain greatly [317]. Most of the telecom operators around the globe offer connectivity services, but such services only represent a tiny amount of the entire smart agriculture market. Considering its worth, especially in rural areas, the cellular operators have to offer a new range of services targeting the growers' demands. Accepting the fact that most of the community belong to this industry are not highly educated and mostly unaware of new technologies, hence the operator should provide end-to-end solutions other than just providing the connectivity. If so, then it will certainly help to increase the market share of mobile and telecom operators. Further, these operators need partnerships with the investors to provide end-to-end solutions, which demands higher investment, even before advantages can be seen. The results of success when inviting the investors depend on the nature of the partnership and the involved bodies, like device manufacturers, solution providers, non-cellular connectivity service providers, system integrators, etc. On one side, the outcome of this partnership would help operators to enter deeper into the industry, ultimately boosting their market share. At the same time, this opportunity can create strong relationships among the organizations and farmers to help to educate them about the benefits of smart agriculture.

The success of cellular technology is only possible when service providers leverage its real benefits like portability, flexibility and luxury of two way communication to offer low cost but customized solutions. They must provide what the farmer is in need, at the place they choose. Furthermore, to provide fast penetration in agriculture industry, policy changes are required in order to provide access of reliable and quality inputs. The research conducted in [172] which considers 23 studies where mostly belong to developing countries, concludes that the cellular services and smartphone technology carry a promising future for smallholder farmers being capable to improve their yields.

Furthermore, licensed LPWA (low-power wide-area) technology is expected to be a game changer for smart agriculture. Due to its characteristics and supported services including low power consumption and efficient coverage are well suited to the geography and economics of agriculture hence expected to play a critical role in future smart farming. Consequently, narrowband IoT (NB-IoT) got strong industry support and becoming an effective global standard for LPWA connectivity. It has the potential to provide major connectivity changes in agriculture industry by changing the perceptions about Internet capabilities. Believing in its future success, it is expected that leading cellular operators with strong IoT ambitions can generate significant revenues by providing smart agriculture services when collaborating with LPWA technology providers. In order to achieve long term success of these short, mid and long range communication technologies, necessary steps for infrastructure construction are required towards attaining the technology-based agriculture.

C. UAVs AND OTHER ROBOTS

Drones are being widely used by farmers for crop growth monitoring and as a means to combat hunger and other harmful environmental impacts. Furthermore, they are being used to spray water and other pesticides efficiently, considering the tough terrains, especially when the crops possess different heights. Drones have proven their value, not only in terms of spraying speed but precision, as well, when compared with traditional machinery of same purpose. With recent advances in swarm technology and mission-based control, groups of drones equipped with heterogeneous sensors, including 3D cameras, can work together to provide farmers with comprehensive capabilities to manage their land. With the inclusion of UAVs in agriculture, farmers are able to put their eye in sky, but many challenges need to be addressed in order to enjoy the real advantages of this technology, especially the integration of other technologies and how to use them in poor weather conditions.

Beside drones, robotics within agriculture have improved productivity and resulted in higher and faster yields. Such robots, like spraying and weeding robots, are reducing agrochemical use. Robots equipped with laser and camera guidance are being used for identifying and removing weeds without human intervention. They navigate between rows of crops on their own, ultimately increasing the yield with reduced manpower. More recently, plant-transplanting and fruit-picking robots are emerging to add a new level of efficiency to traditional methods.

D. MACHINE LEARNING AND ANALYTICS

Machine learning and analytics are used to mine data for trends. In farming, machine learning is used, for example, to predict which genes are best suited for crop production. This has been giving growers all over the world the best seed varieties, those which are highly suitable to respective locations and climate conditions. Machine-learning algorithms, on the other hand, have indicated which products are of high demand and which products are currently unavailable in the market. Thus, for the farmer, this has given valuable clues for future farming. Recent advances in machine learning and analytics will make it possible for farmers to accurately classify their products and weed out less desirable crops before they arrive to customers.

E. POWER CONSUMPTION, RENEWABLE ENERGY, MICROGRIDS, AND SMART GRIDS

Despite its future opportunities, smart agriculture facing some limitations that are holding back the growth of IoT. One of them is power issue as due to its nature; smart farming requires wide use of energy. Among the main reasons of extensive power consumption some are including, long term sensor deployment, use of GPS repeatedly and transmission of sensed data via GPRS. Traditionally, farmers in remote areas have bought and utilized renewable energy sources randomly and at a hefty price, which has limited their ability to use them in farming to a great extent. However to solve the power issues in long term, deep analysis of power consumption sources like remote data transmission can help to tackle the problem at some extent. Further, smart grids and microgrids, however, lend themselves to seamless integration of distributed energy sources (DERs), thus, making them appealing for adoption by farmers. The emergence of smart power meters has further given the farmers the confidence to invest in DER, especially since they have the option to sell the excess power to the grid. Recent advances in energy storage devices, integrated electricity and heat systems will make DER even more attractive for farmers, as they will be able to store energy and use the heat generated by cooling and heating when needed. However, healthy investment requirements and public perceptions are two other barriers on the way to making these solutions successful.

F. HYDROPONICS AND VERTICAL FARMING (VF)

Other than employing the advanced technologies, new agricultural practices can be very crucial to overcome the geographic and resource limitation challenges. On one side, arable land is shrinking, and, at the same time, it is estimated that three million people around the globe are migrating to cities, resulting in more pressure on the existing limited urban resources [318]. Considering this rapid migration, it is estimated that by 2030, 60% of the world's population is going to depend on cities, and this number is further expected to rise to 68% until 2050 [319]. Considering both of these issues, it could be disaster for food production in the near future with current agriculture practices. VF is an answer of these issues, as it meets the challenges of land and water shortage and, at the same time, looks highly suitable to be adopted near the cities. VF is portrayed as the answer to the looming shortage of food and shrinking arable land, at least in some areas of the world. Further, hydroponics can play a key role, as this method lowers the requirements of water and space to a great extent. Rapid growths in computer power are propelling scientific discoveries in plant nutrition and growth that would make VF even more appealing to growers.

Along VF and hydroponics, new and advanced solutions are required to increase the arable land without disturbing the forests and other natural animal habitats. For this, we have to focus on the deserts as these cover one third of the Earth's land surface. The solutions are started already as Norwegian and Chinese firms/experts are doing efforts in Dubai, Qatar, Jordan and Chinese deserts [320]–[322].

Agriculture is not just an industry; in fact, it provides the basis of human society, as the goal is not just to grow crops, but the target is the perfection of human being. A vibrant and prosperous agriculture sector can provide the basis for a happy and healthy society, as recent decades witnessed this. The presence of advance technologies, especially the involvement of the IoT, matters a great deal in regard to reaching this goal. Environmental issues continue to cage the planet, which increases the need for safe and clean agriculture. This is the reason humanity is witnessing a second green revolution, largely based on the IoT. The use of these technologies makes the farming industry highly productive with reduced labor and other resource consumption; same time, minimizing the impact on the environment.

Our planet has the resources, but we have to learn how to utilize them wisely and precisely. Sensible use of technology can lead us where we can utilize these resources efficiently in order to ensure the food security of the current and coming generations. For this purpose, we need collective efforts to build such institutions that can shape long-term decisions and polices to eliminate hunger effectively. On this route, the experience, tools, and support from those nations that have succeeded in overcoming hunger should provide to those regions that are fighting to feed its local mouths. Although growth in every industry matters, growth in agriculture, particularly among small growers, can be highly effective to control the undernourishment issues, as more than 70% of the population of developing countries belongs to rural areas and somehow depends on agriculture sector.

VIII. CONCLUSION

The focus on smarter, better, and more efficient crop growing methodologies is required in order to meet the growing food demand of the increasing world population in the face of the ever-shrinking arable land. The development of new methods of improving crop yield and handling, one can readily see currently: technology-weaned, innovative younger people adopting farming as a profession, agriculture as a means for independence from fossil fuels, tracking the crop growth, safety and nutrition labeling, partnerships between growers, suppliers, and retailers and buyers. This paper considered all these aspects and highlighted the role of various technologies, especially IoT, in order to make the agriculture smarter and more efficient to meet future expectations. For this purpose, wireless sensors, UAVs, Cloud-computing, communication technologies are discussed thoroughly. Furthermore, a deeper insight on recent research efforts is provided. In addition, various IoT-based architectures and platforms are provided with respect to agriculture applications. A summary of current challenges facing the industry and future expectations are listed to provide guidance to researchers and engineers.

Based on all this, it can be concluded that every inch of farmland is vital to maximize crop production. However, to deal with every inch accordingly, the use of sustainable IoT-based sensors and communication technologies is not optional—it is necessary.

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