Internet of Things Empowered Smart Greenhouse

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***Abstract*—The rapid change of climate, population explosion, and reduction of arable lands are calling for new approaches to ensure sustainable agriculture and food supply for the future. Greenhouse agriculture is considered to be a viable alternative and sustainable solution, which can combat the future food crisis by controlling the local environment and growing crops all year round, even in harsh outdoor conditions. However, greenhouse farms persist many challenges for efficient operation and management. The evolving Internet of Things (IoT) technologies, which encompass the smart sensors, devices, network topologies, big data analytics, and intelligent decision is believed to be the solution in addressing the key challenges facing the greenhouse farming, such as greenhouse local climate control, crop growth monitoring, crop harvesting and etc. This paper reviews the current greenhouse cultivation technologies as well as the state-of-the-art of IoT technologies for smart greenhouse farms. The paper also highlights the major challenges that need to be addressed.**

***Index Terms*—IoT, RFID, sensors, smart farming, greenhouse farming, agriculture.**

I. Introduction

With the fast growth of population, industrialization, climate change, the spreading of environmental pollution, the arable land around the world are decreasing year by year [1]. This poses significant challenges for future food security. According to a recent survey conducted by United Nation Food and Agriculture Organization (FAO), the population of the world would increase to 9.73 billion by 2050 [2] and 11.2 billion by the end of 2100 [2]. This upsurges a global concern for the farmers to meet future food demands. Moreover, the abrupt changes in the weather and increase of salinity in the freshwater spiral the pressure for the farmers [3]. Therefore, the traditional agriculture industry requires a radical change to ensure ecological and sustainable food supply. Greenhouse agriculture or farming technology is considered to be one of the viable and alternative solutions to provide food security and to ensure socio-ecological sustainability in the future [4].

Greenhouse farming technology was first introduced commercially in The Netherlands and France in the nineteenth century [5]. Since then, greenhouse farming has become one of the fastest-growing industries in the world [6]. Greenhouse farming is a house-like structure, constructed with glass or plastic materials to produce various types of crops in any season [7]. The roof is generally covered with transpicuous material to preserve the required climatic conditions for the plant growth (such as, temperature, humidity, lighting, and so on) and also to safeguard the plants from the pests, diseases and adverse environmental conditions [8].

Greenhouse farms can be employed in different environmental conditions. In an extreme cold weather condition, "cold frame;" a type of small-scale greenhouse farms can be installed. A cold frame can trap the heat from the sunlight and can preserve the temperature for the plants. On the other hand, for dry and hot weather, "shade house" greenhouses are used to provide shades and preserve the moisture for the plants [9].

The advantages of these greenhouse farms are that it can help the farmers to produce different types of crops by changing the local environmental conditions according to the plant's requirement (temperature, light, moisture, nutrients) [6]. It can prolong the growing season for the cultivation and can provide high quality crops with efficient use of pesticides, manures, water and labors [10], [11]. Greenhouse farms can prevent plants from harsh environmental conditions, such as heavy rainfall or high solar radiation. It prevents the plants to be infected by aerial borne diseases as it provides a protected environment for plant growth [12]. Depending upon the greenhouse facilities, the yield of the crops can increase up to 10-12% than the traditional farming [9]. The greenhouse can also be used to grow crops which are not able to survive the outdoor conditions. However, the maintenance of the greenhouse farms is quite strenuous as it needs more resources than the traditional farms [9]. The yield of the crops are greatly dependent upon the appropriate parameter control, such as cooling, heating, lighting, water flow, ventilation, level of CO_2 and etc. inside the farm [6]. This can influence the economic profits and can increase the complexities of the decision making process for the farmers. Integrating the Internet of Things (IoT) technology with the greenhouse to make it "smart," i.e., the smart greenhouse, is believed to be the solution. Hence, smart greenhouse farming can leverage these problems and aid the farmers to increase the yield of the crops [13].

The term "Internet of Things (IoT)" refers to a mass-system which is connected to numerous sensors, embedded controllers, decision-making platforms, Internet, and a cloud server. The sensors collect the data and automatically feed them to the cloud server. The cloud servers store and allow

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TABLE I
GREENHOUSES BASED ON CLIMATIC CONDITIONS

Climatic conditions	Type of greenhouses	Construction materials	Crops grown
Cold or temperate	Cold frame [18] or solar greenhouse [19]	Solid plastic or glass [20]	Spinach, lettuce, carrots, scallion [21]
Tropical or sub-tropical	Shade house [22]	Metal and polyethylene fabric [23]	Cucumber, tomato, strawberries, capsicum, orchids [23]
Arid or semi-arid	Screen houses [16]	Steel and plastic film [24]	Musk melon, watermelon, hot pepper, cucumber, tomato [24]

TABLE II
TYPES OF GREENHOUSE CULTIVATION TECHNOLOGIES

Greenhouse technologies	Construction material	Automation level	Crops grown	Cost($/ m^2)	Suitable climate
Low Technology Greenhouse	Wood	Poor	Vegetables and flowers	25-30	Cold or temperate
Medium Technology Greenhouse	Metals	Average	Vegetables, flowers and decorative plants	30-100	Tropical or sub-tropical
High Technology Greenhouse	Galvanized Iron	High	Vegetables, flowers and decorative plants	100-200	Any climate

the data to be accessed remotely [14]. Therefore, IoT systems are implemented mainly to monitor and take intelligent actions without human intervention, such as cooling, heating, lighting, irrigation, on and off of the motors and actuators by analyzing the sensor data [15], making the farm smart. Smart greenhouse farms can also aid the farmers to gain knowledge about the season or the most suitable time for harvesting, quality of the soil, amount of nutrients needed for healthy plant growth, quality of water and many other important factors. In other words, smart greenhouse farming can make farming reliable, cost-effective, and maximize the yield of the crops with the minimum number of labors [13]. This can help the farmers to manage the farms and optimize the resources efficiently. It is envisioned that in the future the growing of crops inside a smart greenhouse (or at least part of the process) can be fully automated and remotely controlled.

This paper aims to assist researchers and practitioners in the related fields, to gain the knowledge of the smart greenhouse farming, the state-of-the-art and the current challenges. The paper summarizes the existing greenhouse cultivation technologies, analyzes the current status of IoT technologies and their suitability for applications on smart greenhouse farming, and highlights the shortcomings of the different IoT systems. This paper aims to serve as a baseline for the researchers to resolve the current challenges.

The paper is organized as follows. Section II discusses the different types of greenhouse cultivation technologies that are currently used. Section III reviews the current IoT architectures being used in smart greenhouse farmings. Section IV discusses the sensor technologies that are used in monitoring the climate, soil condition, plant growth, and disease development. Section V describes the data transmission and processing. Section VI concludes the paper by highlighting the major challenges for potential future research directions.

II. GREENHOUSE CULTIVATION TECHNOLOGIES

Since 1991 [11], there has been a substantial increase in the practicing of greenhouse agriculture around the world. This is mainly due to the advent of plastic technology which lowered the cost of construction. However, the construction of the greenhouse farms does not only depend upon the material (plastic, glass). It is highly dependent upon the local climatic conditions [16]. The common requirement of constructing a greenhouse farm is to select a flat land site by ensuring adequate (all year round) solar radiation [16].

The primary principle and the history of the greenhouse farms depict that it was used to grow crops or vegetables which requires heat for the growth in the cold climatic regions. This is due to the greenhouse effect and wind-break effects which aid in plant growth. However, with the advancement of new technologies and smart systems, greenhouses have become more versatile and now they can be constructed in almost any climatic condition. Generally speaking, climatic conditions can be classified into three main categories: 1) cold and temperate winter 2) tropical and sub-tropical 3) arid or semi-arid regions [16]. Depending upon the weather and the investment of the farmers, the selection of the shape, construction material, roof covering and ventilation of the greenhouse is varied [17]. Table I summarizes the types of greenhouse farms, their construction materials, and the crops being grown within.

In terms of cultivation technologies, greenhouses can be mainly divided into three types [25] as presented in Table II. A brief description of each type of greenhouse is stated in the following.

1) *Low Technology Greenhouse Farms (LTG):* Low-Technology greenhouse farms are made up of a simple house like a wooden structure which has a roof covering with plastics. It is normally built in colder or temperate zones [12]. This type of farm has no/low-grade heating system, no ventilation and often has poor control of the internal climatic conditions. LTG farms are usually used to produce vegetables and flowers and the installation cost is less than $25-$30 per square meter of the total field area [11], [25]. This type of greenhouse farms is out of the scope of this paper.

2) *Medium Technology Greenhouse Farms (MTG):* Medium Technology Greenhouse Farms are constructed with metal frames. Both plastic and glass panes are used as roof covering. Unlike LTG farms, MTG has better efficiency in controlling the climatic conditions, making the farm independent

from the external conditions. This makes it easier to construct in the tropical or subtropical climate zones [12]. Advanced farming technologies, such as hydroponics, aeroponic and nutrient film farming employs MTG. MTGs are often semi to fully automated farms and can be used to cultivate high-end flowers, such as roses, decorative pot plants and out of season vegetables. The installation cost of the farm is around $30-$100 per square meter [11], [25].

3) *High Technology Greenhouse Farms (HTG):* High Technology Greenhouse Farms (HTG) are usually constructed with galvanized iron frames and glass as the roof covering. HTG farms have all the advanced climate control technologies, making it suitable for any climatic conditions [26]. It can control the heating by sensing the internal climatic conditions and provide forced cooling and ventilation. Also, it can control the humidity, luminous level and CO_2 levels inside the greenhouse. HTGs are used in vertical farming and it can minimize the labor cost for the farms. It is often employed in colder climatic regions to produce different types of vegetables and decorative plants. The installation cost of HTG farms are about $100-$200 per square meter [11], [25].

A. Challenges in Greenhouse Farming

Greenhouse farming faces many issues. Some of them have been tackled and many of them are still lingering around. For example, the fluctuation in temperature, and humidity, and the inadequate lighting. The temperature variation which is a common problem in the greenhouses changes the physical parameters of the plant. Depending on the variation extent, it might reduce the productivity of the crops, delays the harvesting time and make it non-viable for all year round production. On the other hand, the fluctuation in humidity might result in nutrient deficiency and pest attacks of the plants. Furthermore, inadequate lightning can decrease CO_2 level and the rate of photosynthesis for the plants. This directly affects the yield and the quality of the crops [11].

The main challenges for the greenhouse farms are that it requires extensive supervision to control and maintain the required atmosphere for the plant growth in order to achieve expected yield and crop quality [27]. This introduces the need for skilled/ knowledgeable labors for the monitoring of the environmental conditions (temperature, humidity, luminosity) and taking an efficient decision to protect the crops from pests or other problems [28].

B. Potential Solutions With Smart Greenhouse Integrated With IoT

To resolve the aforementioned challenges integrating IoT into the greenhouse to make it smart is believed to be the most suitable solution. IoT can not only automate the monitoring and controlling system of the farm but it can also aid the farmers in decision making and the efficient utilization of the resources (water, pesticides, heating and etc.) [29]. The integration of smart technologies, which now become part of IoT with greenhouse farming is also known as "Smart Greenhouse Farming". By definition, smart greenhouse farming refers to high technology-based cost-effective greenhouse farms which can grow all year round crops for sustainable food supply [30]. The environmental parameters can be monitored by installing IoT enabled sensors and controlled by IoT enabled infrastructures. To eradicate the manual monitoring problem for the farmers, a cloud server is connected through the Internet with the sensors [30]. The installed cloud server makes it possible for the remote data processing and the control of IoT enabled infrastructures, such as the window opener and irrigation valves. The IoT empowered smart greenhouse provides an optimum and capital-intensive solution and reduces the need of most manual interventions [30], thus solving the challenges discussed above.

III. Overview of IoT Architectures Used in Smart Greenhouse Farming

Nowadays, the IoT enabled devices are widely used in the control and diagnostic systems of the agriculture industry [31], [32]. The IoT technologies comprise of sensors, actuators, cloud computing based data amenities, drones, navigation and analytical system, which allows the architecture to make intelligent decisions to increase the crop yield [33]. IoT devices can provide information about the environmental variables including, humidity, temperature and climatic conditions, and also about the field variables such as soil and plant bio-masses [34]. It can be employed to predict and monitor the quality of the crops for the consumers [35]. Additionally, IoT can be used to collect data and store them in cloud computing devices to create alert and send short messages services (SMS) to the farmers. The data stored in the cloud can also be used to develop predictive models which can prognosticate the variables that affect the crops [35]. An illustration of the envisioned IoT empowered smart greenhouse farming is presented in Fig. 1. This section overviews the current state of the IoT architectures that are used for smart greenhouses, in particular, the three typical greenhouse growing techniques, i.e., traditional, hydroponics and vertical farming.

A. IoT Implementation for Traditional Greenhouse Farming

Traditional greenhouse farming technique is mainly adopted for the growing of fruits and vegetables. A general IoT architecture for this type of crop growing is presented in Fig. 2 One of the main goals of employing IoT in greenhouse farming is to ensure a long term sustainable solution for the farmers. In 2012, Li *et al.* [36] developed an IoT based environmental monitoring system for the greenhouse by integrating wireless networks, mobile network, and the Internet to perform remote monitoring of the plants in real-time. The architecture comprises of CC2420 (ZigBee) Radio frequency modules, temperature and humidity sensors, single-chip microcomputer (STC9051 SCM) with wireless transmission module. This architecture could help to warn the farmers about the plant conditions through short messages and also could provide real-time information of the plants [36].

In 2014, Kaewmard and Saiyod [37] designed a portable measurement system which included the sensors to measure air humidity, temperature, and moisture of the soil to control

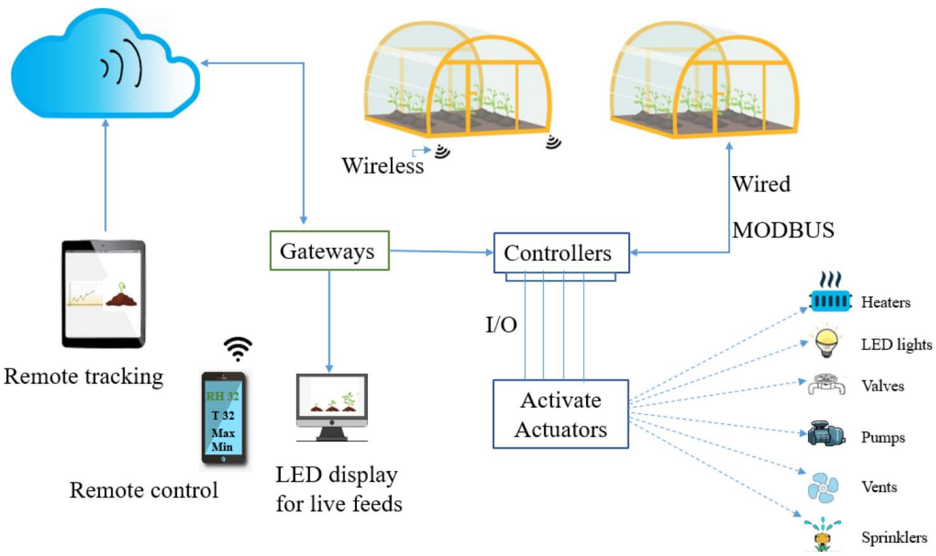

Fig. 1. Envisioned IoT empowered Smart greenhouse.

the water flow/ irrigation system of the vegetables via smartphones and wireless sensor network. An underground water flow sensor was developed and installed in the root of the vegetable crops to monitor soil moisture and instruct the Xbee module to take action (supplying water) [37]. Minh *et al.* [38] developed a light-weight prototype by combining sensor data and communication modules to automate the environment of the greenhouse farm and named it as "Smart IoT Kit". The study was conducted on the growth of maize and oyster mushroom and the prototype could help the farmers to control the farms from any place and time [38].

Mittal *et al.* [39] developed a system which can measure up to fourteen ambient parameters under the surface of the soil with the aid of different IoT enabled devices and cloud. The system is also capable of monitoring the growth of cabbage and capsicum. This system includes ZigBee WSN, sensors to measure the temperature and moisture of the soil, and the relative air humidity. It is integrated with mKRISHI platform and HTTPS is used as transport protocol between the edge and cloud computing. This monitoring system was reported improving the production of the crops by up to 10% and reducing the cost by 20% [39].

Park *et al.* [40] introduced a layer-based data analysis approach to monitor the growth of tomatoes. The data was collected from their own developed IoT architecture which comprised of humidity, temperature (indoor and outdoor), soil moisture, CO_2 concentration sensors with Raspberry Pi 3 and DART framework for IoT gateways. The results from this study showed that the data generated from the system could help the growers predict the yield of tomatoes and the layered analysis could ensure the privacy of the data [40]. Another study on tomato fields was conducted by Rupanagudi *et al.* [41] to monitor plant growth and the diseases. The authors used robotic platforms to collect videos of the tomato plants from the field and the live video feed is processed with the help of Java, cloud computing devices and machine learning algorithms. The study concluded that the developed network was very efficient for monitoring the plant growth and detecting disease of the tomato plants, and was 1.71 times faster than other established detection methods [41]. Aleotti *et al.* [42] presented a mobile based platform with embedded IoT devices combined with an intelligent decision making system (Irriframe) to control the water and monitor the growth of tomato plants in real time. An unmanned aerial vehicle, UAV (VirtualRobotix SPARK quadcopter) which is connected with Raspberry Pi 3 computer and a Raspberry Pi NoIR camera was used to collect images. The images are then processed with Orthophoto Processing Module providing the condition of the tomato plants to the farmers [42].

Another study regarding the distribution of water was conducted by [6], where they designed an embedded IoT based system which has intelligent sensors and actuators. It uses Arduino as an integration platform, ZigBee and cloud services for networking and smart interactions. The system also incorporates IoT hardware-encryption security (TM4C129E) to ensure data security. The work assisted the farmer to improve the harvest of the vegetables [6]. Medela *et al.* [32] developed a new IoT architecture by incorporating sensors, wireless networks and weather data to monitor the growth of grapes.

Although significant progress has been made so far for the development of IoT architectures targeting the efficient growth of fruit and vegetables, such as the monitoring of global environmental conditions inside the greenhouse and the detection of diseases, many obstacles are still laying ahead. For example, the parameters obtained from the sensors (temperature, humidity, luminosity) are not enough for the building of an efficient decision making platform. More environmental parameters such as field water level, plant nutrients (nitrogen, calcium), chlorophyll are required. Another example is that the automated watering systems in the current IoT based greenhouse farms are not crop specific and it often ends up over-watering the plants [36]. This pushes for the optimization of the irrigation/water supply [42]. Furthermore, a broad knowledge of

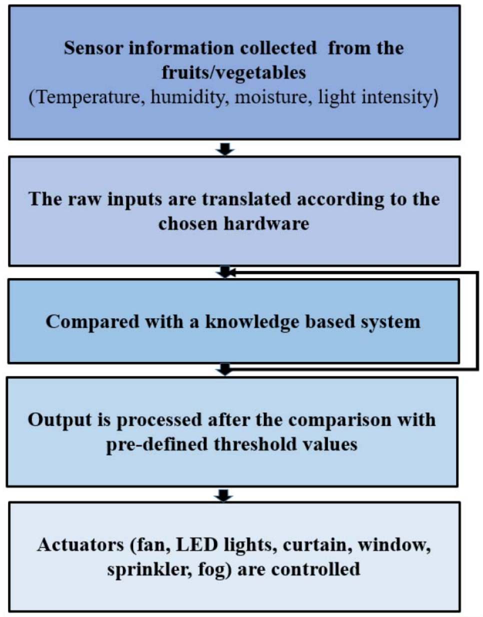

Fig. 2. A general IoT architecture for fruits and vegetables.

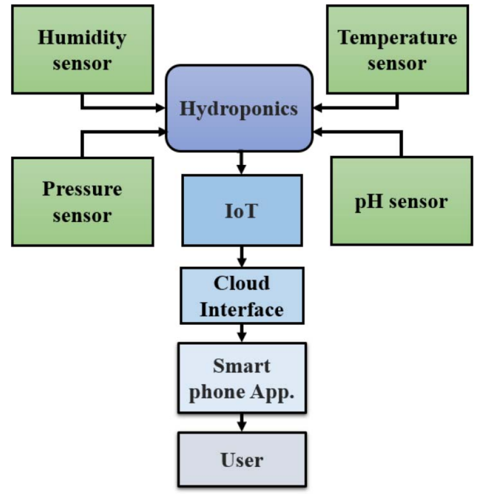

Fig. 3. A typical block diagram of hydroponics in smart greenhouse.

the environment and how to grow different types of crops is required in order to respond efficiently from the collected data. Even though the current IoT devices aid in the automation of the actuators or pumps, the decision making system is not there or not intelligent enough to be crop specific [37]. For instance, when the lights are automatically turned on with the aid of sensor data, the current system is not capable of indicating that how long the light should be on and what should be the light intensity for the specific crop that is being planted [38]. This leads to energy waste.

B. IoT Implementation for Hydroponics

The word "hydroponic" refers to the condition where plants are grown in the water instead of soil. Hydroponics are particularly suitable for greenhouse farms. One of the most common hydroponic greenhouse vegetables is lettuce [43]. Nowadays, broccoli and tomatoes are also planted through hydroponics [44]. However, growing those plants is very difficult as they are very sensitive to the change of pH in the water and the level of proper nutrients. Therefore, IoT architectures were explored to automate the monitoring of the plants inside the greenhouse [44]. Saraswathi *et al.* [44] developed an IoT based mechanism to control the pH of the water through a smartphone application which could help to monitor the current condition of the plants. A Raspberry Pi 3 board is interfaced with the humidity, temperature, pH and pressure sensor. An android smartphone application is developed by using Python programming language which can help the farmer (users) to know about the current condition of the plants. Fig. 3 shows a typical IoT architecture for hydroponic plants in the greenhouse.

Ferentinos and Albright [45] developed a GUI control system with the aid of the Bayesian predictive network. The system actuates the control based on the feedback from the sensors which include the plant growth data, water level, pH, light intensity and globe environmental humidity sensors. Mehra *et al.* [46] proposed a prototype for tomato plants which integrates sensors with the Raspberry Pi 3 and Arduino board to monitor the environmental parameters in real-time. The prototype also uses Artificial Neural Network (ANN) to process multiple parameters (such as light intensity, humidity, temperature and so on) and store the data on the cloud in real-time. The developed model showed a satisfactory performance (88% accuracy) and it can be improved by considering other important parameters [46].

Paulchamy *et al.* [47] developed an "Intelligent hydroponic box" with IoT which can automatically turn on and off the actuators by sensing the change in the sensor data. This architecture is capable of lowering the CO_2 level and can control the water flow through the intelligent plant care hydroponic (IPCH) box [47]. Pitakphongmetha *et al.* [48] proposed to use a wireless sensor network (WSN) to transmit the sensor data to the cloud. It is interfaced through an android application called "Blynk" was claimed to be able to successfully monitor the plant growth of hydroponics [48].

The advantage of IoT based hydroponic greenhouse farming is that it does not require unnecessary pesticides for the soil. The water requirement is less than the traditional greenhouse farms. Also, the plant yield is unaffected by any external environmental changes [49]. Despite of the IoT enabled devices, the main challenge of hydroponic farms are that it requires extensive manual monitoring to sprinkle waters and to provide the required nutrients [46]. The scalability of the hydroponic farm is also a big issue as the IoT based hydroponic architectures have high initial investment to set up. The communication network that is usually used in the hydroponic farms is not suitable for long distance communication [49]. Therefore, an efficient and reliable communication network should be developed to improve the communication system to easily access the data. In addition, how to correlate the plant growth data with the climatic conditions and nutrient levels is still in its infancy. This poses great challenges for the development of decision making algorithm. In majority cases, the decision making process is still experience based.

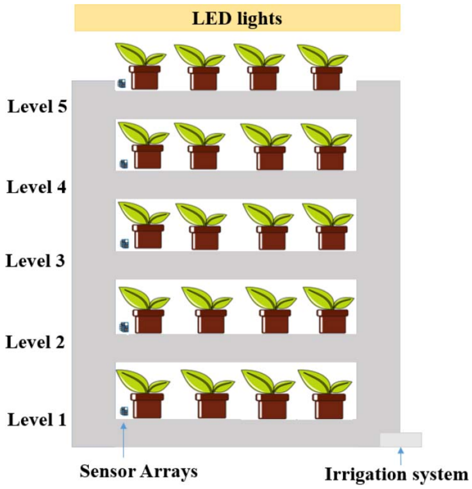

Fig. 4. An illustration of a vertical farm.

C. IoT Implementation for Vertical Farming

Vertical farming is a vertical assembled farm which is often built-in indoor greenhouse farms (controlled environment). Vertical farming is an eco-friendly and an insecticide free farm. However, this type of farm requires high level of maintenance to grow the plants. In vertical farming, LED lights are used to compensate for sunlight. Fig. 4 shows a typical vertical farming layout. Similar to other greenhouse farms, the temperature, humidity, soil moisture also needs to be controlled [50].

Recently, Bhowmick *et al.* [50] proposed to use IoT based wireless monitoring for vertical farming. The IoT architecture incorporates sensors to obtain the data of temperature, light intensity, humidity, and soil moisture, a wireless microcontroller module for data transmission and a Web-based application to observe the sensor data. The sensor data are analyzed through a wireless module (Intel Edison) with the Arduino board, which is connected with Linux OS, Eclipse and Intel XDK. The Web server that is used to interface the data to the cloud is ThingSpeak and for mobile devices, the Virtuino android app was used to send SMS [50]. Bin Ismail and Thamrin [51] developed an IoT based plant monitoring system for " Typhonium Flagelliforme" herbs. The architecture incorporates automatic on/ off system for the water pump, wireless sensors, (one water level sensor and three soil moisture level sensors) and LED lights for photosynthesis. The system is interfaced with the Ethernet shield which helps for communication purposes. The system shows promising results but it could be further enhanced by using efficient LED lights and by integrating alarm systems for the farms [51]. Belista *et al.* [52] developed an Internet based modular network which could effectively transmit the sensor data to the clouds to monitor the plant growth for lettuce farms. The developed server was named "Samba" and through Raspberry Pi 3 it could be connected to any operating system (Windows or Linux). The designed network performed well and it can be further optimized by considering more environmental parameters [52].

Smart vertical greenhouse farms have many advantages. One of them is that the productivity of the crops remains the same even if any natural calamities (typhoon, storm, hurricanes) take place [51]. Smart vertical farms can have an automatic irrigation system and can reduce the labor expenses. However, vertical farming requires adequate lighting/ luminosity levels which increases energy consumption. This also adds to the investment capital. Vertical farming is relatively new in studies. Therefore, different types of alert systems can be integrated to warn the farmers. Also, no studies related to the fully automated and optimized models of vertical farming are conducted yet.

IV. Sensor Technologies for Smart Greenhouse

One of the most indispensable parts of the IoT architectures is the sensor systems which provides information about the environment and plants in the greenhouse. With the emergence of new materials, new theories and new fabrication process, agriculture technologies have also matured a lot [53] through the efforts of some leading manufacturers such as ENDEVCO, Bell & Howell, HoneyWell, Solartron and Foxboro [54]. The most common sensors that are deployed in smart greenhouses are humidity, temperature, soil moisture, light intensity, heat and gas sensors.

The sensor technologies that are used in greenhouses can be mainly divided into two types, i.e., bio/chemical sensors, and physical parameter sensors [54]. Biosensors [55] are the type of sensors which monitor the information directly related to the plant/organism including microbial sensors, adaptive sensor [56], and enzyme sensor [57]. This type of sensor is often used to identify the residue of insecticides, antibiotic and toxic elements (gas) [58], [59]. Physical sensors are mainly used to collect the data related to the environments such as temperature, humidity and heat sensors [54]. Micro electro-mechanical system (MEMS) has been employed to make low power, compact, cheap and reliable sensors [60]. The following section discusses different types of sensors that are being widely used for monitoring purposes in smart greenhouse farms.

A. Monitoring of Climate

One of the most importan components of smart greenhouse farming is to monitor the climatic conditions or the environment inside farms. The real-time monitoring can help the farmers to take preventive measures for the adverse conditions and protect the plants from diseases. Marques and Pitarma [61] developed an automatic environment monitoring system with Sun Spot, an affordable wireless sensor network which is programmed by Java. The system uses Java virtual machine (VM) with the Arduino board to monitor the temperature of the greenhouse and data are accumulated through Facebook [61]. Wu *et al.* [62] developed a WSN based modular environment monitoring structure for smart greenhouse. The structure comprises of three layers, i.e., sensor layer, transmission layer and application layer. The WSN can obtain the environmental data of the tomato farms in real-time and transmit the data to the cloud server. The results of this study show that WSN is a stable network for monitoring the plants growing conditions [62]. Saraswati *et al.* [63] proposed and implemented an android based climate monitoring system for spinach plants by integrating sensors to gather the data of humidity,

TABLE III
DIFFERENT TYPES OF SENSORS THAT ARE USED IN GREENHOUSE FARMS

Environmental Parameters	Sensor Technologies	References
Soil humidity and temperature	DHT11, SHT21, EC sensor (EC250), HA2001, Pogo portable, SHT71, SHT75	[15, 38, 50, 67, 68, 69, 70]
Soil moisture	SKU: SEN0114, FC-28, ECH2O, Hydra probe II, MP406, YL69, HA2001, Pogo portable	[71, 67, 69, 72, 73]
Air humidity	DHT22, CM-100, HMP45C (Vaisala's HUMICAP RH-chip), SHT17, Met Station One (MSO), Cl-340	[38, 69, 72, 73]
Air quality index	MQ-135	[67]
Temperature	SKU: DFR0026, 107-L (BetaTherm 100K6A1B), SHT17, XFAM-115KPASR	[71, 69, 72, 73]
Light intensity	BH170, S1133 (Photo diode), S2506 (Infrared diode), LM-393, YL-369	[38, 70, 67, 71, 74]
CO_2 level	Figaro's CDM4161A, TPS-2, PTM-48A, Cl-340	[70, 69]

temperature, light intensity and level of carbon dioxide inside the greenhouses.

Some particular plants such as onions and shallots require very cold climatic conditions to grow whereas plants like melons and cucumber require warm climatic conditions. Hence, Danita *et al.* [64] proposed an IoT based embedded technology which could integrate sensor parameters (moisture, temperature, humidity) with a Raspberry Pi 3 and ThingSpeak cloud interface to provide the ideal conditions for the plants inside the greenhouses. Pahuja *et al.* [65] proposed an integrated WSN to monitor the micro-climatic conditions inside a greenhouse farm by using VPD-based multiple inputs and multiple-output (MIMO) controller with a battery operated RS-485 actuator and embedded temperature and humidity sensors. A model based on pre-programmed TinyOS was used to automate the environmental conditions inside a greenhouse farm. Their study proved that the climatic analysis of the greenhouse could aid the farmer to determine effective conditions for greenhouse vegetables, leading to a higher yield of crop production [65]. Nayyar and Puri [66] developed a low-cost Smart Stick which could provide live monitoring information of the environmental sensors (temperature and soil moisture). The stick is placed at the farms to obtain live feeds and synchronized with smart devices (phones and/or tablets). The stick comprises of Arduino Mega 2560, BreadBoard BB400, ESP8266 Wi-Fi Module, 11.2 V Li-ion battery, solar plate, soil moisture sensor and DS18B20 temperature sensor. The results from this device showed 99% accuracy [66]. Table III summarizes the sensors that were used to monitor the climatic conditions inside the greenhouse farms.

he studies conducted for the monitoring of climate mainly based on real-time monitoring of the environmental parameters, employing the low cost WSN solutions and the integrated embedded technology. Nevertheless, no predictive analysis models have been proposed yet for the analyses of the environmental parameters. Thus, a subsequent decision making model for predictive analysis models should also be proposed to understand what are the actions that are supposed to take by the farmers and at what time they should take the appropriate actions.

B. Monitoring of Soil Conditions

Soil moisture is an essential element in all types of farms (traditional or greenhouse) [75]. This is because plants or crops

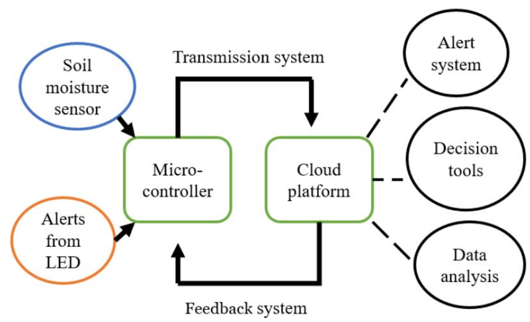

Fig. 5. A block diagram of soil moisture monitoring system.

are all dependent upon the moisture level of the roots in the soil. The information about soil moisture can help the farmers to comprehend the conditions and make decisions. Soil moisture evaluates the water content of the soil [75]. Studies showed that almost 80% of the crop is damaged due to over irrigation which helps to rot the plant roots and makes the root more fungal prone [76]. Also, if the water level is insufficient, plants may die out due to the insufficient nutrients and oxygen levels. Hence, monitoring the soil moisture level is a crucial part of the agriculture industry.

For illustration, a block diagram of a soil moisture monitoring system is presented in Fig. 5 [75] developed a low cost soil moisture monitoring system which can inform the farmers via email and short messages. The architecture is designed with NodeMCU V1.0 modules consisting of ESP826 micro-controller. The Losant platform (MQTT) is used in this architecture to visualize all the data from the sensors in real-time and from any place [75]. Adamo *et al.* [77] proposed an acoustic algorithm to measure the soil moisture in real-time.

Similar research was carried by [78]. The main aim of the study was to develop an efficient and cost-effective soil moisture monitoring system so that small-scale and large scale farmers can use it. The system is developed in an Arduino board. A neural network is used for automatic correction of the system so that the required soil moisture is maintained. The preliminary results from the system showed a promising performance [78]. Zhang *et al.* [72] proposed a combined system for monitoring soil moisture, soil temperature, air temperature and humidity by interfacing with JN5139 node and IEEE802.15.4 or ZigBee protocol for citrus growing. HA2001 and HA2002 sensors were used for soil moisture and temperature measurement respectively, while the SHT17 sensor was employed to monitor air temperature and humidity [72]. Apart from those sensors discussed above, YL69 is one of the popular soil moisture sensors that is used in research [73].

Monitoring the soil moisture is a challenging task as high accuracy is required. It was found that even a slight deviation from the target moisture value could cause either over-watering or under-watering. For monitoring soil moisture level, precise irrigation models need to be developed as soon as possible. A programmable user interface devices which can measure against a threshold can be designed and interfaced with the microcontroller to receive the signals through multiplexing [76]. Also, in-depth knowledge of crop features, such as the rooting period, indeterminate growth [78], harvesting period and plant cutting period should be known by the farmers so that the soil moisture can be controlled accordingly.

C. Monitoring of Plant Growth

In order to improve the crop yield and production, monitoring of the plant growth is essential. Recently, Khan and Hussain [79] proposed a novel sensing architecture which could monitor the climatic conditions inside the greenhouse farms. The novel idea was that instead of placing the sensors (temperature, humidity, soil moisture sensors) close to the root of the plants, the sensors should be placed on the leaf of the plant. In this way, the exact values or the measurement for the plants can be obtained. Therefore, an ultra lightweight sensory platform is developed by Khan and Hussain [79] which is transparent and integrated with light, humidity and temperature sensors, batteries and electronics. The sensory platform weighs about 0.44g which makes it suitable to place on the leaf of the plants. Besides, their research developed another flexible type of strain sensor which can monitor the growth of the plants at the micrometer level.

The strain sensors are equipped with batteries enveloped inside a biodegradable paper and deployed through drones in larger greenhouse farms. The drones itself can take readings at regular intervals from the wrapped strain sensors which can provide the humidity, temperature, and moisture of the farms. The sensor was tested for plant growth of bamboo shoots and the results were very satisfactory [79]. Okayasu *et al.* [80] also presented a cost-effective smart sensing architecture which can monitor the field conditions as well as can monitor the plant growth. The field monitoring system incorporates humidity, air temperature, light-intensity, CO_2 and soil moisture level sensors with a micro controller and it is powered with solar panels. However, for monitoring the plant growth, a typical RGB-D sensor (Kinetic sensor, a product of Microsoft, Technologies, as illustrated in Fig. 6) which integrates both the RGB camera and an IR camera, is used. The distance recordings are taken from Time of Flight (ToF) technology. The test was conducted for a leafy type of plant, named as "Komatsuna" and the sensors measured 2.5D image of the plants. The plant features such as color of the leaf, height, shape and size were all measured through the Kinetic sensors [80].

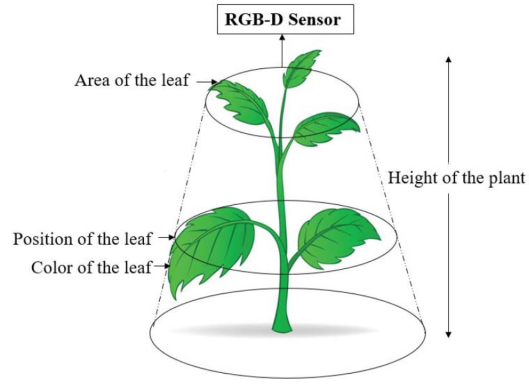

Fig. 6. Plant growth monitoring with Kinetic sensor.

Hadabas *et al.* [81] proposed a similar study by using Raspberry Pi 3 interfaced with IoT-cloud gateway to develop a low cost plant growth monitoring system. The architecture also uses RGB camera sensors and they are placed at the top of the plants. The designed platform exhibited satisfactory results in determining the plant conditions (growth, size and color) [81]. Slamet *et al.* [82] proposed a cost-effective optoelectronic sensor to monitor the growth of guava fruits. The optoelectronic sensor is built on a reflective tape like structure which is enclosed around the fruit. The sensor collects the real-time data of the fruit growth and transmits it to the cloud. The estimated error for the radial growth of the fruit was less than 2 mm, proving that it can be an effective sensor to monitor the plant/ fruit growth [82].

There have been substantial studies on the plant growth, particularly the accurate height measurement of the plants. Low cost sensors have been explored for the real-time plant/fruit growth monitoring. Nevertheless, the major challenge of the monitoring system of the plant growth is that the system requires extensive calibration and the calibration varies from one hardware to another [73]. Therefore, a complete versatile platform with effective and efficient sensors should be developed by considering all the potential situations of the plant growth (for example, direction or angle of plant growth).

D. Monitoring of Plant Diseases

Although greenhouse crops or plants are grown in the controlled environment, the plants are still prone to pests and diseases. Therefore, to maintain the high production yield of the crops, farmers should monitor the plant diseases and make decisions to prevent the diseases as soon as possible. Patil and Kale [83] developed an integrated system which takes all the necessary data from the temperature, humidity, light and pH sensors and aids in predicting the pest and disease of the plants with Ubi-Sense Mote (M) and communicates via an IEEE 802.15.4 to the farmers with SMS. The disease identification is also done from the images that are collected from camera modules for the tomato fields. The study shows that farmers were benefited from this type of monitoring system [83].

Materne and Inoue [84] developed an early disease and pest detection system by using the eight environmental parameters

Fig. 7. Monitoring plant diseases with cameras. The image has been used from [85] and reproduced with permission.

from the sensor data. The system uses Linear Regression, Logistic Regression, KNN cluster algorithm and Random Forest to predict the break out of the diseases inside the farm [84]. Jumat *et al.* [85] also developed a low cost smart disease detection system which can identify the early break-outs for the greenhouse farms by using Raspberry Pi 3 and RF as a classifier (example is shown on Fig. 7) [86] developed a smart disease detection system for rice fields. Drones and cameras are used to capture the image of the plants and images are directly transferred through GPS sensors via the Wi-Fi communication protocol. Images are processed with machine learning and segmentation algorithms to predict the possibilities of disease development. The results from this study showed that location and types of the disease that the plant is going to develop can be pre-identified and an alert can be sent to the farmers to take necessary actions [86].

For monitoring the plant diseases, early detection is very crucial. Many studies regarding low cost early detection of plant disease system has been done with the help of predictive analytics or neural network algorithms. Image processing has also been used in some of the studies. However, none of the studies included the meteorological information [84], which is a key factor of the plant diseases or pest attack. Also, no studies regarding the disease classification [86] of the plants were conducted. These studies could help the farmers in decision making process and also make the decision making tool to be robust.

In summary, sensors have found wide applications inside the smart greenhouse. One of the main issues facing all types of sensors is the cost. The current technology only allows the implementation of sensors at a global level. It is impossible to install sensors for the monitoring of each crop, or every part of the big plant. Several kinds of research have been undertaken to make the IoT sensor based system efficient and cost-effective. Minh *et al.* [38] proposed a cost effective architecture with lightweight communication system, which is believed to be affordable for both small-scale and large-scale farmers. Heble *et al.* [70] proposed a low cost system with low powered network with high battery life. Reference [74] reports an affordable large-scale WSN sensor network for smart greenhouse farms. For the plant growth and environment monitoring, [80] and [87] designed a low cost monitoring device for plants inside the greenhouses. For predicting the yield of the crops, [67] proposed an affordable real-time integration of machine learning with sensors data summarizes several low cost solutions published in Table IV.

Hardware reliability is another big issue facing the implementation of the sensing system inside greenhouses farming. The environment conditions inside a greenhouse could be very harsh, such as extremely dry, extremely humid, extremely high solar radiation and etc. The harsh condition might damage/shorten the life of sensory nodes including the battery. Very few studies have been conducted in this area.

TABLE IV
SUMMARY OF COST FOR THE DEVELOPED SYSTEM FOR SMART GREENHOUSE

Developed System	Cost (USD)	References
Low power, Low cost IoT	63	[70]
Smart Farm IoT kit	100	[38]
Netatmo WSN modules	200	[88]
Smart farm	93.27	[31]
G-IoT	123	[89]
IoT LoRa Solutions	77.37 (70 Euros)	[90]
USP-MQTT smart modules	813	[91]

V. DATA TRANSMISSION AND PROCESSING

The data transmission system is one of the fundamental components of the IoT technologies used in greenhouse farming. Like many other industries, greenhouse farming is heavily dependent upon the real-time information of the farms as delays in data transmission might rupture the entire farm.

In recent years, wireless sensor networks (WSN) have gained popularity over wired transmission technologies, such as field bus [54]. This is because WSN has efficient protocols, is easy to maintain and relatively cost-effective than cable based technologies. The following section provides detail reviews on state-of-the-art data transmission technologies that are used in the agriculture industries.

A. Wireless Sensor Network (WSN)

WSN comprises of the multiple number of devices which is often known as the sensor nodes. The sensor node consists of microcontroller, batteries, sensors (temperature, humidity and so on), data transmission unit, and small-scale computational devices [92]. Fig. 9 shows a general block diagram of a sensor node. These sensor nodes are then dispersed into different areas to accumulate the data and perform simple post-processing in accordance with the integrated decision making framework. The post-processed data are then sent to the access point (AP) which aids the remote monitoring of the region of interest [92]. Fig. 8 shows a typical deployment of WSN in greenhouse farms.

WSN can be divided into two main categories: Wireless underground sensor networks (WUSN) and terrestrial WSN (TWSN) [93]. In smart greenhouse farms, WUSN is placed inside the soil and the underground sensor node relays the information through a gateway node. This information can be transferred to the Internet and stored in remote databases to inform the farmers through smartphones [94]. Nevertheless, the downside of the WSUN is that it can only be used for small distance communication and the large quantity of nodes are necessary [93]. On the other hand, TWSN is the sensor nodes that are planted on the ground surface to collect the information regarding temperature, soil moisture, pH, humidity and CO_2 level of the farms and etc. TWSN usually are a type of MEMS sensors and the nodes communicate with

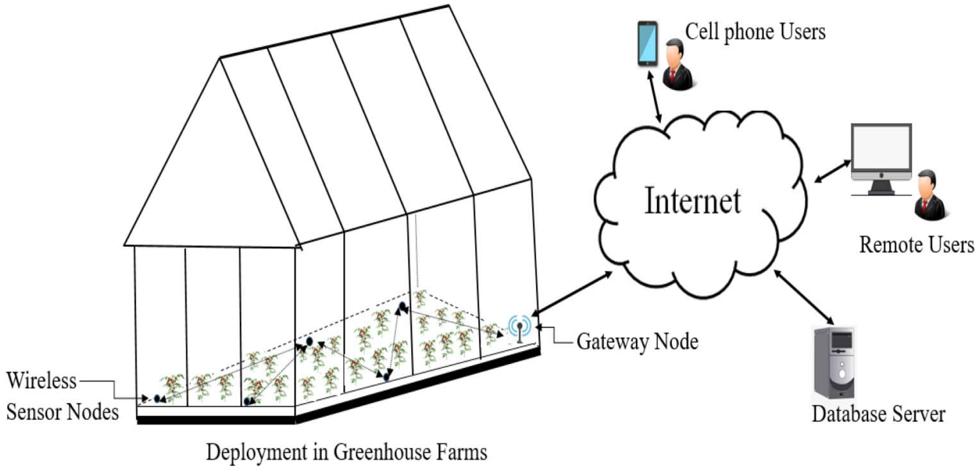

Fig. 8. Deployment of Wireless Sensor Nodes (WSNs) inside a greenhouse farm.

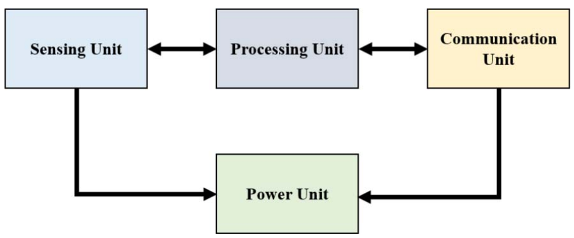

Fig. 9. A typical block diagram of a sensor node [96].

themselves to make intelligent decisions on the basis of the sensed data [93].

In the past few years, the IoT technologies have evolved a lot and so does the WSN protocols. The protocols are mainly developed in terms of cost, battery life, bandwidth and data rate [95]. The following section briefly describes some commonly used WSN protocols (summarized in Table V).

1) IEEE 802.15.4: The IEEE 802.15.4 standard WSN protocol is one of the most used communication protocol in smart greenhouse farms. It uses the Medium Access Control (MAC) layers and the physical (PHY) layers of the Low-Rate Wireless Personal Network (LR-WPAN). LR-WPAN is a cost-effective network which consumes very low power and has low processing requisite. Additionally, LR-WPAN is easy to install and it can transfer data very efficiently within a short range of operation. It has a good battery span and it is relatively cheaper than all other communication protocols [97]. In smart greenhouse farms, IEEE 802.15.4 protocol is often integrated with radio modules, such as TelosB (TPR2400 which operates with 2AA alkaline battery), ATMega256RFR2 (built-in temperature and RGB sensor with a rechargeable batteries) and OpenMote-CC2538 (ARM Cortex-M3 core and XBEE boards) [92].

2) ZigBee: Similar to IEEE 802.15.4, ZigBee uses LR-WPAN wireless system which ensures reliable and secured data transmission and communication between the networks. In smart greenhouse farms, ZigBee is now considered as a global standard for WSN communication protocol. ZigBee devices consist of a coordinator, a router/ modem which has three main topologies for the network such as, Star, Mesh and Cluster Tree. A ZigBee network is created when a coordinator chooses an available network and a channel [98]. Once the channel is created, the router and the end device start to communicate and transfer the data to all the connected devices from the same address. However, the end devices are always battery powered but they are designed to operate in low power modes [99].

3) BLE: Bluetooth Low Energy (BLE) is used in the IoT integrated devices as it can operate in short range (10 m) and lower bandwidth [100]. The benefits of using BLE is that it consumes less power and has a lower initialization time with extensive support for star topology sensor nodes. BLE is often used to collect sensor data (for example, soil temperature and moisture) via mobile phones [101]. However, the downside of BLE is that the connectivity and data transmission security is low. Also, currently, it can communicate only with two devices [100].

4) 6LoWPAN: This is an IPv6 protocol which can support star and mesh network topologies with IEEE 802.15.4 and has lower bandwidth. 6LoWPAN also consumes lower power [95]. It has been used to monitor the soil variables and climatic (moisture, temperature) condition of the greenhouse plants [102]. Suryady *et al.* [103] presented a performance based evaluation study on the greenhouse plants with 6LowPAN. The study shows that there are some packet transmission delays between the sensor node to the gateway and this is because the packets were routed by the gateway [103].

5) Cellular: Cellular protocol is suitable for those devices which require a higher transmission rate of data. It uses 3G, 4G and GSM modules to ensure the high speed reliable transmission of data through the Internet. This technology is good to be deployed for an underground wireless network. However, it requires more battery power and the operation cost is slightly higher [104].

6) LoRa WAN: LoRa WAN is based on IEEE 802.11 ah standard and it uses LoRa network, which allows to operate for long distance communications. It is based on Peer-to-Peer (P2P) and star topologies. LoRa WAN also consumes very

TABLE V
TYPICAL REPORTED WSN COMMUNICATION PROTOCOLS THAT WERE USED IN SMART GREENHOUSES

WSN protocols	Topologies	Data transmission rate (bps)	Operating range	Power Consumption
IEEE 802.15.4	Star and Peer-to-Peer [123]	20-250 kbps [92]	10 m [124]	Low [123]
Zigbee	Star, Tree and Mesh [125]	250 kbps [126]	10-100 m [69]	Low [125]
BLE	Star and Tree [127]	1-2 Mbps [69]	30 m [69]	Low [127]
6LowPAN	Star and Mesh	0.3-50 kbps [69]	10-100 m[128]	Low [128]
Cellular	2G/3G frequency bands [129]	10 Mbps [129]	Several miles [129]	High [129]
LoRa WAN	Star and Peer-to-peer[69]	Less than 50kbps [128]	5-50 km [128]	Low [128]
RFID	Peer to peer [69]	50 tags/s [69]	10-20 cm [69]	Ultra low [69]
Wi-Fi	Star [69]	0.1-54Mbps [128]	Less than 92 m [128]	Low [128]

low power and it can cover a wide range of area when it is deployed in the greenhouse farms [105], [106].

7) RFID: Radio Frequency Identification (RFID) architecture aids the machine to affirm and record all the sensor information by using radio waves [107]. The architecture comprises of host, tags and readers [108]. The reader collects all the information through radio waves and communicates with each other [109]. Three types of tags are used, i.e., active, passive and battery assisted passive. The active tag consumes more power and is battery powered, which can be detected far away. The passive tag only consumes the power harvested from the reader and can only be read in a short distance. RFID protocol has been explored for the monitoring of the crop conditions as well as the environmental conditions [108].

8) Wi-Fi: Wi-Fi is the most commonly used WSN protocol and it is based on IEEE 802.11, 802.11a, 802.11b, 802.11g and 802.11n standards [69]. Wi-Fi uses Wireless Local Area Network (WLAN) connectivity and it has been used to monitor plants, climatic conditions [110], and irrigation control in smart greenhouse farms.

The smart greenhouse means that there must be uninterrupted and efficient connection between the devices under adverse environmental conditions and the Internet. However, cases were reported that the WSN was damaged due to the environmental conditions [111], [112], [113] within the greenhouse farms. Moreover, the plant growth can sometimes develop multi-path distribution problem which introduces noise in the background and decreases the data transmission speed [114].

Recently reported in [54], ad hoc wireless network can be used to the situations where the nodes are exposed to harsh conditions. However, ad hoc wireless network uses LPWAN which has exorbitant deployment and gateway cost [54]. Smart greenhouses also have interoperability issues as there are too many standards of communication protocols and data modeling interface. This generate problems in the connectivity (poor coverage of 3G/4G) of the devices which is another key issue to solve in smart farming [33], [69]. Although, SigFox and LoRa network technologies have leveraged this issue for small dataset but there is no solution yet to deal with large dataset [115].

B. Edge and Cloud Computing

1) Edge Computing: In the year of 1990, Akamai proposed "Content delivery networks" (CDN) to improve the performance of the Web which can use less bandwidth to retain the video information by using edge nodes to cache the content [116]. Edge computing is one extension of this paradigm which supports the cloud computing system. It supports data storage and has considerable integration of computing technology which is named cloudlets [117] and fog nodes (microdata center) [118]. Fog nodes are often deployed close to the sensors or cell phone devices [119].

Chen *et al.* [120] proposed fog computing "ThriftyEdge", also known as mobile edge computing network, as an alternative to the traditional cloud computing network for smart greenhouse farms. The network uses sorting topologies which employ the edge resources with minimum occupancy and fulfills the requirements to maintain the quality of standard QoS for the data transmission. The results from the defined network were superior to all other proposed networks and can help the end user (farmers) to obtain all information very efficiently [120]. Zamora-Izquierdo *et al.* [121] proposed a versatile three-tier platform that mitigates the software and hardware compatibility issues through "Network Function Visualization" (NFV) to substantiate decision-based operations in the edge layer of the platform. Message Queue Telemetry Transport (MQTT) was used as a communication medium to communicate with other subsystems and FIWARE is used as a cloud layer to store all the data and aid the farmers to monitor and control the farms in real-time [121].

Fan and Gao [122] proposed an intelligent IoT based mobile edge computing (MEC) water monitoring system by using the real-time sensor data from the crops (as illustrated in Fig. 10). It can speed up the data transmission process by establishing an efficient feedback mechanism between the sensors and the devices. Generally, a traditional water monitoring system consists of 1) sensor unit 2) data transfer unit 3) router unit 4) network management unit 5) open-ability unit 6) edge server unit 7) network server unit [122].

2) Cloud Computing: Cloud computing is an Internet cloud reservoir which uses centralized or distributed computing technology. Cloud computing can apply parallel and distributed computing simultaneously or individually and it can be developed on the data center virtually or physically [130]. Cloud computing provides different types of services such as infrastructure, hardware and software services to IoT enabled devices. The advantage of cloud computing is that it can facilitate dynamic monitoring of the virtualized computing system and store the data at a very low expense [131], [132]. This aids the farmers to use the video, image and short message services to obtain the information about the greenhouse

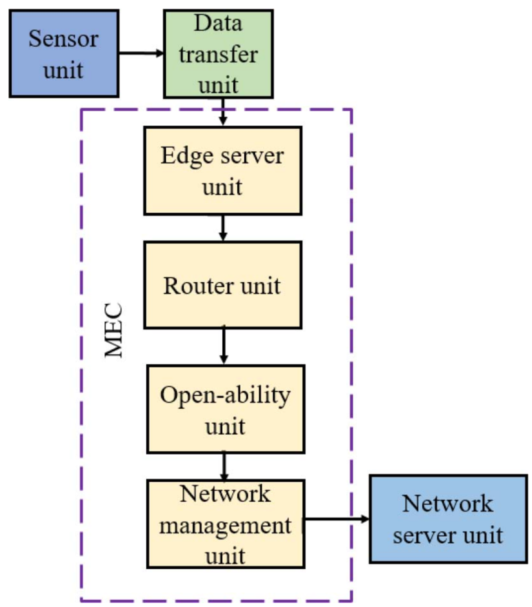

Fig. 10. MEC based water monitoring system.

farms at a minimum cost [133]. Also, cloud computing can handle large scale intelligent computing systems at the same time [41].

In smart greenhouse farms, cloud computing uses three different model layers: Infrastructure, Platform and Software [134]. For instance, Rupanagudi *et al.* [41] used Intel core-i3 32 bit processor as the Infrastructure (hardware), Microsoft Azure as the platform and Java application as the software to identify diseases and unripe tomatoes by using real-time video footage of the Web camera. Hsu *et al.* [135] developed a cloud integration platform to perform data analysis on large data set and to automate the farm monitoring process even if the information of the network is limited. The developed network could also increase the data processing speed which can be used in the pest management of the smart greenhouse farms [135].

Gayatri *et al.* [136] proposed a real-time smart monitoring platform to improve the yield of the crops by using a cloud-based wireless network. The embedded wireless network could operate very efficiently by transferring all the sensor data to the cloud which aided the farmers to use energy efficiently [136]. Abdullah *et al.* [137] developed software called "Agri-System" with the integration of cloud computing, IoT and sensor data. The system aims to maintain the sufficiency of the smart green house farms by ensuring all the environmental parameters are under control. A fuzzy controller is used to minimize the complexity [137]. Channe *et al.* [138] proposed a mobile based application, "Agrocloud" which is an integration of big data, IoT, sensor and cloud technology. The Beagle Black Bone of IoT helps to obtain the environmental and soil parameters and transfer it to the Agrocloud to store the data. Agrocloud also provides agro-vendors, marketing and government schemes to support farmers during and after the harvest time [138].

Data and system security have become a vital challenge in recent years. Network or cyber attacks make all the data very vulnerable and it can completely be wiped out from the entire system. As there is the lack of homogeneity in the network coverages, verification and privacy protection also varies. Two of the most commonly data security problems arose due to RFID tags and WSN [54]. RFID tags can be rewritten from the Internet through the readers this leads to the possibility of invasion in the data protection system. For WSN, the sensor nodes are open as it is deployed for unsupervised monitoring purposes. This makes it susceptible to the illegal users and external intrusion, such as, node capture attack, information tapping, replay attack and so on [139], [140]. Data processing capacity is another challenge: There are several devices available in the market which claim to offer superior data processing power. However, how to do this with a reasonable investment. This affects the medium and small-scale smart farmers as they can not afford expensive powerful data processing devices to their farms [33].

C. Decision Making

In tradition farming, decision making is generally experience based. Those decisions include the crop planting and harvesting time, fertilizer applying, irrigation, pesticide applying and etc. As all those decisions are subject to the environmental conditions, particularly the weather and soil conditions, it is difficult to develop an expert system to facilitate the decision making for field farming. Nevertheless, in a smart greenhouse, the soil condition and local environment can be precisely monitored and controlled, also the plant condition can be monitored in its whole growing cycle. This makes it possible to develop an expert system to grow crops inside a smart greenhouse, just like setting up a cooking program.

Machine learning or artificial intelligence [141] is the approach being taken to process the sensing data collection and facilitate the decision making process. Some examples include Naive Bayes, Gaussian Mixture Model (GMM), artificial neural networks, decision trees, k-nearest neighbor, deep learning [142], fuzzy logic's. Machine learning can make predictions and can find the correlation between variables to provide intelligent decisions or solutions for the smart greenhouse farmings. This technology has been already used to plan irrigation systems, identify and predict plant diseases [143], [144]. In [145], yellow sticky papers were used to capture the pests. The pests were then counted with the aid of machine learning and image processing algorithms. The machine learning algorithm could also identify a variable (light intensity) which had a direct impact of the pest growth on the greenhouse cabbage farms [145]. Jumat *et al.* [85] proposed a machine learning based prototype to identify and classify "Septoria" plant diseases in smart greenhouse farms. The proposed prototype uses Raspberry Pi 3 module and Random Forest as a classifier to detect the plant diseases efficiently [85].

Machine learning was also used by Khirade and A. Patil to detect plant decease [146] image data was fed to the machine and artificial neural networks were used to classify the disease of the plants. In addition, a machine learning IoT based commercial system is developed by Palli *et al.* [147] to automate the farm monitoring, fertilizer spraying and notify the farmers when pests are attacking the plants.

In [41], the proposed cloud technologies and the designed algorithms in Java determined the amount of insecticides that needed to be sprayed on the plants. This can avert the excessive usage of insecticides and can protect the plants, the farmer and consumer's health and the environment. Apart from this, several fuzzy logic based models were developed to control the microclimate inside the greenhouse farms [148], [149]. In addition, models have been developed to utilize the greenhouse infrastructures (water pumps, actuators, lighting and etc.) in a most efficient way [42], [130], [150] as well as estimate the crop yields, for example TOMGRO [136], TOMSIM [151] and TOMPOUSSE [152], [153] have been developed in recent years to estimate the tomato yield from the smart greenhouse farming.

The decision making part (also called an expert system) of the IoT architecture for smart greenhouse farming is currently in its early development stage. Significant efforts are required to make them applicable or become a "menu" type system. Several factors greatly contribute to this, including,

- Lacking of proper IoT technology to monitor crop growth, such as height, growth rate, maturity and quality.
- Lacking of local environment condition parameters surrounding the crops. Current sensing technology only monitors the global environment inside the greenhouse which can be very different from the local ones.
- Lacking of the correlation between the crop growth data and the environment data.

VI. Conclusion and Future Perspectives

As discussed in this review paper, although IoT empowered smart greenhouse farming offers countless current and potential benefits, the technology has also advanced remarkably in recent years. It is believed that major efforts from the researchers, engineers and farmers are needed in order to improve the crop yield at lower cost, particularly if we envision the future smart greenhouse farming as a "menu selection" process similar to the cooking. Below are the summary of the major challenges facing the IoT empowered smart greenhouse farming:

- Low cost and reliable solution for the monitoring of plant growth, including all the plant traits (height, leaf decease, fruit/grain/leaf dimension and etc.) and quality (protein, sugar and etc.).
- Low cost and reliable sensor solution for the monitoring of local climate surrounding individual crop or most part of a large plant.
- Low cost and reliable sensor solution for the monitoring of soil conditions (chemical compositions).
- A unified data transmission protocol. The inter-operability and generalized standards for data annotation, visualization and decision should be considered. This would require the coordination between major industry associations.
- Secure data transmission and storage. Integrating blockchain technology with the IoT empowered smart greenhouses provides a viable solution for this. Reference [154] reported research in this area.
- The development of an "expert system" to facilitate farmers in the decision making process, this needs to integrate the environment data and the crop growing data using artificial intelligence.

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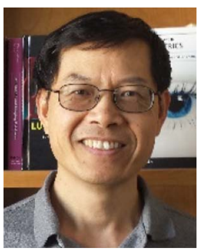

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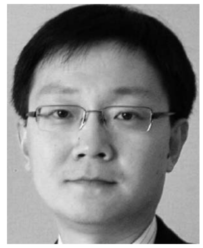

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