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Internet of Things in Greenhouse Agriculture: A Survey on Enabling Technologies, Applications, and Protocols

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ABSTRACT The greenhouse is one of the sustainable forms of smart agricultural farming. It is considered as an alternate method to overcome the food crisis which is generated due to high population growth, climate change, and environmental pollution. Although this method supports off-the-season crops within the enclosed area even in severe climatic zones. It has required to efficiently control and manage the crop parameters at a greenhouse in a more precise and secure way. The advancement of the Internet of Things (IoT) has introduced smart solutions to automate the greenhouse farming parameters such as plant monitoring, internal atmosphere control, and irrigation control. The survey presents a hierarchy on the major components of IoT-based greenhouse farming. A rigorous discussion on greenhouse farming techniques, IoT-based greenhouse categories, network technologies (cloud/edge computing, IoT protocols, data analytics, sensors) has been presented. Furthermore, a detailed discussion on mobile-based greenhouse applications and IoT applications has been presented to manage the greenhouse farm. Moreover, the success stories and statistical analysis of some agricultural countries have been presented to standardize IoT-based greenhouse farming. Lastly, the open issues and research challenges related to IoT-enabled greenhouse farming has been presented with state-of-the-art future research directions.

INDEX TERMS IoT, smart greenhouse, hydroponics, vertical farm, security issues, network technologies, communication protocols, IoT sensors, mobile apps.

I. INTRODUCTION

The continuous growth of world population, environmental change, industrialization, the arable land over the globe is decreasing every year [1]. Therefore, the demand and requirement for hygienic food and crop yield have been growing continuously. A survey conducted by the United Nations of Food and Agriculture Organization (FAO) estimated that the population of the world is expected to reach 9.73 billion in 2050 [2]. It is expected that more cropland and water will need to meet the future food demands globally. Furthermore, other challenges such as abrupt changes in climate, lack of labor, and water scarcity spiral the pressure on agriculturists and farmers [3]. The challenges faced by traditional agriculture and greenhouse farming need a fundamental change to develop sustainable and ecological food. Greenhouse farming is one of the best alternatives to overcome the food crisis as well as to ensure the sustainability of socio-ecological. Initially, the greenhouse farming method was introduced in France and Netherland 19th century [5]. At present, greenhouses have become one of the ideal farming methods in the agriculture world [6].

The greenhouse is a structure like a house that is covered with a plastic material or glass mainly designed to cultivate multiple crops in any season. In order to increase the quantity and quality of food, a greenhouse can regulate the growing patterns of plants accordingly. Traditional greenhouses are specifically designed with dry lands and ignore the multiple environmental variables such as temperature, humidity, among others [7]. Usually, a smart and productive greenhouse

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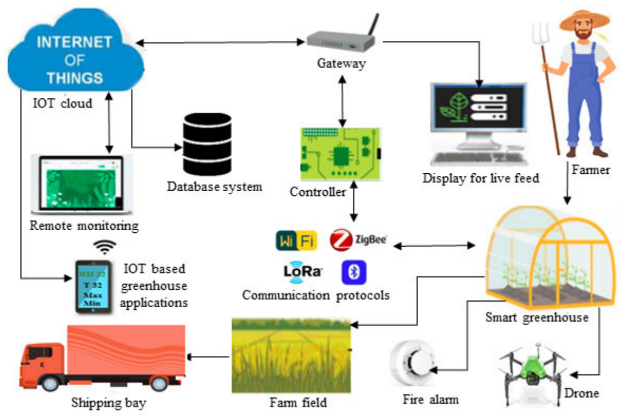

FIGURE 1. IoT based greenhouse farming trends.

requires environmental monitoring and control devices, to manage various weather parameters [8].

In the conventional greenhouses, climatic variables and other growing methods were depending upon the cultivators' assessment and demand for the number of growers [9]. In the last few years, the smart farming concept has attracted the broad attention of farmers, agriculturists, and researchers. Smart greenhouse farming is an enclosed cultivation process that manages the farm by using information and communication technology (ICT) to enhance the quality and quantity of crops with minimal human involvement [10], [11]. The emerging IoT technology provides a high potential for innovative methods and smart solution development which can transform the agriculture sector in all aspects. Thus, integrating the IoT with a greenhouse to convert it into a smart and automated greenhouse is considered to be one of the foremost and ideal solutions. Thus, IoT-enabled greenhouses can mitigate these challenges as well as assist growers to enhance the productivity of food and crops [12].

Figure 1 shows the IoT-enabled greenhouse farming trends. The deployment of a wireless sensor network (WSN) enables climatic data to be gathered and distributed for understanding and monitoring the internal system of the greenhouse, but there is a need to handle several other features which can cause significant destruction to the grown plants, such as, less or high-water supply, bad weather conditions, and light intensity. The eradication of these issues can be done through a precise system that helps to automate the monitoring and control methods for a smart greenhouse [15], [16].

Current research developments demonstrate that how researchers are exploring and utilizing the IoT technologies in greenhouses for different farming practices. As a result, there are several prototypes, applications, and services in IoT-based greenhouse farms. In a smart greenhouse, the research trends consist of network architectures, new applications, interoperability, and security challenges. Therefore, it is expected that a state-of-the-art understanding of current research on IoT-based greenhouse farming is highly informative and valuable for agriculturists, farmers, stakeholders,

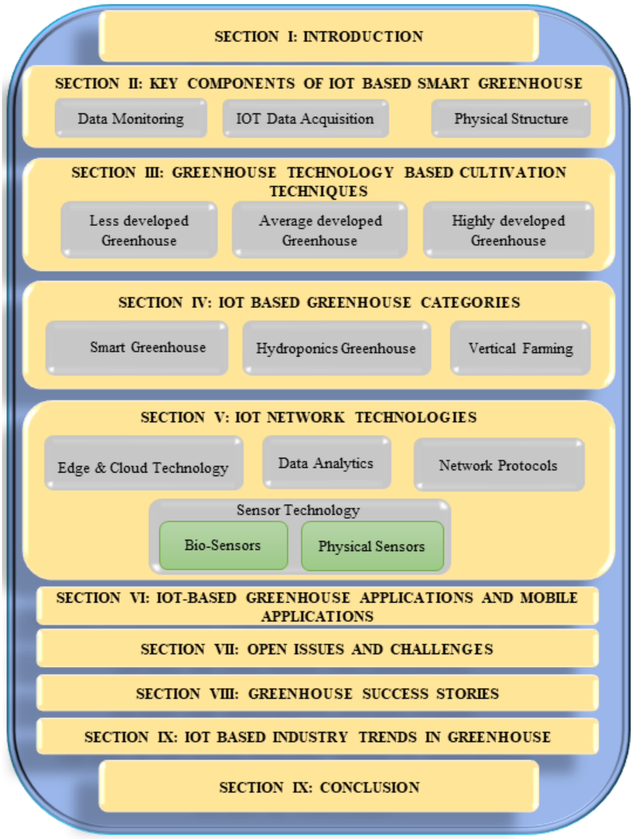

FIGURE 2. Structural flow of the paper.

and researchers. Although a huge amount of research has been accomplished in the area of IoT-based greenhouse farming, still there is a need for detailed study in this area to understand the current research status. The motivation of the survey is to investigate the IoT-enabled greenhouse research trends and various open issues that are vital to transforming greenhouse farming technologies through IoT modernization. The modification of greenhouse techniques on the basis of IoT advancement is explained in this paper by analyzing several approaches, communication protocols, network technologies, applications, challenges, and industry trends in smart-greenhouse farming.

The structural flow of this paper is presented in Figure 2 which contains the following sections:

- Major components of IoT-based greenhouse are presented in section II.
- In section III, a brief discussion is given on technology-based cultivation techniques related to greenhouse farming.
- IoT-based greenhouse farming categories are discussed in section IV.
- Section V presents IoT-based greenhouse farming technologies which consist of edge/cloud computing, big data analytics, IoT communication protocols, IoT sensors/devices.
- Mobile applications and IoT applications for a smart greenhouse are discussed in section VI.

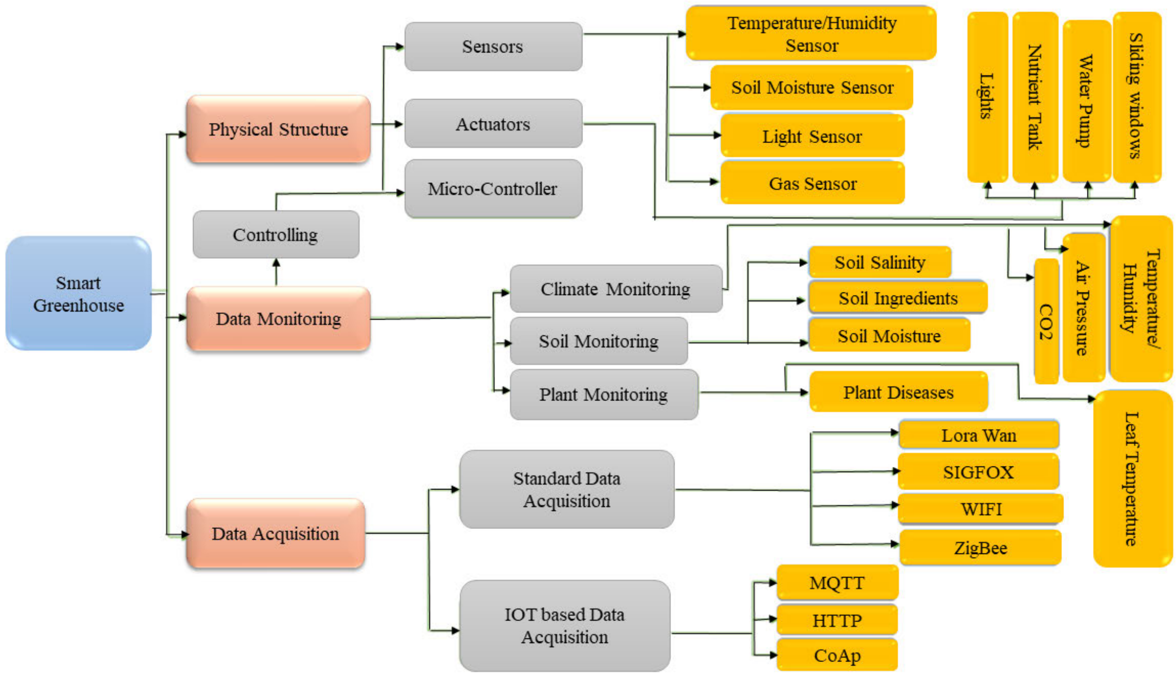

FIGURE 3. Major components of IoT-enabled greenhouse.

- The major problems and challenges regarding greenhouse farming with future research direction have been explained in section VII.
- Top technology firm's trends have been discussed in section VIII that provides detail on how technology industries are investing in this area.
- IoT-based smart farming success stories and statistical analysis made by different countries to boost greenhouse farming are presented in section IX
- The survey is concluded in section X.

II. KEY COMPONENTS OF IoT-ENABLED GREENHOUSE

The smart-greenhouse structure has been shown in Figure 3. The structural design is based on three key components which are used to accomplish several tasks. The first component named physical structure is divided into three sub-components namely actuators, sensors, micro-controller. Sensors act as a prominent part to accumulate information regarding internal climatic situations using light sensors, humidity/temperature sensors, gas sensors, soil-moisture sensors. These sensory devices transfer the gathered data to a micro-controller for taking a decision accordingly by interacting with the user remotely by using the internet. Actuators consist of a nutrient tank, water pump, lights, and windows for greenhouse farming. They are used to implement the command given by the user.

Monitoring is the second major component of smart greenhouse farming that consists of plant, soil, and climate monitoring. In climate monitoring, the appropriate observation is done by the devices to balance the environment that is mandatory for the certain crop which is cultivated within the greenhouse. In case, climatic factors like temperature, CO2 level, humidity, air pressure are not matching to the limit defined by the user, at that time micro-controller is informed to trigger the devices for balancing the internal environment. In soil monitoring, all the essential ingredients like phosphorus, potassium are examined by the sensors. Besides this, the level of soil wetness and soil salinity is also observed for avoiding damage to the grown plants. Plant monitoring contains observation of crop diseases and leaf temperature to recognize the behavior of the plant growth so that users can be able to get information about the health of plants. This data can be evaluated for further cultivation practices in greenhouse farming.

IoT data acquisition contains two sub-components i.e. standard data acquisition and IoT-based data acquisition. Standard type includes communication protocols, for instance, SIGFOX, Low Range Wide Area Network (LoraWAN) Wi-Fi, ZigBee for remote and small range communication purposes. They are managed according to the required conditions.

IoT-based data acquisition holds three major protocols which are MQTT, HTTP, and CoAP. These protocols are used for long-range communication. Further, IoT-based data acquisition is used to maintain the conditions within the greenhouse to surge the production rate of quality crops efficiently.

III. TECHNOLOGY BASED CULTIVATION TECHNIQUES OF GREENHOUSE

The productivity and efficiency of a greenhouse farm are widely depending upon the growing structure of the crop.

Although there exist multiple structures to select from, but it is more important to have deep knowledge about the challenges and benefits of each greenhouse farming method. In this section, three technology-based cultivation techniques namely; less, average, and highly developed greenhouse are discussed.

A. LESS DEVELOPED GREENHOUSE (LDG)

LDG is a permanent greenhouse farming technique that is suitable for flowers and vegetables not applicable in hot regions because they do not have ventilation techniques. Additionally, the wooden stuff is commonly available, so it is easy and affordable to construct a greenhouse by the agriculturists who do not have sufficient budget to build advanced technology-enabled greenhouses. However, the structure has poor environmental control and fewer investment charges. Moreover, farmers can also attach multiple units of the greenhouse to generate a larger one [17].

B. AVERAGE DEVELOPED GREENHOUSE (ADG)

Greenhouse based on Average technology has more flexibility as compared to LDG. The structural design is generally constructed by polythene or glass sheet with a well-organized environmental control mechanism. The ventilation method in this technique can be static or moveable for permitting the air to blow within the greenhouse which makes it capable to manageable in hot regions as well. For these partial automatic procedures, the cost ranges from 30 to 100 $/m^2 in which vegetables, as well as high-quality plants, can be cultivated [11]. These greenhouses are applicable for quality production with the cheapest cost and consume less power as compared to highly-developed greenhouses [18], [19].

C. HIGHLY DEVELOPED GREENHOUSE (HDG)

A type of greenhouses that minimizes the labor expenditure by automating the tasks. The methodology has an extra maintenance cost that is more than 100 $/m^2, due to which, it is not certainly affordable for farmers. HDG has a glass/iron structure in which the internal weather is entirely independent of the external atmosphere. The climate can be set accordingly by monitoring climatic factors like temperature, CO2 level, and humidity. The use of this type of greenhouse is suggested in cold-winter areas to develop nursery production [17]. To surge the quality and yielding rate of crops, this eco-friendly technique is efficient for use [18].

IV. IoT-BASED GREENHOUSE CATEGORIES

Nowadays, devices based on IoT are used at a large scale in the monitoring and controlling systems of several sectors. The IoT-based technologies consist of different kinds of actuators, sensors, drones, cloud computing, analytical system, and navigation which make efficient decisions to surge crop production with less human involvement [20], [21]. The usage of these sensors and devices is to observe the atmosphere and collect information like temperature, humidity, the intensity of light, and soil moistness. The collected information related to the environment is stored on the cloud computing server that can be analyzed and visualized by the user at any location using the internet [22], [23]. This section presents the greenhouse technologies based on IoT particularly three techniques named; Smart-Greenhouse, Hydroponics, and Vertical-farm.

A. SMART-GREENHOUSE

Greenhouse can be defined as an agricultural modernization for providing a controlled and organized atmosphere to plants. A packed loop is formed in the greenhouse and plants are protected from the external climate. A safe situation is produced for growing crops and it shows a high significance in the varying climatic circumstances. Hence, greenhouse acts as a great illustration of precision farming. Greenhouse's efforts are based on the conception of the ''greenhouse effect''. Light enters into the greenhouse via walls/roof and is trapped within the greenhouse because of sealing arrangements. Today's greenhouses are furnished with smart technologies such as cameras, lights, Arduino/Raspberry Pi, and wireless sensors to offer automatic controllers for the intensity of light, temperature, soil moistness, and the level of humidity for maintaining the necessary atmospheric condition which is necessary for the plant growth. WSN is used to assist in monitoring and controlling these devices and create an optimized climate for crops [24], [25]. For example, soil sensors assist to gather facts on the flows of water by the land to track fluctuations in soil wetness, temperature, and nitrogen/carbon levels.

This process lets the growers to optimize, observe, and regulate the cultivation of sensitive crops, to maximize their crop yield while maintaining its quality for the end product. They are able to sense data such as moisture, light strength, and value of temperature to alter the sequence of irrigation for avoiding the chances of damage. A greenhouse climate monitoring system is shown in Figure 4. Irrigation plays a vital role in a good production rate to guarantee that agriculturalists would be able to meet the water load for the crop. However, poor planning for irrigation and ineffective usage of water resources are limiting crop production in several agricultural areas. Through a traditional irrigation method, soil moisture faces great variations in its concentration. Sometimes, the soil is completely dried, and then irrigating it with a high volume of water creates a vertical surge in the value of soil moisture. These thrilling alterations are not beneficial for crops, because they need moistness in the soil to keep themselves at a moderate limit. Additionally, dry soil consumes a high-water quantity for irrigation because it cannot keep the water just like slightly moist soil [26]. Irrigation procedures are commonly automated using computer control, timers, and specialized controllers. In an open-loop irrigation system, the output measurements are not implemented to alter the inputs, this irrigation is based on predetermined time intervals, for example, time-clock scheduling.

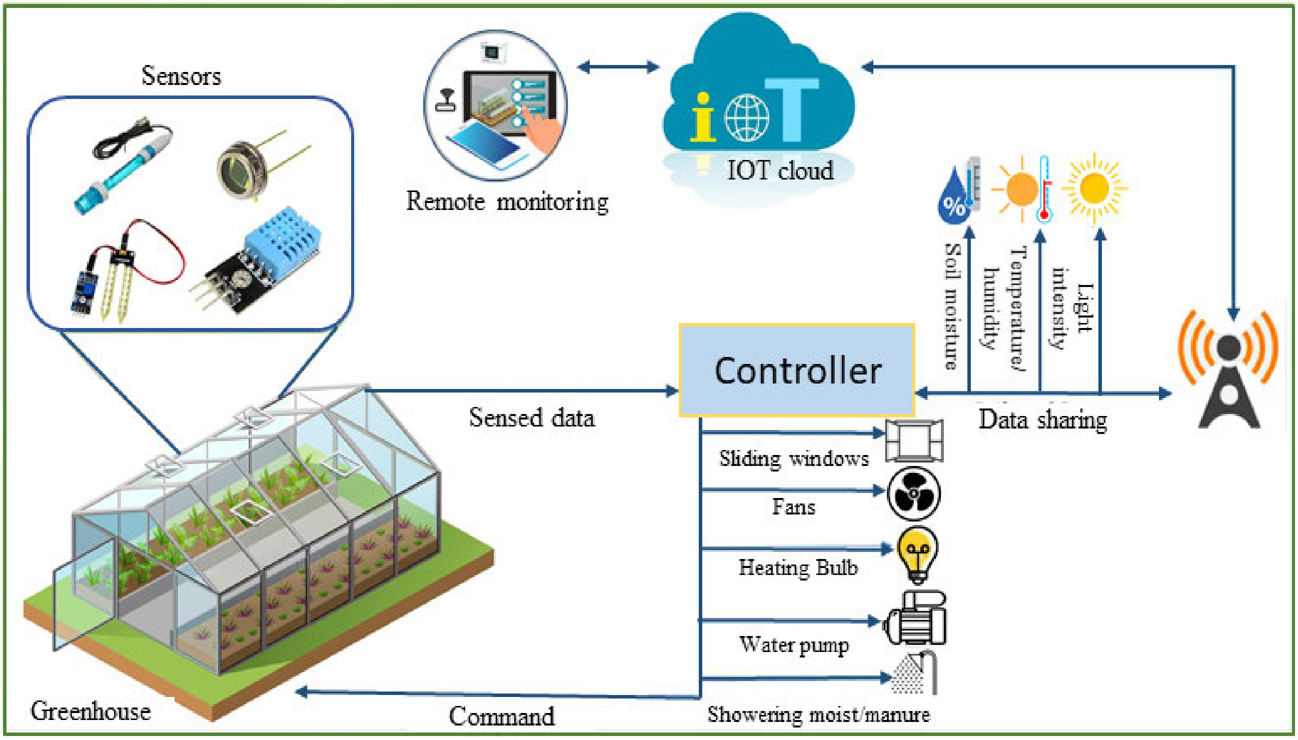

FIGURE 4. Smart-greenhouse.

An enclosed-loop controlling method is used in the irrigation based on feedback, in which the system offers growers real-time output data to reschedule irrigation, for example, drainage percentage and plant water position. In a feed-forward irrigation system, water usage is estimated through transpiration and growth models [27]. Another method of irrigation is through an overhead crane that is linked with a pipe, in which green manure/water is shifted to a crane for crops. Crane moves vertically/horizontally to deliver the stuff in plants [28]. Moreover, maintaining suitable humidity and temperature inside a greenhouse climate is crucial. Temperature altering can damage crops within a few hours, this decline in productivity. Thus, the environment is a vital parameter for plant growth [29].

When humidity surges, it causes more chances for crop diseases. Further, the dew condensation arises in the greenhouse at the time when the temperature of a dew point is greater than the crop's temperature, and its relation is deep with relative humidity [30]. A pack of sensor nodes is used to sense the temperature and humidity within the greenhouse. The hygrometer sensor monitors the humidity and pyroelectric film is used to monitor the temperature. The modification gathered by both sensors is transferred to a mutual analog/digital signal converter (ADC) system which alters these analog signals of information into a digital signal for ease of understanding and decoding through server [31], [32]. Another parameter naming as light intensity is also important to monitor for healthy plant growth. The light sensor's output voltage modification depends upon the intensity of light.

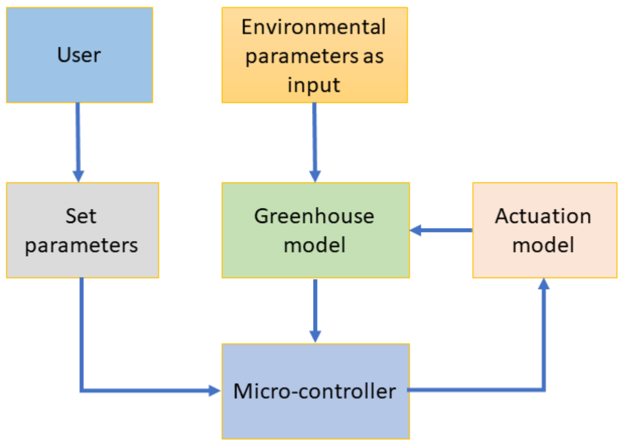

FIGURE 5. Environment monitoring in greenhouse.

The increasing intensity identifies high voltage in the result and when the intensity becomes low, then the resulting voltage drops [25]. Figure 5 shows that once the sensors create the context information, it is then sent towards a gateway or micro-controller that is used for integrating all the deployed devices at a single platform [33], [34].

Micro-controllers are assumed as the heart for a greenhouse system in which several actuators and sensors are interconnected to construct a precise automated system [29].

The connectivity of Wi-Fi within the Cloud facilitates data transmission towards the cloud by using a microcontroller and then kept in the database based on the cloud. The material saved within the cloud is repeatedly conveyed to the user's mobile through the internet for initiating a distant checking so the user can be able to alter the threshold for the greenhouse climate.

This enables the ''human towards machine'' communication and offers a ''machine towards machine'' collaboration. The drivers of the motor circuit connected with sliding windows and coolers are fixed to help the motor for regulating the movement of air inside the greenhouse. Depending on the threshold fixed for the humidity, temperature, light, and moisture, the micro-controller activates the driver circuit for regulating the airflow and stabling the temperature [25]. In case, there is dryness inside the greenhouse, the water sprayer is triggered for increasing the level of humidity. The sprayer can be switched off. Moreover, if the humidity surged inside the greenhouse farm, then a rooftop is opened for lowering the humidity level [31].

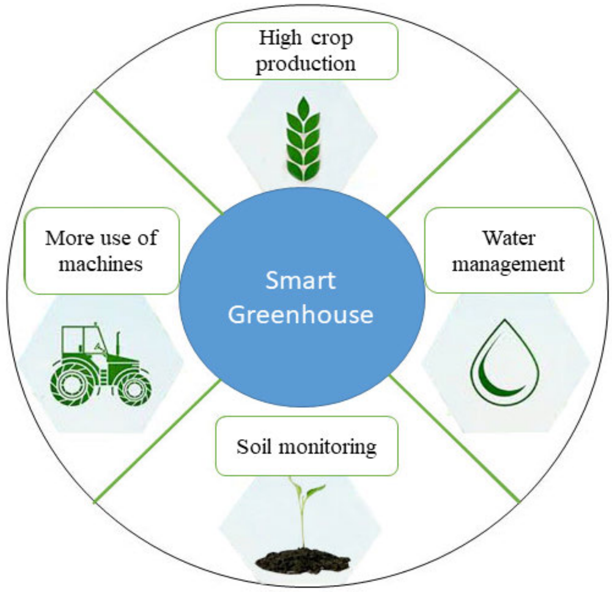

FIGURE 6. Benefits of smart-greenhouse.

1) BENEFITS OF SMART GREENHOUSE

The platform of the IoT offers an automated greenhouse environment that enables a significant association among tangible things and people. A user is allowed to gather real-time data processing, analysis, and meditation. The system is deployed to offer automation for monitoring as well as controlling. The deployed system collects and transfers the sensed information via the IoT cloud for easy access from anywhere and at any time.

Thus, IoT enabled greenhouse farming to enhance productivity and decrease labor costs. A farmer can grow multiple crops in the appropriate season with less human effort as shown in Figure 6. The efficient use of water and proper soil monitoring results in high crop production.

B. HYDROPONICS GREENHOUSE

Hydroponic-Greenhouse system is a cultivation technique using water instead of soil. It shows that soil is not vital for plant cultivation, only the vital minerals, nutrients, and adequate pH are required within a specified range inside the water [35]. This system is a highly productive and fast process as compared to a plantation in soil. Moreover, vegetables are cultivated via the hydroponics process. Hydroponics farming has a short harvest time and is usually rounded up for minimizing costs [36]. Hydroponic farming required precise control of climate parameters for high-quality production. The most important parameters are humidity, light intensity, pH, temperature, and electrical conductivity. These parameters can be monitored through any sensing and monitoring devices. Sensing/monitoring devices are controlled by a micro-controller known as Raspberry Pi [37]. The micro-controller is managed by connecting to the Wi-Fi module, which transfers all sensing devices' information related to hydroponics to cloud storage. A typical hydroponic structure is shown in Figure 7 which contains the hydroponic water pressure pump, pipes, nutrient container, artificial lights, water tank, and adjustment of PH solutions. The sensors related to Electrical Conductivity (EC) are standardized using low, high, and dry EC adjustment by using solutions having dissimilar EC levels. PH and EC are significant aspects to maintain the healthy growth of the crop and plants. In the hydroponic method, the concentration of EC can be increased by following the instruction mentioned in the solution container. The primary objective of the pH controller is to investigate and identify the existence of bicarbonates or carbonates within the nutrient solution by which pH values can be determined. The pH levels of bicarbonate-ion (HCO3) are altered from 4.5 to 8.3 and the nutrient solutions which are containing carbonate-ion (CO3) surge levels of its pH beyond 8.3. Hence, the solubility of salts having calcium-carbonate is reduced. Once the precipitation process has been done, it is challenging to re-establish the value of the solution's PH. The greatest way to avoid this problematic situation is taking out constant usage of marketable acids which deactivate and also finish the bi-carbonates created within the solution. Acid's amount that requires to be combined with nutrient's mixture relies on the used water and bicarbonates in the nutrient combination. Additionally, acid would lead the pH level to that value where it can be dangerous for crops [35], [38]. The PH and EC controlling methods enable farmers to efficiently manage nutrients in solutions that can be reused by rapidly detecting instability that arises in the nutrient [39]. The liquid flow within the hydroponic method is also necessary to control, for example, there are chances that the crop size can be small or it would die in case the system delivers a slight hydroponic liquid. In another case, if supply goes beyond the required limit, it may return abnormally-shaped crops. Hence, system function and system supply should be controlled.

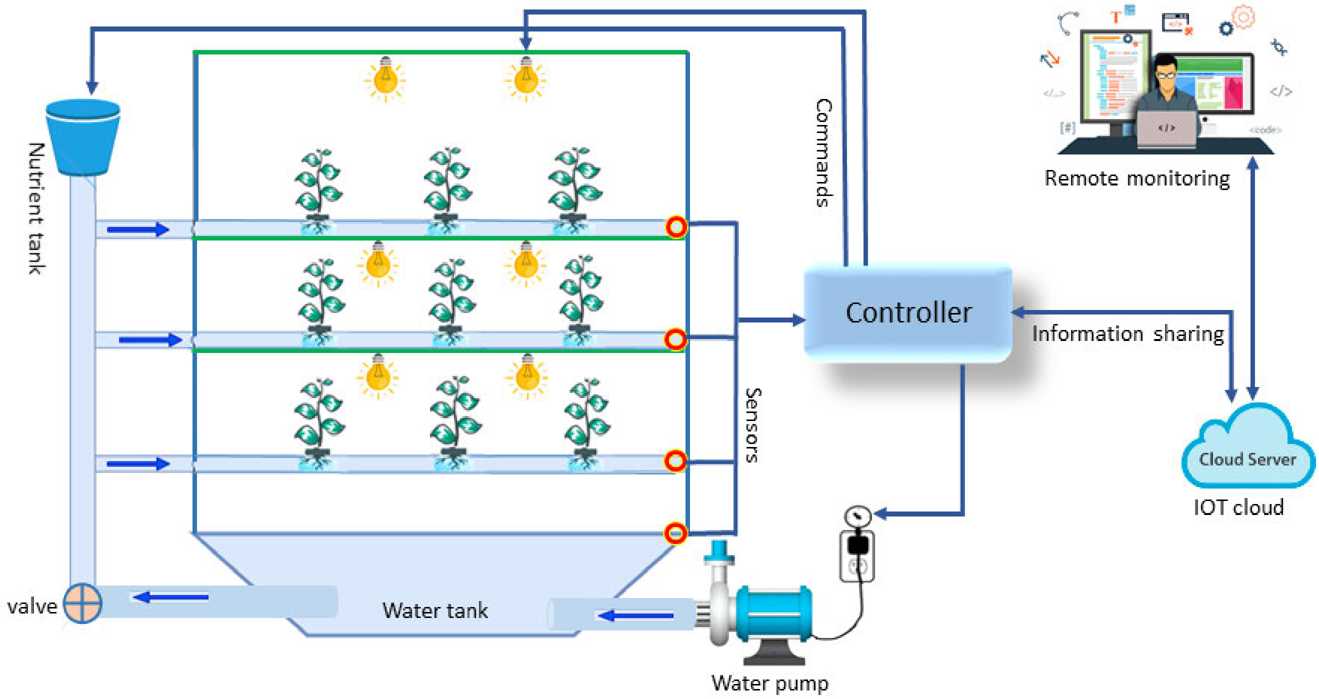

FIGURE 7. Hydroponics greenhouse.

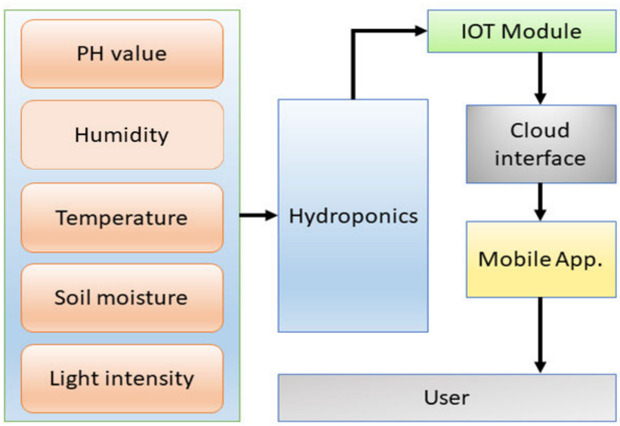

FIGURE 8. Hydroponics functional platform.

The quantity of hydroponic fluid supply can be determined through evapotranspiration, which is measured by Relative-Light-Intensity (RLI) and Vapor Pressure Deficit (VPD). In Evapotranspiration, process water is wasted through the leaves of plants. The use of relative humidity and temperature enables the calculation of VPD. RLI means the ratio of light quantity which is dispersed at the upper and bottom sides of the crop. The deployed sensor nodes within the hydroponic structure gather greenhouse environment information on the crop's conditions.

The accumulated data is then transferred towards the sensor's gateway via the sink node that collects the important information from all the nodes shown in Figure 8. The data is authenticated by sensor gateway and shifted to the actuator controlling system and cloud storage. Lastly, the actuators are driven by the system and supply the required amount of hydroponic fluid that is mentioned in the received information. The system also permits the user to visualize the collected information and put control information by staying anywhere using a web browser. Hence, the ease of use can be enhanced by arranging both data and information of the actuation process on a cloud-based server. If the Internet failure occurs, the control signals will be unable to reach the controlling program, then the actuators will not be controlled by the system. Moreover, when entire data is stored only on cloud then data can be lost or unavailable whenever the Internet would not be available. Therefore, it is vital to prevent data loss even in case of failure in uplink/downlink to attain effective climatic control by keeping data storage as a backup through the local network [40].

1) BENEFITS OF HYDROPONICS GREENHOUSE

Unnecessary pesticides are not required for the soil in this method. The water need is fewer as compared to traditional greenhouse farming. The plant production is not affected due to any external change in the environment.

2) ISSUES OF HYDROPONICS GREENHOUSE

The need for manual checking to deliver the essential nutrients is extensive [21]. Scalability issue arises due to

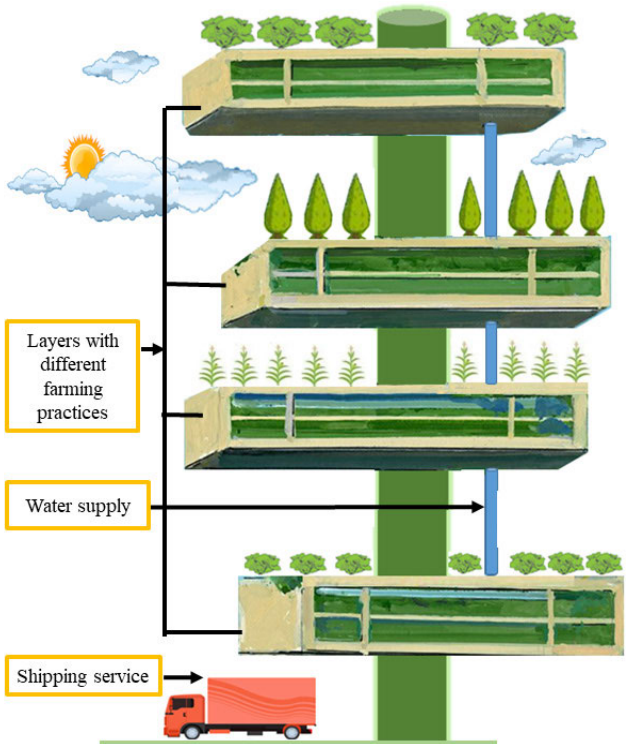

FIGURE 9. Vertical farm.

heavy starting investment for structure. The system that is normally used for communication within hydroponic farms is inappropriate for remote communication [41].

C. VERTICAL-FARMING

The concept of food supply in cities has already existed, but the awareness of a whole building occupied by crops is an emerging idea. In vertical farming several crops are cultivated inside an enclosed region, that is structured like an elevated style to accommodate plants [42]. The vertical farming concept is presented in Figure 9. Generally, the structure of vertical farms is designed to cultivate plants in the high-tech buildings that normally reside in the middle of a city. The vertical farm act as a type of advanced agricultural system which is completely surrounded by a controlled climate and used to eliminate the external factors related to the environment. There is no need for a wide land area for the installation of vertical farming. The system can be set within any building which has raised a global environment without considering the current environment as the winter or rainy season [43], [44].

The information of environmental conditions is crucial to monitor and control through an appropriate device. These factors are helpful to define the working for the devices and their facilities as well. Environmental parameters contain both the outdoor and indoor climate conditions.

The everyday atmospheric situations like climate limitations require to be processed and manipulated. The seasonal factors and regular climate differences are necessary to consider for more precise developing conditions. In an indoor system, the environmental situations and the conditions related to soil are given important concern. Figure 10 shows the conceptual design of a smart greenhouse. Several devices, for instance, actuators, sensors, and controlling tools are installed inside the vertical farm to observe and control the services. Sensors are linked directly to the climate parameters, through which collected data is transmitted to the server by IoT protocol. Moreover, the link of actuators to the parameters is indirect. Actuators regulate the control devices such as a heater, humidifier, air-conditioner, sliding window, and lights. The variation outcomes of environmental conditions force the actuation process to reset the required standard condition by regulating the devices [45]. The simulation of sunlight within the vertical farm is with the usage of LED lights which enables the crop for carrying out the process of photosynthesis. Hence, light monitoring is necessary to give optimal photonic energy to achieve proper photosynthesis.

Thus, for this purpose, the light sensor is used in the system. Humidity and Temperature are also vital for the good health of the crops in an enclosed environment. This makes the need for the deployment of sensors related to temperature and humidity. Window sliding is used to control these factors. Finally, a continuous process is required to monitor the moisture content of the soil, and enable a burglar alarm to measure the fall of required moisture level [46]. A sensor for soil moisture assists to identify the humidity. If the reading shows a humidity level lower than the fixed threshold, it indicates that the soil has a low amount of water.

Thus, the valve is opened for watering the affected soil within the vertical farm. In case, the level of reading is higher, it shows that the soil contains an extra amount of water. To avoid an excessive amount of water the valve stops the flow of water on the farm [43]. The sensed information by the sensor is transmitted towards the cloud server by using IoT protocol. The detected data is stored within the database and the control actions are performed for maintaining the optimal situation in the environment [47].

1) BENEFITS OF VERTICAL FARMING

Vertical farming acts as a climate-controlled farming method. In this farming method, the occurrence of seasonality issues is very less because crop production is continuous for all-year. The system provides organic food that is healthy and uncontaminated. Moreover, its enhanced productivity improves income and it is useful for lowering energy and food costs as well.

2) CHALLENGES OF VERTICAL FARMING

Start-up costs for the vertical farm can be high if the farming area is obtained within commercial districts. In this system, the farming procedure cannot be as wide as compared to rural areas. Furthermore, yielding capacities don't increase as in a wide region farming as well as leads towards increasing complexity and cost.

FIGURE 10. Conceptual design of Greenhouse farming.

V. IoT-BASED GREENHOUSE NETWORK TECHNOLOGIES

The digital gap between IoT technologies and agricultural producers has been reduced. Productivity will be improved by using IoT technologies through sustainable food cultivation. Smart agriculture (i.e. IoT-based Greenhouse) contains actions such as automated irrigation, automated environment controlling mechanism, remote monitoring, fertilization, and frost protection. These control activities are assisted through the integration of IoT technologies with other technologies i.e. cloud computing, hardware, integration platforms, operating systems, and monitoring/controlling processes [48].

A. IoT-ENABLED GREENHOUSE NETWORK ARCHITECTURE

The smart greenhouse has been coined after describing smart farming notions such as sensors, communications technologies, and variable rate technology for plants growth and crop management. An IoT-based greenhouse network architecture has been presented in figure 11 in order to obtain precision greenhouse farming. The architecture contains multiple components in order to interact, analyze, and predict the farming data through end-user applications. Sensor technology is deployed for data acquisition purposes. However, the data collected through deployed sensors is transmitted towards the gateway for analysis and mining purpose. IoT communication standards such as Zigbee, COAP, MQTT, WIFI, Bluetooth, etc. support all interactions in the network architecture. These communication standards are widely used for precision greenhouse farming where IoT devices and sensors can collaborate and interoperate with any underline communication.

B. EDGE & CLOUD TECHNOLOGY

Cloud computing states a cloud of resources on the internet that is either in a centralized or distributed form. Clouds are built with physical or virtualized resources over large centralized or distributed data centers. Smart monitoring methods mainly pay heed to monitor and controlling plant growth in the greenhouse [49]. The participation of IoT-agriculture and cloud computing helps the process of monitoring to become faster, easier to maintain, easily understandable, and precisely solve the problems of greenhouse farming [49], [50]. The use of cloud-based design allows the information to be collected by the sensors and analyzed by comparing with given constraints.

Then the server will be able to make a decision that is distributed to the subscribed users. In this way, if a disturbance occurs, a notification must be transmitted to the user through mobile [49], [51]. Moreover, edge computing acts as a backbone for cloud computing and plays an important role within the greenhouse to control and monitor the internal environmental conditions. Key control actions of

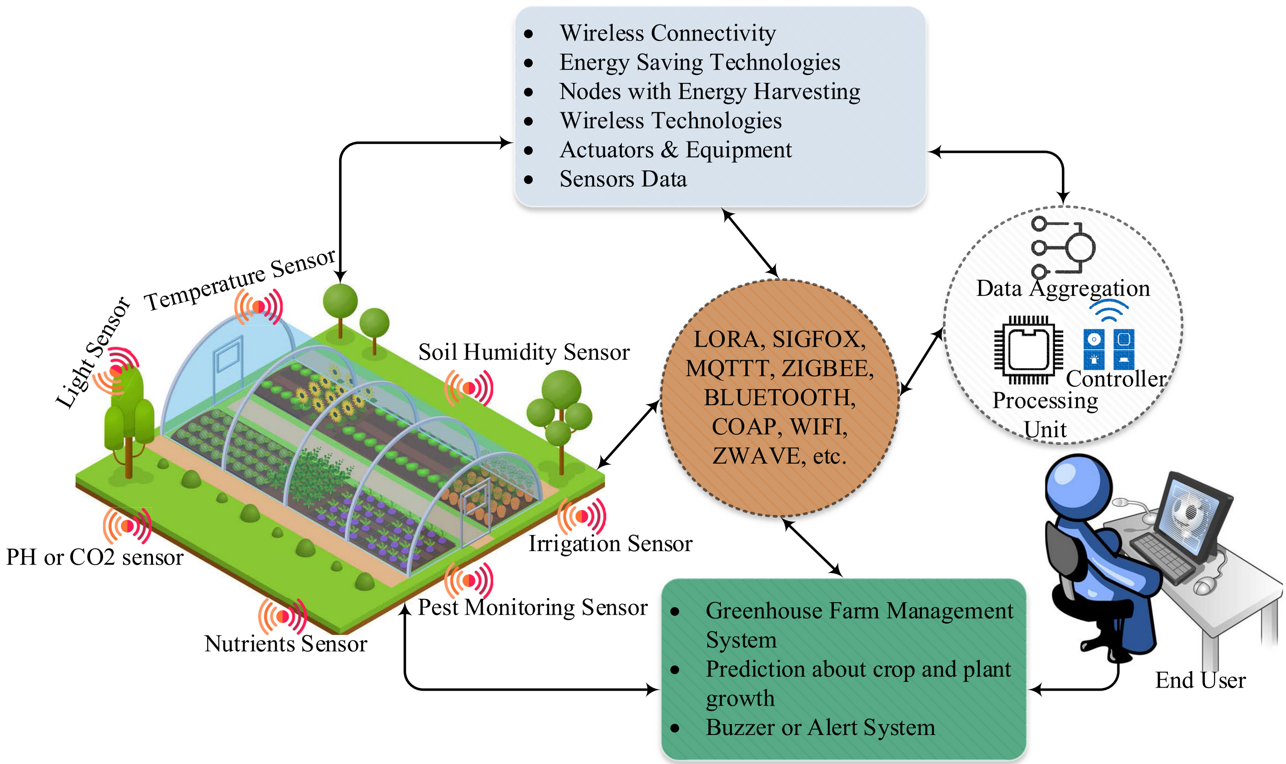

FIGURE 11. IoT-based greenhouse network architecture.

a greenhouse are arranged through a layer at the edge which consists of other controlling segments for climate, nutrition, irrigation, and supplementary tasks. The 'Network-Function-Virtualization' (NFV) is used to power them, hence they are instantiated at dissimilar nodes alongside the network path that is from crop to cloud [52]. The cloud-based greenhouse farming structure is shown in Figure 12 which is using four different layers named Cloud Storage, Fog/edge Computing, Gateway, and hardware segment. The cloud storage component delivers the resources on request by centralizing the greenhouse environmental information. Gateways are used to play a significant role in data distribution for those devices which have no design capability to share information directly by using the internet.

Fog/edge computing is helpful to integrate all the resources for the distributed components. The resource's scalability is surged by decreasing the computational burden at the cloud.

Lastly, the hardware segment contains multiple sensors, actuators, microcontrollers (Arduino or Raspberry PI), and a central processing unit (CPU) which are used to measure several greenhouse farming variables. Fast communication can be achieved in a smart greenhouse by using IoT communication protocols such as MQQT, COAP as Representational State Transfer (REST), and MQTT.

C. BIG-DATA ANALYTICS-BASED GREENHOUSE FARMING

Big data means a large amount of data like business data, sensor data, and public networking data is collected in several ways for a long duration. The significant challenge is to get, analyze, store and search. Processing of business data is done using a big-data technique to find secret patterns within the information. In the agriculture domain, it is useable for supporting the management chain of agriculture products, to reduce the cost of production [53], [54]. The big data analytics model contains several modules which are shown in Figure 13. The prediction model acts as an optimization segment that is useable to guess parametric standards that are not accomplished by the sensors, for example, photosynthesis. The prediction has been given based on parameters that are already available. Artificial neural networks are useable as a tool for the implementation of predictive modeling which can be helpful in constructing a proactive model for greenhouse farming.

All these models are used to estimate the values of general parameters, for instance; humidity and temperature by analyzing them with previously collected data to lessen sampling load and execute proactively [24] The farmer or user experience component assists the greenhouse owners to observe crop growth, climate situations, and soil capability. The multiform analysis explains the various greenhouse farming techniques to reduce the destruction risk of plants by using scientific ways.

The sensing/Monitoring unit is used to collect and analyze the internal greenhouse farming parameters by means of multiple monitoring and sensing devices. This precise data

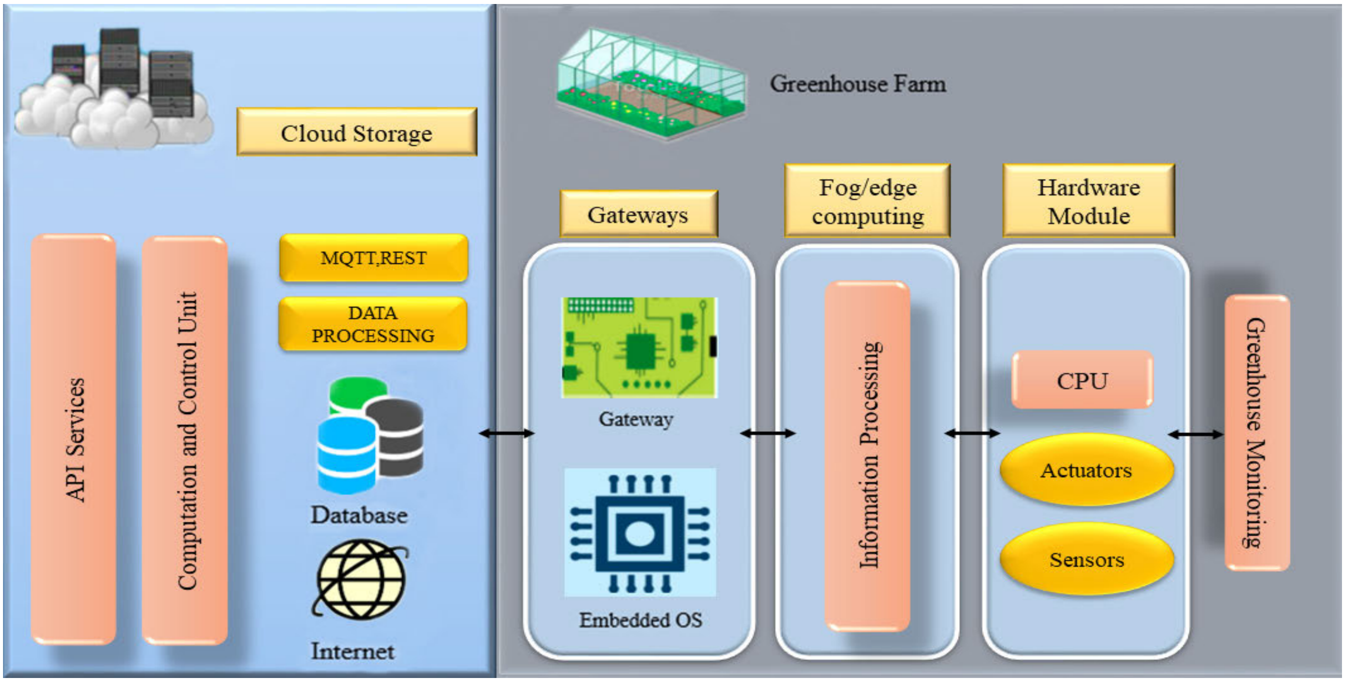

FIGURE 12. Cloud-based greenhouse network structure.

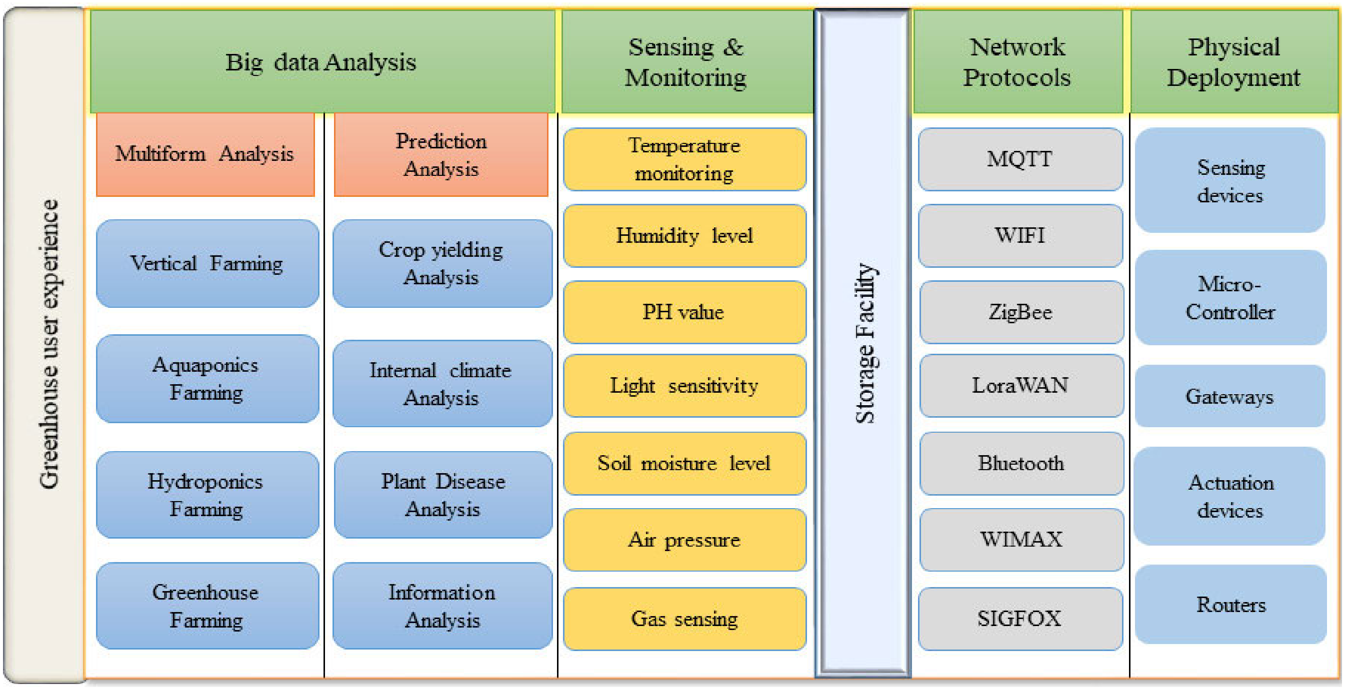

FIGURE 13. Big data analysis based greenhouse mode.

is delivered to the farmers or farm managers for keeping them updated about crop growth. To achieve long/short-range communication, several protocols like LoRaWAN, WIFI and ZigBee are used in greenhouse farming. Farmers keep information regarding crop health for making improved analyses in the future.

In the physical implementations module, some hardware devices like micro-controller (Arduino or Raspberry Pi), routers, sensors, gateways, and actuation devices are deployed to observe the greenhouse environment.

D. DATA TRASMISSION PROTOCOLS

Smart greenhouses demand great struggle for data acquisition systems like wired connection and distribution of sensors which is expensive and complex. Moreover, some crops need modification of point's location with time which is easily

TABLE 1. Comparison of IoT transmission protocol.

Parameters	Standard	Data rate	Frequency Band	Power consumption	Transmission range	Cost
WIFI	IEEE-802.11 a/c/b/d/g/n	1 mbps to 6.75 gbps	5 to 60 GHz	High	20 to 100 m	Large
LoRaWAN	LoRaWAN R1.0	0.3 to 50 kbps	868 to 90 MHz	Very low	<30 km	Large
RFID	ISO-18000 6C	40 t0 160 kbps	860 to 960 MHz	Low	1 to 5 m	Small
MQTT	OASIS	250 kbps	2.4 GHz	Low	-	Small
SigFox	SigFox	100 to 600 bits/s	200 KHz	Low	30 to 50 km	Small
WiMax	IEEE 802.16	1 mbps to 1 gbps (fixed), 50 to 100 gbps (mobile)	2 to 66 GHz	Medium	<50 km	Large
Bluetooth	IEEE 802.15.1	1 to 24 mbps	2.4 GHz	Very low	8 to 10 m	Small
ZigBee	IEEE 802.15.4	40 to 250 kbps	2.4 GHz	Low	10 to 20 m	Small

possible by the wireless-sensor network due to its mobility and simple implementation. A WSN consists of multiple nodes which are distributed within the greenhouse to find the plant growth by gathering information via communication protocols shown in Table 1. These protocols gather, encapsulate, and transfer greenhouse farm information. Similarly, WSNs are cheaper as well as have fewer energy-consumption methods and let the networks connect and provide flexibility in information sharing [55], [56]. Some data communication and transmission protocols are discussed in this section which is playing a vital role in greenhouse farming.

1) IEEE 802.11 WiFi

The IEEE 802.11 is a well-organized wireless local-area-network protocol due to its capability of taking heavy information like audio/video file transmission [56]. It is based on IEEE 802.11 b, IEEE 802.11 ac, IEEE 802.11 a, IEEE 802.11 g, and IEEE 802.11 n. Although it is a much expensive, short-range, and power-hungry communication standard it is useful for sensor networks in a greenhouse with distinct benefits. Portable devices which are used in greenhouse farming, contain this protocol broadly. In addition, it provides the facility to carry high agricultural information. This communication standard is highly effective for monitoring irrigation in the greenhouse by wireless cameras and drones [57].

2) LoRaWAN

A communication protocol that is organized by the LoRa-Alliance to connect IoT devices wirelessly for long-range bidirectional communication in greenhouse farms. This protocol has slight maintenance with less energy consumption that makes it capable of dealing with several types of sensors [58], [59].

3) RFID

The structural design of Radio-Frequency Identification (RFID) uses radio waves for keeping the gathered data safe and secure on a machine. RFID method includes tags (active and passive), readers, and hosts. The tags consist of an ID number of greenhouse atmospheric objects. The ID number is attached to the object which can be identified by the reader to read data and then transferred to the end host.

An active tag has more energy consumption value and is expensive as compared to another one. The host acts as a processing portion of the RFID method [60].

4) MQTT

A bidirectional, publish/subscribe and asynchronous protocol named as Message-queuing-telemetry protocol was designed by IBM in favor of machine-to-machine (M2M) communication to offer flexibility, less bandwidth usage, and computational resources [61]. Singh *et al.* [62] have been developed an IoT-enabled greenhouse monitoring system by using the MQTT protocol which monitors and controls the climatic parameters within a greenhouse to provide efficient growth of the crop. Through MQTT, an irrigation method with less cost has been analyzed to collect and transmit sensed data [63].

5) SIGFOX

A SIGFOX is a long-range, low data-rate protocol that is used to transfer collected information by global positioning system (GPS) to a central server by consuming less power [64], [65]. SIGFOX uses a two-tier topology like LoRaWAN, where its gateways transfer the traffic flow towards cloud servers. The robustness of network transmission in the greenhouse can improve by repeating the message several times over dissimilar frequency channels [66].

6) WiMAX

A protocol that offers 100 MB/s to 1 GB/s for mobile or fixed stations respectively [47]. Greenhouse farming can get portable/fixed communication by using a multi-access connection through WiMax using wireless/wired media. In Ghana, this technology has been implemented to empower the end-users to attach using WiMax networks [67].

7) BLUETOOTH

A low-cost, short-range, and low-power communication protocol named Bluetooth (IEEE 802.15.1) was designed for personal area networks (PAN) to communicate greenhouse data with multiple mobile devices. The information can be transmitted over different frequencies in dissimilar intervals of time by using medium access control (MAC) protocol [68]. The other version of Bluetooth with ultra low cost and low power is known as Bluetooth low energy (BLE) which was combined with v4.0 standard Bluetooth in the early stages [69].

8) ZigBee

ZigBee protocol is low energy consuming protocol having low cost, great performance, and capability to prevent interference. It comes in the topmost standards of IEEE 802.15.4 and has high-level communication. The consistency for wireless communication can be improved significantly in greenhouse farming by implementing this protocol [70].

E. SENSOR-TECHNOLOGY

In this era, there is a keen focus on the precise use of resources in greenhouse farming to enhance crop productivity. Many tasks are involved that are accomplished within the field, for instance, seeding, fertilizing, and watering, which are repetitive and required labor work [71]. Sensor technology is implemented within the smart-greenhouses for assisting the farmer to automate several tasks inside a greenhouse and to deliver precise climatic conditions (temperature/humidity, CO_2, and irrigation) which are necessary for the effective growth of crops [72], [73]. Hence, sensor networks create a link between the real world and cyberspace to connect agriculture and IoT [74]. Following are the most widely used IoT sensors in greenhouse farming:

1) BIOSENSORS

The excessive amount of pesticides to increase crop productivity cause the wastage of water and oil. In this situation, smart greenhouses use environment friendly and energy-effective technology which consists of bio-sensors as well as physical sensors. Bio-sensors are a sub-group of chemical sensors that contain biological recognition components (enzyme, receptor, antibody, micro-organism) to analyze the crop health, growth, pesticide, and required quantity of fertilizer [75]–[77]. For example, the microbial sensor can simply discover the microbial activity within the soil. Their self-maintainability allows them to be dormant, tailored to accept the modification, and reusable to accomplish long-term monitoring procedures within the greenhouse. The deliverance of energy to sensors is achieved by the microbial fuel cell (MBC) [78]. Some functions that are performed by bio-sensors are detailed below.

a: SOIL PESTICIDES

A large number of bio-sensors are used to detect pesticides in water and a heavy amount of nanostructured (bio) sensors have been realized for pest detection and monitoring in water and other resources. For instance, quantum dots, gold nanoparticles, and carbon nanotubes are the most widely used sensors. Similarly, a tyrosinase/TiO_2 biosensor is used for herbicide (atrazine) detection in soil.

b: DETECT NUTRIENTS

Bio-sensor is inexpensive and competent to recognize the mandatory precise fertilizer doses at particular stages of plant growth by analyzing comprehensively soil and water patterns. For example, Mura *et al.* have been discovered nitrate discovery in water [79].

2) PHYSICAL SENSORS

The physical sensors recognize the signal transformation via physical variation of the material inside the sensor which is principally humidity, temperature, and PH [80]. Some processes achieved by the physical sensor are discussed below:

a: TEMPERATURE/HUMIDITY DETECTION SENSOR

Temperature/humidity is recognized using DHT 11 sensor that contains two-component named as pyroelectric-film (for temperature recognition) and hygrometer (for humidity recognition). It is a power-efficient and reliable temperature and humidity monitoring sensor [32]. Besides this, PIR sensors are also used to sense heat within the greenhouse. When temperature surges inside the greenhouse, the sensor transforms the effects into high-voltage output [1].

b: PH SENSOR

For detection of PH value in greenhouses, a reliable sensor is required that can make a precise PH measurement. For this purpose, a PH sensor is used to dip into pipelines, tanks, and open channels. It has a serial output form that shows a PH range from 2 to 12 [81].

VI. IoT BASED GREENHOUSE APPLICATIONS

The advancement of IoT technology empowers things to be regulated remotely. Instead of controlling and monitoring a greenhouse farm manually, users can observe the day-by-day progress of cultivated crops by using IoT sensors/devices and mobile applications remotely. Several applications have been developed for making the farmers capable of efficiently controlling their greenhouse farms. In this section, we have discussed the applications of IoT in the greenhouse and a few mobile applications in table 2.

TABLE 2. Smart-greenhouse mobile applications.

Application Name	Working
Blue-term:	This application is helpful to control the actuators. For instance, motors for irrigation purposes, windows for ventilation, and lights in greenhouse farms [96].
Auto-Gate:	Farmers can analyze the composed information by sensors using this application [97].
Agro-Tick:	The knowledge regarding smart greenhouse farms can be distributed through this application [98].
Agro-tech:	It is used to manipulate the information and provide the capability to the farmer for analyzing the data that is assembled by sensory devices which are deployed within the greenhouse farm [48].
Agri-app:	Information on greenhouse farming practices for different kinds of crops can be delivered in multiple languages. Besides this, users can get news and also communicate with the experts to get informative tips regarding crop cultivation [99].
M-Kisan:	Farmer can be able to access the valuable information that is shared by farming specialists related to smart greenhouse farming [100].
We-Farm:	Provides the platform to small-scale farmers for asking questions freely about farming procedures from experienced officials [100].
E-farmer:	A farmer can keep the record of farming processes, cultivated crops, and the location of the planted crops in the field using this application. This record can be useful for further plant observation in the future [101].
Mbeguchoice	This application provides the facility for the farmers to approach different suppliers for getting a variety of quality seeds [102].
Cropx	Farmers can use this application in the greenhouse farm to acquire irrigation services by saving energy and water cost as well as increasing crop production [91].
eFertigUAL	It helps to find out the required amount of water and fertilizer required for a specific type of plant that is cultivated within the greenhouse [113].

A. MONITORING

In greenhouses, the crop is cultivated under a controlled environment. The cultivation of a smart greenhouse is highly strong, therefore it needs high precision in terms of monitoring. Humidity, temperature, and light are the most important factors to monitor to obtain the high quality of the crop. The constant monitoring of such variables gives valuable and informative data to greenhouse farm managers for better understanding. Recent studies show that how IoT technology is innovating greenhouse farming patterns by minimizing the labor cost, human effort, and providing direct communication among farmers and stakeholders. Most of the researchers have concentrated only on remote monitoring greenhouse farming [82], [83], [84]. Further, to obtain high precision in greenhouse farming the well-evaluated crop models have been implemented which helps the farmers to take accurate measures [85]. The low power and low-cost nature of IoT networks make them the top choice among agriculturists and growers in the greenhouse to monitor the soil moisture content. Heble *et al.* [86] developed a low-cost and power-efficient system for monitoring greenhouse soil humidity. Moreover, IoT-enabled monitoring systems have approximately 83% prolonged lifetime at minimum cost.

B. CONTROLLING

The greenhouse is an under-controlled farming method to cultivate plants and crops. To obtain a high yield of plants and crops, continuous controlling of environmental variables such as light intensity, soil PH, temperature, and CO2 are necessary. However, the major aim of IoT utilization in the greenhouse area is to develop cost-effective and simple solutions for controlling climatic parameters to achieve optimum growth of plants. Vimal *et al.* [87] developed an Arduino-based low-cost system to control the environmental parameters which are updated on regular basis. Multiple sensors/devices such as LDR sensor, PH sensor, and DHT11 sensors are implemented to measure the exact value of greenhouse environmental variables. The monitoring parameters are sent to the mobile phone in the form of short message services (SMS) to identify the present status of environmental factors. When the sensor value exceeds a certain amount of defined level, an SMS is sent to the greenhouse manager or farmer. In this way, a farmer can control his greenhouse farm from anywhere by knowing the present status of different controlling parameters. Subahi and Bouazza [29] proposed an intelligent greenhouse temperature controlling system by implementing IoT technologies. The objective of the developed structure is to control and monitor the internal temperature in order to maintain good conditions that increase productivity. Moreover, controlling the microclimate parameters in greenhouses is a real problem due to which growers face different microclimate issues. Sagheer *et al.* [88] proposed a multitier cloud-based IoT platform to control the microclimatic issues in the greenhouse. The proposed platform was implemented on the cultivation of cucumber in a commercial-sized greenhouse to enhance productivity and improve quality. Different actuators, controllers, and sensors were deployed in the greenhouse farm to offer wide-range communication to control the greenhouse.

C. TRACKING

The IoT asset tracking application can track the location of assets, audit as well as monitor the assets in order to keep the centralized records accurate in all greenhouse farming businesses. The emergence of IoT with big data, AI, satellite images, drones, and GPS enables the farmers to put less human effort to track the greenhouse farm remotely. Besides this, the IoT-enabled system also helps the farmers to track machinery (drones, tractors) and unwanted movement on the farm. Satyanarayana *et al.* [70] has been proposed a crop health monitoring architecture that monitors the different soil patterns. In the proposed architecture ZigBee is integrated with GPS and GPRS for real-time data tracking. GPRS provides connectivity with a monitoring device and gives an alarm to the greenhouse farm, the owner when suspicious activity occurs. In this way, farmers can take corrective measures spontaneously in order to avoid any hassle. Although the maintenance cost of such a system is high it is extremely effective due to its exact tracking ability.

VII. OPEN ISSUES AND CHALLENGES

Although IoT has brought a great revolution in smart farming, still there exist some fundamental, development, and conceptual challenges in this area. In this section, IoT-based greenhouse farming technical and non-technical challenges have been discussed.

A. IoT-BASED GREENHOUSE NON-TECHNICAL ISSUES

Digital farming faces new management and operation issues that suffer various non-technical challenges such as cost, plants disease detection, and marketing pricing. In this sub-section IoT-based greenhouse, non-technical challenges have been discussed.

1) HUGE INVESTMENT

A smart greenhouse does not use the sun as the key source of light for the procedure of photosynthesis [89]. They use artificial lights which are organized within the greenhouse farms. Therefore, lots of energy consumption by LEDs create a challenge for the greenhouse farmers to bear the energy expenses. Although the solar panel technique brings into use in vertical farms which are used in a larger range within the cities. But it is still difficult to accomplish the necessary amount of energy through this approach because of high building shades [90]. Moreover, plant growth may be affected due to the deficiency of these natural resources. Furthermore, IoT-based greenhouse farming has also nutrient supply issues. A huge investment is required to retain the equal distribution of nutrients to all portions of greenhouse farms [21].

2) FOSSIL FUEL

The greenhouse farmers face difficulty to take the produced yield to the market, as they have to manage the expenditures of transportation. The demand for fossil fuel and heavy machinery to plow seeds and harvest the crops is high which is costly. Therefore, it becomes hard for local farmers to take initiative in this regard. Furthermore, on a large scale, the extra use of fossil fuel can cause air pollution which is hazardous for human beings [91].

3) CROP DISEASE

Sometimes, crop disease is a major issue for the farmers because of having less knowledge for the transfer of the proper amount of nutrients. Unequally irrigating the plants inside the greenhouse can damage crop growth and cause different kinds of diseases [90].

4) SOIL SALINITY

Greenhouse farming becomes challenging in some regions due to the high salinity of the soil and water. Thus, the usage of saline water for irrigation purposes in the greenhouse at these locations can make the crop growth slow and lessen the production rate [78].

5) LESS GOVERNMENT SUPPORT

Designing or developing an IoT-based greenhouse farm is a big challenge for the local farmers without government support. Some farmers follow indirect ways like the internet, agricultural exhibitions, and trial-and-error techniques to eradicate the trouble they face while running their greenhouse farms. These approaches lead them towards financial destruction [112].

6) MARKETING PRICING

The market prices fluctuate day-by-day which is another problematic issue for the farmers. They try their best and invest their savings for greenhouse cultivation but in the end, they don't get enough return due to which they shift to another crop, and shortfall for those specific crops arises [113].

B. IoT-BASED GREENHOUSE TECHNICAL ISSUES

In literature IoT technical issues in greenhouse farming have attracted a lot of attention such as communication protocols, connectivity issues, interoperability issues, low power WSNs, and sensor design. In this sub-section state-of-the-art IoT-based greenhouse technical challenges have been discussed.

1) SECURITY AND PRIVACY ISSUES

Lack of security and privacy in IoT-enabled greenhouses is a key challenge. Therefore, it is difficult to handle the collected data regarding greenhouse environmental parameters. In case, there is a slight vulnerability within the system, the sensitive data may be lost. There are also low communication competencies and less storage that makes the implementation procedure of complex algorithms difficult. Likewise, chances of intrusions in wireless communication methods are more, for example, Distributed Denial of Services (DDOS) attack, forwarding attack, and congestion attack [90]. Thus, the security of smart-greenhouse farming consists of three major elements i.e. data confidentiality, authorization, and access control [104]. These three countermeasures must be employed for the data access phase. In addition, the authentication of particular entities can stop external attacks.

Several security threats like Information leakage, wire-tapping, tampering, and replay attacks can bring severe destruction to sensitive data of greenhouse farms. Users can overcome the probabilities of these outbreaks by implementing encryption algorithms and robust intrusion monitoring policies in the greenhouse network systems.

2) LACK OF CONNECTIVITY

Connectivity is the major challenge of IoT in greenhouse farming due to poor 2G/3G/4G coverage. Although some low power wide area technologies such as Sigfox and LoRa provide overcome such issues but they are not able to handle large datasets [105].

3) SENSOR DISTRIBUTION NETWORK STRUCTURE

The sensors distribution directly impacts on controlling and monitoring parameters of a greenhouse farm [106]. Specified certain monitoring and regional requirements, the objective of this operation is to develop a sensor distribution network under specific constraints such as sensor cost and range. The optimization standards may be conflicting, such as the lowest costs and highest precision. Furthermore, the process models will be unique when sensors are portable. In addition, besides static network sensor models, dynamic and multi-objective optimization is also obligatory [106].

4) SOCIETAL ACCEPTANCE

The implementation of smart and innovative technologies will be a challenging task for non-technical users. Therefore, training and education are highly important to help the users or farmers understand the applicability and utilization of new technologies. However, in developing countries, farmers believe that there is no need for such enhancement and they are not willing to adapt IoT-based farming methods. So, thorough training is necessary for all stakeholders and non-technical users in the smart farming field [21].

5) NODES REPAIRING AND RECHARGING

In greenhouse farming, IoT architecture contains a wide selection of nodes with limited battery time. Furthermore, the nodes in remote areas are not able to connect solar panels and power grids. Moreover, the IoT nodes may be collapse or break down due to unpredicted events like severe weather and other farming activities. In addition, repairing and recharging network nodes implemented in greenhouse farms is one of the most complicated operation challenges. Battery lifetimes of any node in the network are often not stable due to battery types, environments, and discharge rates, therefore, regular recharge plans may cause the failure of network nodes [108].

6) DATA PROCESSING POWER

Accessing the high scale processing power to resolve complex calculations at affordable cost is a significant challenge for medium and small-level farmers. So, the non-existence of data processing services considerably hinders IoT [109].

7) LACK OF INTEROPERABILITY

Data protocols, IoT communication standards, and common building blocks are required for millions of devices to interoperate [109]. This type of standard exists for weather data prediction, semantic modeling, agricultural machinery, and various initiatives such as the association of IoT standards with IEEE standards. Moreover, some standards such as ISOBUS standards have not been designed in parallel to the pace of change and new machinery has trademarked connectivity with the same manufacturer's machinery. This approach follows vendor lockin and extended resistance from growers. So, here the challenge is not the unavailability or lack of standards but the major issue is the emergence of an unlimited number of standards.

8) KEY KNOWLEDGE

Greenhouse farming needed highly skillful and knowledge-able users to run IoT-based smart farming solutions. Unfortunately, in some areas, there are not sufficient resources and ways to get the awareness and appropriate skills about smart greenhouse farming. Hence, it leads the farmers to waste their assets without having the knowledge of the cultivation process [92]–[94].

9) TECHNOLOGY SELECTION

According to the geographical position and climatic circumstances, there are various technologies developed every day in the market. It is difficult for the consumer to choose what type of IoT technology is suitable for their greenhouse farming practices. Moreover, they also need to modernize the greenhouse system by the time which is an expensive and difficult procedure [90].

C. FUTURE RESEARCH DIRECTIONS IN IoT-BASED GREENHOUSE FARMING

Based on this survey and discussion of major technologies, sensors, and communication protocols, we will present future research directions and key developments in the following aspects.

A generic platform is necessary to build for all kinds of crops and plants, quality of service (QoS), integration of explainable artificial intelligence for pest control, and crop growth monitoring. Explainable artificial intelligence is highly necessary in order to understand and analyze the reasons behind any specific decision [115]. It hides the traditional farming method and empowers the farmers or

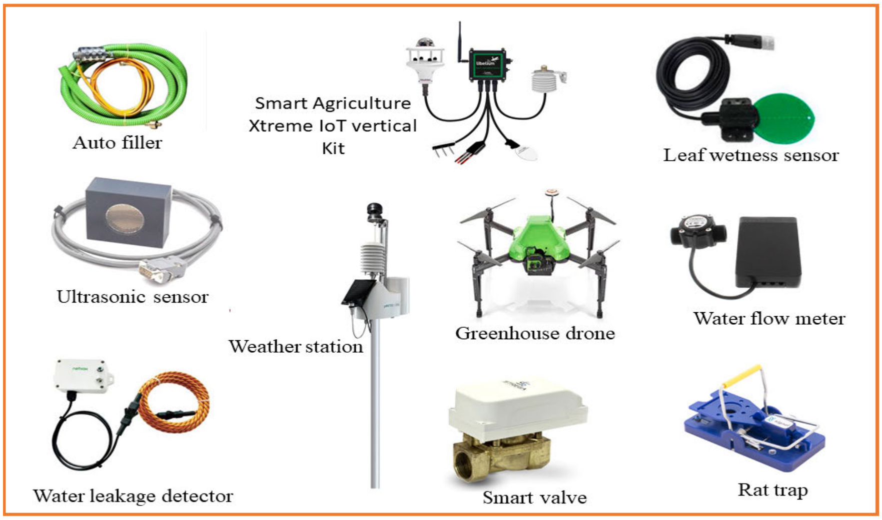

FIGURE 14. IoT greenhouse products.

growers in understanding the factor behind the obtained solution.

At the perception layer, the development of the sensors should concentrate on new and innovative sensitive material, processes, mechanisms, and methodologies with low cost and minimum power consumption. Apart from this, it is necessary to accelerate the deployment of sensors and rapid detection of a plant's life.

On the application layer, organizations and governments should introduce unified standards for communication protocols, sensors, identification devices, and application services in protected greenhouse farming by international negotiation or corporation. The developers should design large and open-source databases as well as libraries of processing algorithms for multiple areas to facilitate the farmers.

Moreover, at the network layer, we should concentrate on low power management strategies, high-capacity broadband communication protocols, and low power networks for complex greenhouse farming application environments. LPWAN is best for some greenhouse farming scenarios where voice and video support are not necessarily due to its low-power consumption, low cost, and high capacity. More focused research is needed in the future on IoT-based greenhouse farming solutions on LPWAN.

With the widespread deployment of IoT sensors, there should be a virtualized sensor in which farmers have access to manage and control their IoT-based greenhouse farms virtually.

A large volume of data is captured, forwarded, stored, and examined for efficient decision-making in an IoT-based smart greenhouse. Big data analytics is used to give predictive insights in smart greenhouse farming procedure by providing operational decisions. The major problem with data analytics is the sustainable integration of big data sources, intelligent processing, and data quality [101]. So, the openness of big data platforms is highly important subsequently it can authorize and empower the growers or farmers in their site in supply chains.

IoT utilization generates a widespread experience of cyber security attacks, threats, and vulnerabilities in IoT-based greenhouse farming. Although, a number of intrusion detection systems (IDS) have been developed to mitigate the security attacks and analyze the network traffic to identify an infected device [102], [103]. But none of them provide a specific solution for smart farming. Therefore, development in ML-based IDS and a farm-specified access control mechanism is an open research direction.

VIII. SMART GREENHOUSE SUCCESS STORIES

A lot of new opportunities for the farmers are provided in the developed countries to tackle the challenges they face, specifically in greenhouse farming. Garcia *et al.* [114] have been elaborated on several technological methods which are used in agricultural farming globally. Some success stories regarding IoT-enabled greenhouses in several countries have been explained in this section.

A. MALAYSIA

Malaysia faced problematic issues to cultivate sensitive crops like strawberries because of the equatorial country, but through the deployment of IoT-enabled greenhouse farms, it is potentially easy to produce strawberry plants [123]. Farmers installed IoT-based greenhouse farms on several locations in Malaysia to automatically regulate and monitor the internal environment which is suitable for the growth of plants. This system has also facilitated the user to remotely track the supply and distribution of the product.

TABLE 3. IoT based greenhouse farming statistics/prototypes.

Country	Plant/crop/ parameter	Case studies/prototypes	Production Result/output
Algeria (North African Country)	Tomato Plants	Mellit et al. [119] designed an IoT-based smart greenhouse in Algeria (North African country) for disease classification of tomato plants. The experimental results presented the feasibility of the proposed system by diagnosing different tomato diseases accurately. So, the designed prototype is applicable for real-time monitoring of tomato plants remotely.	88% accuracy in disease detection to enhance the tomato productivity
Taiwan	More than a hundred plants (vegetables)	A smart farm has been designed in Taoyuan by using IoT solutions to grow multiple vegetables in a controlled environment [120]. The results of deployed solution indicate that productivity is 5 to 10 times more than traditional farming methods. Furthermore, IoT sensors and devices reduce the use of water, electricity, and protect the plants from pesticides.	5-10 increase in productivity
Russia	Tomato plant	Somov et al. [121] implemented IoT based solution in a greenhouse to monitor the tomatoes productivity in Russia. The deployed solution monitors the plant's growth as well as control greenhouse conditions by predicting the growth rate of tomatoes. It shows that IoT helps the farmers to make better decisions and ensure control over greenhouse conditions on the basis of measurements from the multitudes of sensors.	The utilization of light is 50% less than the traditional greenhouse farming method
Italy	Grapes and vegetables	Codeluppi et al. [122] proposed a LoRaFarm platform to monitor the environmental parameters (humidity and temperature) in the greenhouse for different vegetables in Italy. The existing greenhouse was controlled manually by growers without the utilization of any technology. There was no system to monitor the environmental variables of the greenhouse farm. They were open and close the roof of the greenhouse manually to activate the irrigation sprinklers and to adjust the humidity level through natural ventilation. But the deployed IoT nodes predict the environmental parameters accurately that was necessary to enhance the growth of vegetables in a greenhouse.	More than 80% accuracy for greenhouse environmental parameters
Spain	Tomato Vegetable	An IoT-based solution has been applied in Spain, Almerıa to enhance crop production in the greenhouse [123]. In this prototype 8 greenhouses of tomato, crops have been considered. Heterogeneous meteorological stations have been equipped in all greenhouses to monitor CO2 and soil humidity. The collected data about selected variables have been considered valuable for simulation purposes by farmers or agriculturists.	Multiple greenhouse parameters have been predicted more than 90% accurately
Australia	Multiple plants (fruits and vegetables)	Greenhouse gas emission reduction is necessary to improve food security and to develop a climate-smart landscape. There are multiple ways to decrease such gases by using innovative technologies such as IoT. Panchasara et al. [124] explored the key sources of gas emission within the agriculture field in Queensland and other states of Australia to suggest reduction ways of Carbon dioxide. Furthermore, best management approaches are also discussed to assist the stakeholders and farmers managers to take environment-friendly greenhouse farming decisions.	More productive ecological farming approaches have been provided.
Canada	Microgreen kale	An intelligent control system has been developed in Langley, BC Canada for mixing color ration by using LED light in the greenhouse farm [125]. The designed testbed has been deployed in a real-time greenhouse farm to predict the required light for plant growth.	Predict the desirable light and enhance the performance growth of a plant

TABLE 4. Smart-greenhouse efforts by some prominent organizations.

Organizations	Industries Efforts and Directions
SPREAD	An agricultural technology company, which is manufacturing huge, indoor and automated vertical farms (hydroponics greenhouse) by using robots. All the constructed farms would be automated robotically. The goal of this company is to build 20 factories globally in the upcoming five years to help the growers to use their system for better crop production. This will play an important role in solving the food shortage problem and building a sustainable society [146].
HELIOSPECTRA	This Swedish company provides solutions for intelligent lighting in greenhouse farms and controlled crop growing atmospheres. It helps commercial horticulturists and greenhouse users by providing LED lights and heat dissipation tools to develop an ideal situation for plant cultivation [147].
Oracle	Oracle has developed combined PAAS solutions to extend business data, attain an IoT information stream, analyze information for the purpose of pattern recognition, and for improving critical procedures and services [148].
ARGUS-CONTROL SYSTEM	A Canadian company doing great work in greenhouse monitoring and controlling solutions for greenhouse environments. It facilitates the farmers to automate their control system for horticulture, aquaculture, and hydroponics farms [149].
EGATEC	In Denmark, this company improves, produces, and supplies inexpensive automation solutions worldwide for greenhouse farming. By using these automation solutions, growers can achieve uniform quality, minimize repeated work regarding farms and increase productivity ratio [150].
SENSAPHONE	Data distribution in greenhouse farming has the most sensitive nature because of wireless connection. Sensaphone provides a remote monitoring scheme that acts as a safeguard. Besides this, this company offers monitoring devices and sensors as well [151].
IBM	Many approaches have been developed to facilitate the farmers in improving the agricultural method but these techniques demand a lot of human efforts and involvement. For instance, farmers have to put data manually for easy functionality and to access the required data. IBM has overcome this barrier by introducing the combination of Artificial Intelligence, Predictive Insights, and Data Analytics. It will help the users to make an efficient decision-based agricultural system [152].
IRON-OX	In greenhouse farming, proper irrigation is a major problem. Therefore, IRON-OX is reinventing a greenhouse robot for local, cheaper, and sustainable production. Their constructed farms use less energy and 90% less amount of water while producing 30 times more crops in each acre as compared to traditional greenhouse farming approaches [153].
SAMSUNG	Samsung SDS's platform based on IoT allows the user to associate multiple devices and various IoT-based communication protocols like MQTT, LoraWAN, and ZigBee [154].
GROWFLUX	This American company is devoting its efforts to manufacturing LED lights, sensor technologies, and control solutions for greenhouse farming [155].
AUTOGROW	Provides automated and controlled solutions to manage greenhouse businesses and indoor farming to grow different kinds of crops [156].
GROWLINK	Growlink is providing product innovation, performance, security, and capacity for sensor networks to make greenhouse farming smarter and innovative. Growlink has also designed software and hardware solutions for modern indoor farming [157].
METOMOTION	This company is funded by European Union to design a robotic system for supporting greenhouse farming to enhance food production [158].
PHENOSPEX	In different countries like the USA, India, China, and Australia, this Netherland's company is offering smart sensory devices for analyzing the cultivated crops and atmospheric situations within the greenhouse farms [159].

B. KOREA

Smart greenhouse farming is exponentially rising in Korea day-to-day [125]. Farmers breed several types of plants, for instance, tomatoes, strawberries, and sweet peppers efficiently by using IoT-based farming techniques. Park *et al.* [124] elaborated some important factors regarding greenhouse farming in Korea such as farm requirement, crop growing approaches, and pests controlling. The survey originates the significant threats for the greenhouse users and their satisfaction rate related to greenhouse farming. These results will be supportive to cope and design the greenhouse system in the future.

C. ITALY

Agricultural practices are successfully experienced in Italy. They introduced different categories of energy proficient sources for greenhouse farming, one of them is producing electricity through a photovoltaic system that is also environment friendly [126]. Further, they also improved their existing greenhouse farming method to a modular, low-priced, and Long Range Wide Area Network (LoraWAN) based platform to observe environmental conditions related to the plants inside the greenhouse farm [127].

D. INDIA

A controlled greenhouse farm is implemented by the farmers to improve their yielding rate by accessing the climatic parameters (soil moisture, temperature/humidity, $CO2$) remotely within the greenhouse in India [128]. Further, in the hill areas like Uttar-Akhand it is difficult to accomplish greenhouse farming due to severe environmental conditions. Therefore, low-cost IoT-enabled greenhouses have been implemented for the cultivation of off-season crops and accomplished a good return on investment.

E. CHINA

A wireless greenhouse technology has been established which is cost-effective and consumes less energy by controlling the greenhouse atmosphere automatically [11]. One of the Chinese provinces has practiced an IoT-based farm which has decreased the labor charges and surged the crop yielding rate proficiently as compared to traditional farming [129]. However, in rural areas, farmers have developed the agriculture system through government support. The sale procedure of agricultural products has been transferred to E-Commerce which overcome the cost and simplified the trading process [130].

F. RUSSIA

Several agricultural universities as well as a center for special analysis have been established under the Russian Agricultural ministry to train the farmers for digitalizing agriculture. Kulyasov *et al.* [131] described a model which interacts with different objects of agriculture like a smart greenhouse, smart garden, and smart field. This model provides the opportunity of using different digital technologies to precisely monitor and automatically control the atmospheric system for increasing the production rate.

IX. IoT BASED GREENHOUSE INDUSTRY TRENDS

The IoT technology brought a revolutionary change in the agriculture sector all over the world. Top technology firms are also effectively working in the area of greenhouse farming to facilitate farmers all over the world and minimize the key challenges regarding farming practices. Besides this, some IoT gadgets have been shown in Figure 14 that are playing an imperative role in smart greenhouse farming.

Xtreme IoT kit acts as a weather monitoring sensor with the capabilities of improved sensing and efficient accuracy [132]. However, the sensor also measures oxygen volume, the required amount of fertilization, and water quantity in the soil. Leaf moistness can be determined by using a wetness sensor [133]. It uses electrical resistance to find the moisture content on the leaf surface within the greenhouse. A greenhouse drone is used to monitor the cultivation area and find the area that is not properly irrigated [134]. The weather station is used for the distribution of greenhouse data to a master sensor within a 600-meter range [135].

The water leakage detector finds water leakage using a rope sensor within a 3 to 10-meter area and forwards the notification to the farmer [136]. Smart valve is a wireless battery operated and low power consumption valve to irrigate crops in greenhouses farm at long-distance [137]. A rat trap is used to remotely monitor, store, and alert the farmer about rodent activity within the greenhouse farm [138]. The water flow meter monitors the water consumption on a daily basis and informs the user regarding water usage in the greenhouse [139]. The ultrasonic sensor has the ability to identify specific plant growth in the smart greenhouse to keep the farmer updated about the growth rate [140]. Auto filler is used to replenish the water tank automatically when the tank becomes empty [141]. Moreover, table 3 has presented the top technology firm's efforts regarding greenhouse farming.

X. CONCLUSION

The current status of the research has indicated that it was feasible to remotely monitor the greenhouse parameters such as $CO2$, PH, moisture content, humidity, temperature, and irrigation by using IoT sensors and devices. In this survey, we have discussed emerging technologies of IoT and provided a rigorous discussion on IoT-based greenhouse farming patterns. Furthermore, various traditional and developed cultivation techniques are discussed which can help the growers to understand the technological structure of a greenhouse. In addition, we have also discussed the IoT-enabled greenhouse network structure based on cloud and big data analysis, which act as an IoT backbone and help farmers to increase crop productivity. Moreover, this survey provides a state-of-the-art overview of IoT-based greenhouse farming applications, sensors/devices, communication protocols, and technologies. Furthermore, several important dimensions of IoT-greenhouse farming, top technology firm's trends, and success stories performance metrics have been discussed to succor the stakeholders. This article also considers many IoT-enabled greenhouse open issues and security challenges with future research directions. From this comprehensive survey, it is clear that the government and many big organizations have started investing to develop new smart greenhouse farming techniques by using IoT. Lastly, it is expected that this research generates very useful information for agriculturists, researchers, policymakers, and technologists who are researching and working in the IoT-based smart farming field.

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