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Technologies, Protocols, and applications of Internet of Things in greenhouse Farming: A survey of recent advances

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ABSTRACT

Greenhouse farming is considered one of the precision and sustainable forms of smart agriculture. Although greenhouse gases can support off-season crops inside the indoor environment, monitoring, controlling, and managing crop parameters at greenhouse farms more precisely and securely is necessary, even in harsh climate regions. The evolving Internet of Things (IoT) technologies, including smart sensors, devices, network topologies, big data analytics, and intelligent decision-making, are thought to be the solution for automating greenhouse farming parameters like internal atmosphere control, irrigation control, crop growth monitoring, and so on. This paper introduces a comprehensive survey of recent advances in IoT-based greenhouse farming. We summarize the related review articles. The classification of greenhouse farming based on IoT (smart greenhouse, hydroponics greenhouse, and vertical farming) is introduced. Also, we present a detailed architecture for the components of greenhouse agriculture applications based on IoT, including physical devices, communication protocols, and cloud/fog computing technologies. We also present a classification of IoT applications of greenhouse farming, including monitoring, controlling, tracking, and predicting. Furthermore, we present the technical and resource management challenges for optimal greenhouse farming. Moreover, countries already applying IoT in greenhouse farming have been presented. Lastly, future suggestions related to IoT-based greenhouse farming have been introduced.

1. Introduction

With climate change, industrialization, and rapid growth of the world population, arable land worldwide is decreasing yearly [1]. Consequently, the demand for food has been steadily increasing. According to United Nations Food and Agriculture Organization (FAO) research, 9.73 billion people will populate the earth by 2050 [2], which urges attention to agriculture and agriculturists to meet global food demands. Moreover, additional challenges like lack of labor, sudden weather changes, and water scarcity put more pressure on farmers [3]. Consequently, traditional agriculture must transform significantly to produce ecological and sustainable food. Greenhouse agriculture is one of the feasible future alternatives for socio-ecological sustainability [4].

As shown in Fig. 1, a greenhouse is a structure similar to a house covered with plastic or glass and primarily used to raise different crops in any season. A greenhouse can control plant growth patterns to maximize food quantity and quality. Greenhouse agriculture is intriguing as it succeeds in isolating nature's produce and protecting plants from the immediate effects of external climatic conditions [5]. Compared to traditional farming, crop yields can rise 10–12 % depending on the greenhouse facilities [6].

Various kinds of crops need to create an appropriately controlled microclimate and care for environmental parameters, including temperature, light intensity, humidity, CO2 level, water flow, etc. [7], which makes the greenhouse a suitable economical solution for farming since it allows controlling climate variables and thus producing out-of-season crops, especially fruits, and vegetables to meet the demand of consumer [8]. To make the greenhouse "smart," the solution is to integrate IoT technology. The term "Internet of Things (IoT)" is a system of interconnected computing devices, sensors, objects, microcontrollers, and cloud servers that can transmit data across a network and control other devices remotely without human intervention [10]. Therefore, smart greenhouses can aid farmers in raising the yield of their crops [9]. Using IoT technologies in greenhouse farming supports its development [11].

The sensors capture the data inside and outside the greenhouse and

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automatically transmit them to a central cloud server for storing and archiving. These data can be accessed by end-users devices and benefit from the generated knowledge of their crops, suitable harvesting time, energy consumption, etc. [12]. Additionally, cloud edge points can be used for storing the data for more rapid processing. The implementation of intelligent agriculture, Artificial Intelligence (AI), big data, robotics, and IoT in agriculture accelerated the transition from Agriculture 3.0 to Agriculture 4.0 [13] (see Fig. 2). Smart farming (represented in Agriculture 4.0) provides a path to sustainability by applying information and communication technology (ICT) with technologies like cloud computing, IoT, AI, and robotics technologies in the cyber-physical cycle of farm management [14]. Precision farming is a sustainable solution that optimizes performance by providing each plant or animal exactly what it demands to survive and reduce waste and inputs [15]. Also, agriculture 4.0 is essential for optimizing greenhouse agriculture resources, especially energy and water.

Despite much literature reviews have been conducted for the field of IoT-enabled greenhouse agriculture, there is still a requirement for extensive research in this field. Many articles have examined IoT technologies and applications in the agricultural environment [16–29], which urges us to discover the present research progress of smart greenhouse farming based on IoT and provide the researchers concerning solving the current and future challenges in smart greenhouses. Rayhana et al. [30] reviewed the IoT technologies for smart greenhouse farming, including sensor technologies, WSN communication protocols, and edge/cloud computing, as well as the current greenhouse cultivation technologies were discussed. The authors also summarized some challenges facing IoT-based greenhouse agriculture. However, the physical layer components, such as the actuator and microcontroller, were skipped. The study also did not discuss resource management like energy, water, and E-waste management for an optimized greenhouse environment.

Li et al. [31] reviewed smart greenhouse monitoring systems based on IoT. They focused on the environmental monitoring variables, including temperature, humidity, CO_2, and light, and monitoring crop variables, like leaf temperature and humidity. The authors also discussed the physical components of the IoT system, like sensors and microcontrollers, and reviewed the communication protocols but missed the IoT protocols, like MQTT and CoAP. The study also lacked emerging technologies, like fog, edge, and cloud computing. The authors in [32] highlighted the IoT role in agriculture 4.0, resources management, and optimized environment challenges. They also reviewed IoT communication protocols, including ZigBee, MQTT, REST, LPWAN, LoRaWAN, XMPP, DDS, Z-wave, and IPv6. They discussed IoT-based smart agricultural greenhouse-enabling technologies like AI and edge computing. The study did not discuss IoT physical components, such as actuators and microcontrollers; the essential agricultural greenhouse applications based on IoT were not examined.

Farooq et al. [33] also highlighted the key components of IoT-based greenhouse agriculture, like sensors, communication protocols, cloud/edge computing, big data analysis, controlling/monitoring applications, and IoT-based greenhouse farming categories. They also discussed security and privacy issues. Bersani et al. [34] introduced a literature review on the IoT-based monitoring and control applications for smart greenhouse agriculture, including microclimatic conditions controlling, such as humidity, temperature, CO2, soil, and crop quality. The review also discussed the optimization techniques for monitoring and controlling smart greenhouses. Still, fog and cloud computing technologies were not discussed.

This literature review explores recent advancements in the applications, technologies, and protocols in IoT-based greenhouse agriculture. The review begins with an overview of IoT-driven greenhouse farming categories, specifically smart greenhouse, hydroponics, and vertical farming. The subsequent discussion delves into the IoT architecture for smart greenhouse agriculture, which encompasses four basic layers: application, service, network, and physical, detailing the individual components within each layer. It also focuses on cutting-edge IoT-based applications in greenhouse agriculture, such as monitoring, controlling, tracking, and predicting. It discusses resource management challenges for optimized greenhouse farming, such as energy, water, communication service, and construction materials. Also, the technical challenges existing in IoT-based greenhouse agriculture are analyzed.

The structural flow of the entire paper involves the following sections: Section 2 provides the categories of greenhouse farming based on IoT technologies. In Section 3, the key components of greenhouse farming applications based on IoT are presented. Section 4 presents the challenges for IoT-based greenhouse agriculture. Section 5 explores the countries that succeed in using IoT technologies for smart greenhouse farming. Section 6 presents future suggestions in this work. Finally, we concluded our survey in Section 7.

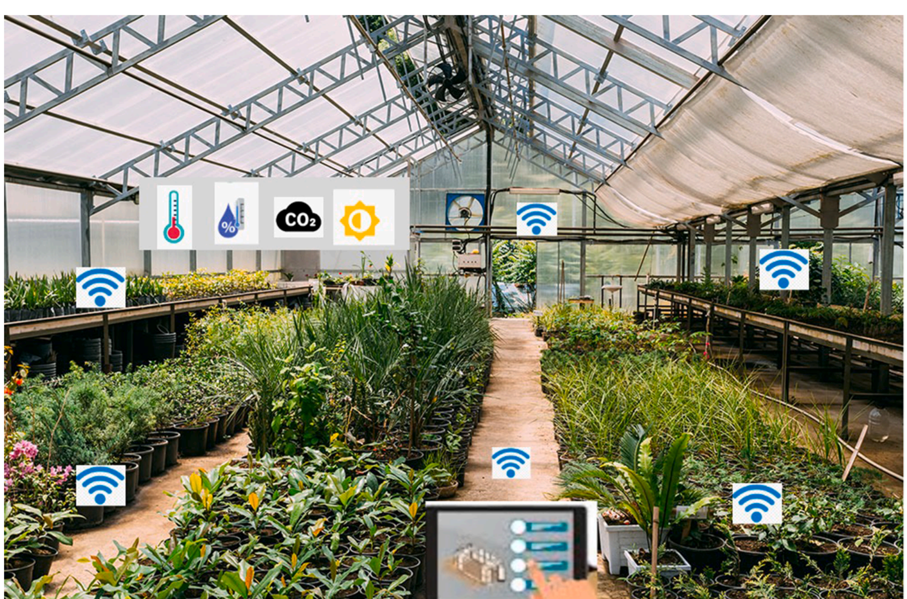

Fig. 1. A Smart Greenhouse Farming.

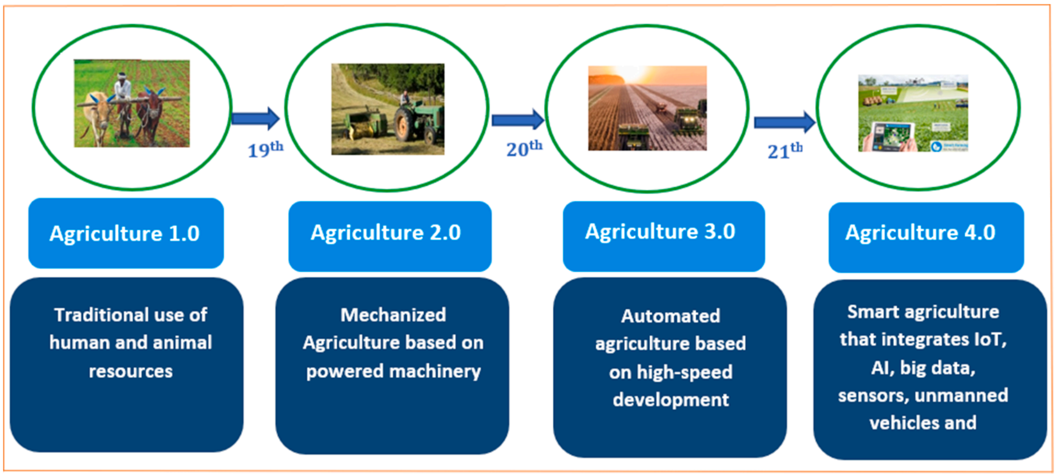

Fig. 2. Agricultural evolution from Agriculture 1.0 to Agriculture 4.0.

2. Greenhouse farming categories based on IoT

IoT-based devices are widely used in monitoring and control systems across many industries, such as healthcare, smart cities, agriculture, etc. In agriculture, IoT-based technologies include sensors, actuators, drones, cloud computing, navigation tools, and analytical systems, enabling effective decision-making to boost crop yield with fewer human interventions [35]. These physical devices and sensors monitor

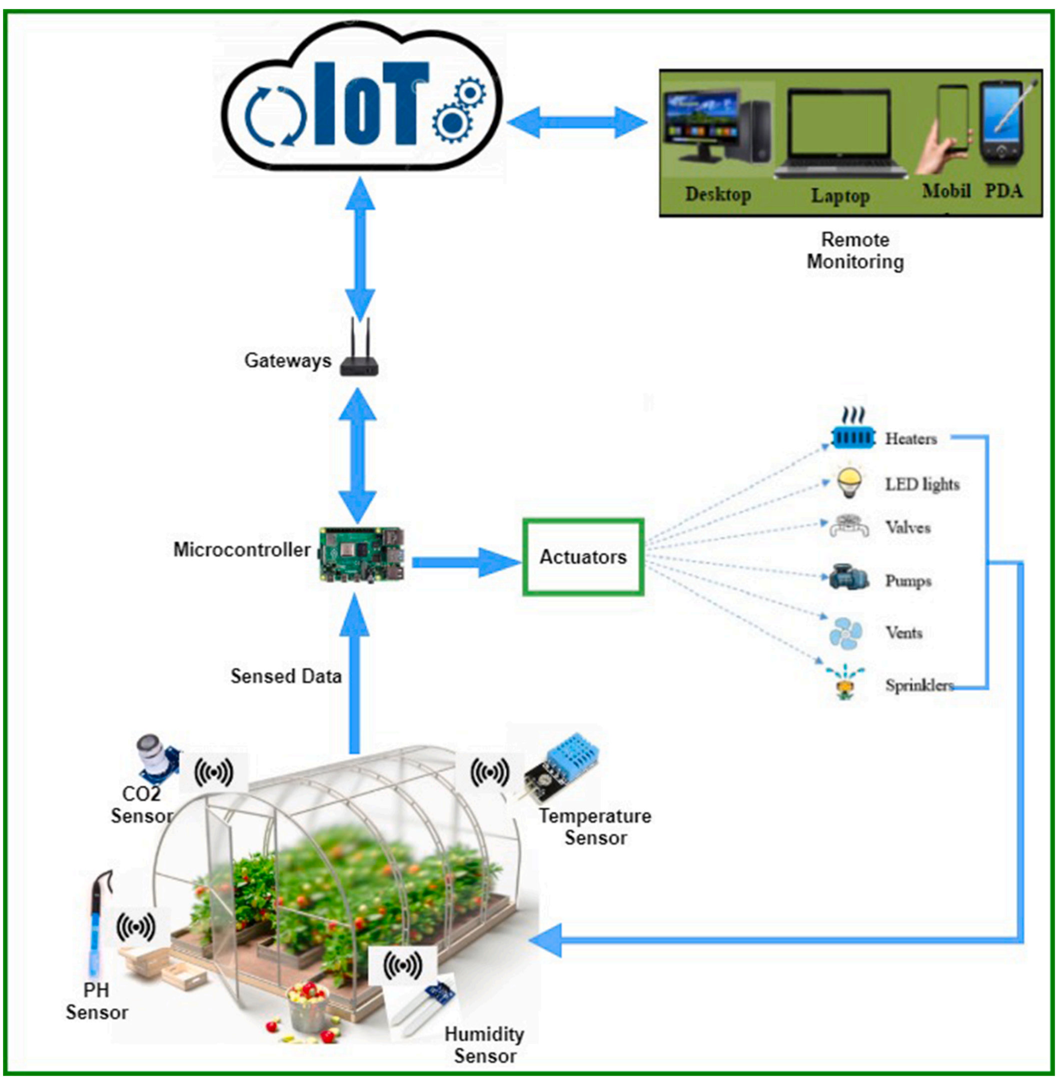

Fig. 3. Explanation of smart greenhouse farming based on IoT.

the atmosphere and gather temperature, light, humidity, intensity, and soil moisture data. The IoT enables the automation of greenhouse farm monitoring and control systems while providing farmers access to environmental data stored on a cloud computing server, allowing decision-making and efficient resource utilization, including water, pesticides, heating, etc. [36]. This section provides an overview of greenhouse farming technologies based on IoT, focusing on three techniques: smart greenhouse, hydroponics, and vertical farming.

2.1. Smart greenhouse based on IoT

Traditional greenhouse farming systems are human monitoring systems for the growth of fruits and vegetables, which necessitate ongoing human monitoring, which causes distress to the worker and reduces yield when the temperature and humidity are not adequately and consistently controlled [37]. Smart technologies like cameras, lights, microcontrollers, and wireless sensors are now used in greenhouses to provide automatic controls for temperature, light intensity, and soil moisture to maintain the necessary atmospheric conditions for plant growth. An illustration of smart greenhouse agriculture based on IoT is presented in Fig. 3. IoT protocol transmits the information collected through sensor devices to the cloud server through the gateway or microcontroller. A precise automated system for a greenhouse relies on interconnected microcontrollers, which act as the central control unit regulating various actuators and sensors. The control devices like heaters, lights, valves, pumps, vents, and sprinklers are regulated by actuators. Farmers use several electronic devices, such as laptops and smartphones, for remote monitoring and making control actions.

Wireless sensor networks (WSN) are utilized to aid in the monitoring and management of the devices illustrated in Fig. 3 while also establishing an optimized climate for crop growth. For instance, soil sensors play a crucial role in collecting information about water flows through the soil, thus enabling monitoring of variations in soil moisture, temperature, and nitrogen levels. This process empowers farmers to optimize, monitor, and control the growth of delicate crops to maximize yield while upholding product quality. By gathering data on environmental factors such as humidity, light intensity, and temperature values, these sensors facilitate adjustments to irrigation schedules that help mitigate potential damage risks. Furthermore, controlling the humidity and temperature levels within a greenhouse is essential. Sudden fluctuations in temperature can lead to crop damage and reduced productivity in just a few hours. Therefore, environmental conditions are crucial for optimal plant growth [7]. Another vital parameter to monitor for the healthy growth of plants is light intensity. The output voltage of a light sensor varies based on the light intensity level. High-intensity levels correspond to increased voltage, while low levels result in decreased voltage [37].

One of the primary goals of using the Internet of Things in greenhouse farms is to provide agriculturists with a long-term sustainable approach. Smart greenhouse farm involves advanced technology and low-cost farming that can grow yearly to provide sustainable food supplies. IoT sensors and infrastructures can monitor and control the environment's conditions. The integrated IoT cloud server enables it to process data remotely and control the infrastructures of IoT, like irrigation valves and window openers. The IoT cloud server also enables farmers to monitor and control through their mobile devices instead of manual monitoring [38]. Consequently, IoT-enabled greenhouse agriculture improves productivity and reduces labor costs by enabling farmers to plant multiple crops with minimal human effort during the appropriate seasons.

2.2. Hydroponics greenhouse based on IoT

Hydroponics is a growing plant technique that uses water instead of soil to provide space for planting and protect from chemicals in the soil [39]. It indicates that soil is unimportant for the cultivation of plants, and the essential minerals, nutrients, and a controlled pH level in water are necessary within a certain limit [40]. For high-quality production, hydroponic farming needs precise control of environmental variables. Temperature, humidity, light intensity, pH, and electric conductivity are crucial factors. Any sensing and monitoring devices can be used to monitor these parameters. A microcontroller is used to control sensing and monitoring devices. The microcontroller is linked to the Wi-Fi module, which sends any hydroponics-related sensing device data to cloud servers [41]. Fig. 4 shows a typical structure of hydroponics in a greenhouse, including components such as the water pressure pump, piping system, nutrient reservoir, artificial lighting, and water storage tank. Electrical Conductivity (EC) sensors are calibrated using solutions with different EC levels, such as low, high, and dry adjustments. pH and EC play a crucial role in promoting the healthy growth of crops and plants. In hydroponic systems, the EC concentration can be adjusted by following the guidelines provided on the solution container [40]. Proper control of liquid flow is also crucial in the hydroponic system. If the system delivers too little liquid, there is a small crop size or plant death risk.

Conversely, an excess supply may result in irregularly shaped crops. Therefore, it is essential to regulate the system's functioning and supply [33]. As indicated in Fig. 4, The sensor gateway validates the data and transmits it to the actuator control system and cloud storage. Subsequently, the system activates the actuators to deliver the precise quantity of hydroponic solution indicated in the received information. Additionally, users can access and manipulate collected information remotely through their mobile devices or a web browser. Peuchpanngarm et al. [42] created an autonomous control mobile application based on IoT for smart hydroponics. The application includes various types of sensors to control the environmental parameters for hydroponics, like water level, temperature, light intensity, and humidity sensors. These sensors are interfaced with a microcontroller for controlling and monitoring hydroponics gardening [42]. Pitakphongmetha et al. [43] used a WSN system to send the collected information to the cloud servers. It is connected to the "Blynk" android application and is used for monitoring the growth of plants in hydroponics. Mehra et al. [44] created a system based on IoT for hydroponics that involves sensors, Arduino, and Raspberry pi3 to monitor the environmental factors, including pH, temperature, humidity, and light intensity. They also used Deep Neural Networks to provide suitable control action for hydroponics. The developed system achieved a satisfactory performance with accuracy reaching 88 % [44]. The benefit of hydroponics greenhouse farming based on IoT is that unnecessary pesticides are not needed for the soil. Also, water needs are lower than in traditional greenhouse farming [45].

In addition, the growth of the plants remains unchanged by external environmental variations. Although IoT-enabled tools are in place, a key difficulty with hydroponic farms is the need for intensive manual oversight to distribute water and supply necessary nutrients. Furthermore, scaling up hydroponic farms poses significant challenges as IoT-based infrastructures require substantial initial investment. Additionally, the communication network commonly used in hydroponic farms is not well-suited for long-distance communication [45].

2.3. Vertical farming based on IoT

As shown in Fig. 5, vertical farming is an advanced agricultural technology that includes growing crops assembled vertically in an enclosed controlled region. Vertical farms are specially constructed to grow crops in urban settings using advanced technology. These high-rise agricultural systems create a controlled environment that eliminates the impact of external factors, allowing them to be established in any building without regard for the surrounding climate or weather conditions.

Several devices like actuators, sensors, and microcontrollers are integrated within the smart vertical farms to monitor and manage

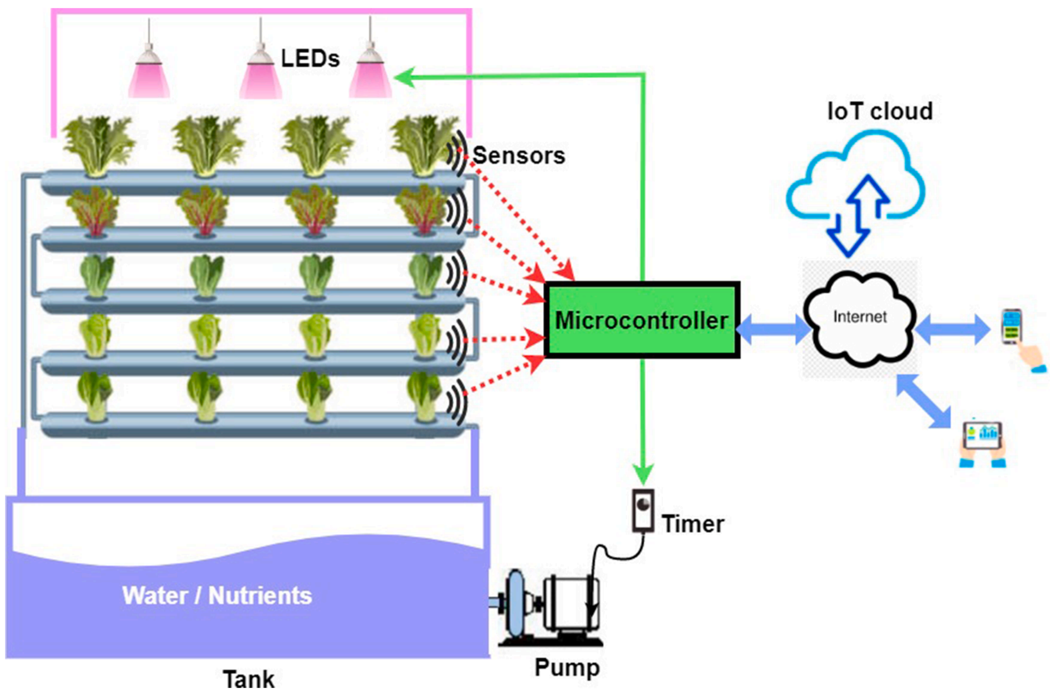

Fig. 4. Hydroponics in greenhouse.

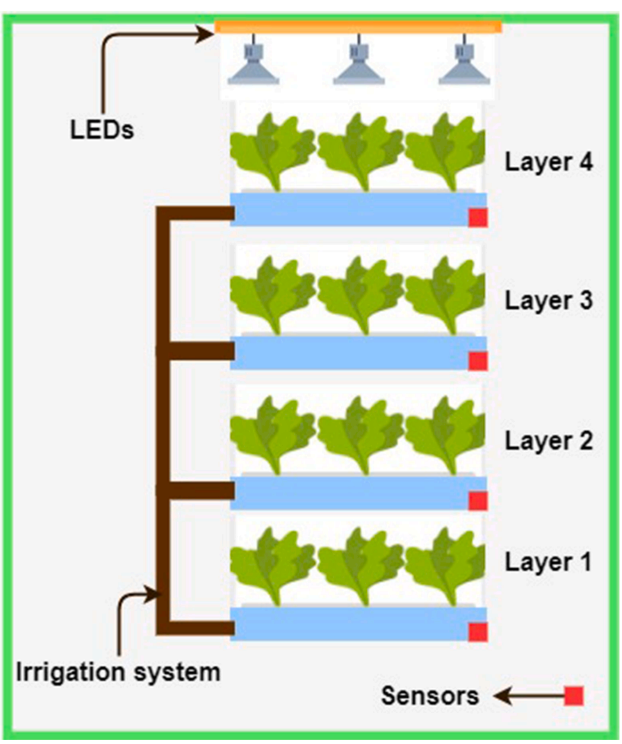

Fig. 5. Vertical farming.

operations. Sensors are connected directly to environmental parameters, transmitting collected data to the server via IoT protocol. Additionally, the connection of actuators to these parameters is indirect. Actuators oversee control devices like heaters, humidifiers, air-conditioners, sliding windows, and lights. Changes in environmental conditions drive the actuation process to adjust the required standard condition by regulating these devices [46]. Simulation of sunlight in vertical farms involves using LED lights to facilitate crop photosynthesis. Therefore, it is essential to monitor light levels carefully to provide the ideal amount of photon energy for efficient photosynthesis. For this objective, the system utilizes a light sensor. Maintaining suitable humidity and temperature levels is crucial for the well-being of crops in a confined setting. Therefore, it is essential to install sensors that monitor temperature and humidity.

Vertical farming has many benefits; one of the key benefits is that vegetables are grown close to consumers and allow for higher yields owing to the control of environmental parameters for production. In addition, vertical farming is pesticide-free and environmentally friendly farming. Yet, this kind of agriculture demands high maintenance to cultivate crops. LED lights are used to replace the sunlight. In vertical farming, the environmental parameters, like temperature, soil moisture, and humidity, must be controlled like in other greenhouse farms [47,8].

Vertical farming can benefit from an autonomous irrigation system, which reduces labor costs. Vertical farming also provides independence from climatic circumstances. As a result, nutritious crops can be cultivated sustainably even in cities or regions with soil contamination or harsh climates [49]. Despite the benefits, vertical farming has challenges, including high energy costs, technical competence requirements, and maintenance costs [48]. The costs for a vertical farm may be substantial when the farming space is acquired in commercial districts. In this issue, the farming process is not as extensive as in rural areas. Additionally, production capacities do not expand as with wide-area farming, leading to increased intricacy and cost [33].

3. IoT architecture for smart greenhouse agriculture

The gap between IoT technologies and agriculturalists has diminished, enhancing productivity in sustainable food cultivation. Adopting Smart agriculture, such as IoT-based Greenhouse technology, involves automated irrigation, environment control mechanisms, remote monitoring, fertilization procedures, and frost protection measures. These functions are supported by integrating IoT technologies with other elements like cloud computing, hardware systems, integration platforms, operating systems, and monitoring/control processes [50,33]. As indicated in Fig. 6, IoT-based architecture for greenhouse agriculture comprises four basic layers: application, service, network, and physical. The

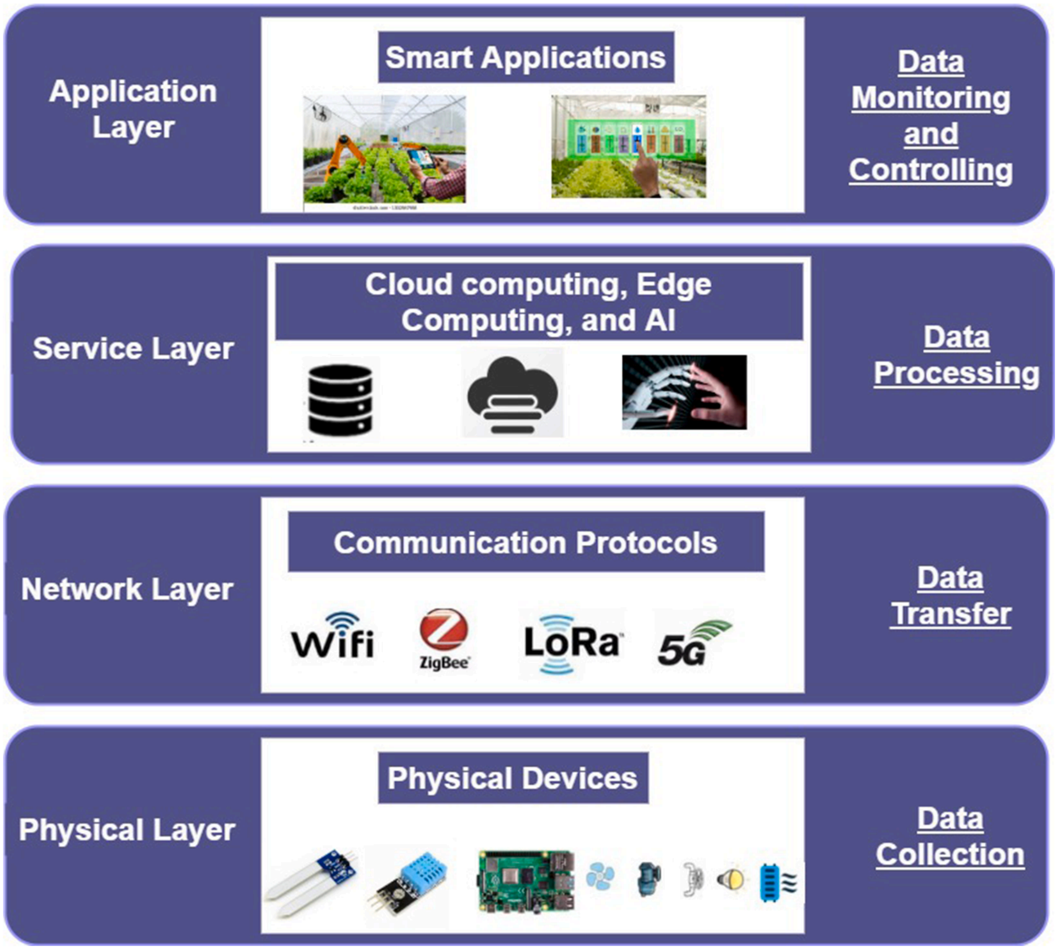

Fig. 6. IoT architecture for smart greenhouse farming.

physical layer contains multiple sensors, various actuators, and microcontrollers. The environmental parameters are sensed at this layer and then actuated according to predetermined instructions. The data transmitted and the instructions received by this layer flow through the networking layer. The network layer comprises standard communications protocols (LoraWAN, SIGFOX, Wi-Fi, ZigBee, etc.) and IoT protocols (MQTT, HTTP, and CoAP). The service layer presents numerous technologies, including cloud computing, fog/edge computing, and artificial intelligence for the application layer. In the application layer, several IoT-based agricultural activities, such as monitoring, controlling, tracking, and predicting, are performed using the previous layers' services.

3.1. Physical components

The physical components include various types of sensors, actuators, and microcontrollers. These components are used for collecting and processing information related to the objects in IoT networks and sending the data that has been processed to the upper layers. Furthermore, the physical components receive control signals from the upper layers, enabling the associated equipment, like farming machinery, to take appropriate actions [51]. Sustainable greenhouse cultivation relies on continuous sensing, monitoring, sharing of data, and device communication to prevent diseases. Crop diseases like fungi can lead to substantial losses due to heavy rainfall, high temperatures, fog, and unforeseen weather conditions. Growers can proactively address potential outbreaks by integrating IoT sensors with mathematical models. This effective analysis of internal and external conditions within a greenhouse involves using essential sensors for temperature, humidity, water levels, CO2 concentration, NH3 levels, pH values, etc [52,53].

3.1.1. Sensor devices

IoT sensor nodes consist of fundamental elements, including sensor devices, networking, processing, and power units. Depending on the specific application, additional components like a power generator, display, and mobilizer may also be present. The analog-to-digital converter plays a crucial role in converting analog signals from sensors into digital signals for transmission to the processing unit, which enables collaboration with other nodes to carry out necessary tasks [54]. Many sensors efficiently analyze the greenhouse's physical, internal, and external conditions. Fig. 7 shows that smart greenhouse farms frequently use temperature, humidity, CO2, light, and soil moisture sensors for optimal plant growth and production [52]. Also, different types of greenhouse monitoring and controlling sensors based on IoT have been indicated in Fig. 8. These sensors gather real-time data in various formats during agricultural operations. The collected sensor data can be processed using a smartphone and web-based application specifically designed for this purpose. Their primary objective is to assess environmental factors, plant health, and soil conditions within the greenhouse farms. In addition, the sensor's role includes monitoring, controlling, securing, alerting, and analyzing realistic and hypothetical data [55]. Sensors make agricultural processes simple and efficient by implementing self-sufficient monitoring systems with minimal human intervention. An instance of such advanced agricultural technology is the smart irrigation system, equipped with multiple water sensors in the greenhouse farm. These sensors enable the system to tailor precise water measurements for specific crop cultivation [55]. Some factors need to be taken into account in the design of the farming IoT network [55]:

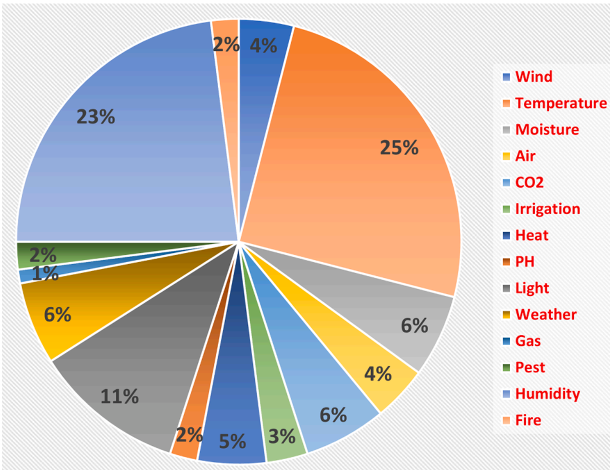

Fig. 7. Frequency of using IoT sensors in greenhouse cultivation.

1- The sensor network should operate reliably in real-environment conditions for an extended period without requiring battery replacement.
2- Additionally, remote sensor network management is essential to facilitate software upgrades, diagnostics, and reconfiguration tasks.
3- Furthermore, there is a necessity for universal sensor networks that will enable seamless integration in the future.
4- The design should be economically viable and ready for commercial use by prospective users.
5- This section discusses various types of sensor devices briefly.

3.1.1.1. Temperature sensors. According to Ferentinos et al. [53], the temperature distribution within greenhouse farms is usually unequal, reaching up to 3.3 °C, with the highest daytime variability emerging in summer. Consequently, the major concern parameter in greenhouse farms is the temperature to which the crops are exposed. The temperature sensors must be positioned above the crops to measure this [56]. As a result, Nelson [57] proposed that these sensors should be placed 15 to 30 cm above the pot lip for a pot-plant greenhouse farm. Various temperature sensors are displayed in Fig. 8 [58,59]. Furthermore, the choice of an appropriate temperature sensor should take into account the specific environmental conditions. For example, if the greenhouse is close to an area with high electromagnetic activity, using a thermocouple temperature sensor would not be feasible; instead, choosing a resistance temperature detector (RTD) would be more appropriate [56].

3.1.1.2. Humidity sensors. Many greenhouse agriculture systems use relative humidity for microclimate monitoring and controlling. Condensation on covering, moisture exchange through ventilation, soil

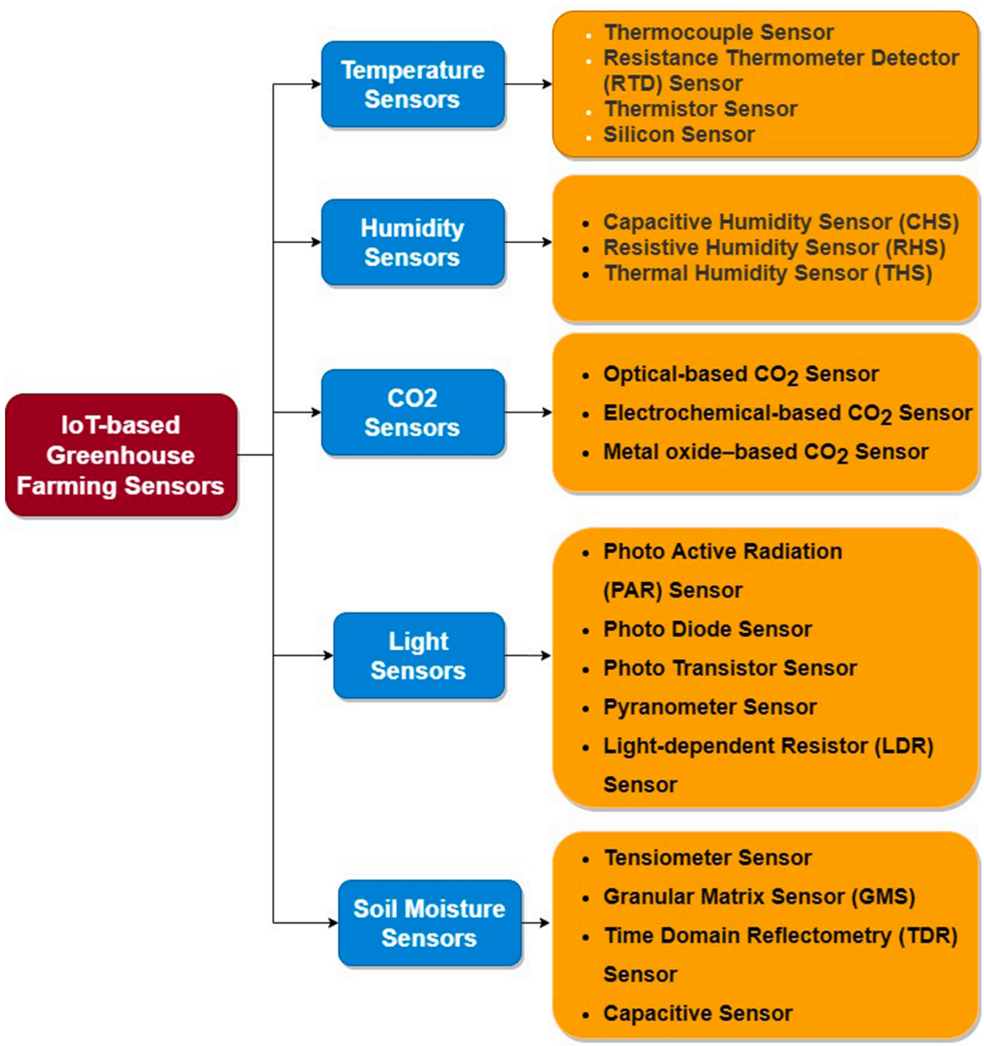

Fig. 8. Different types of IoT-based greenhouse monitoring and controlling sensors.

evaporation, and plant transpiration contribute to humidity, the quantity of vaporized water in the greenhouse [56]. In particular, moisture content modifies the sensor's resistance or capacitance values depending on the sensor type, and these changes are evaluated to determine the amount of humidity. As shown in Fig. 8, humidity sensors can be categorized into CHS, RHS, and THS [60]. Temperature and humidity are closely connected within a greenhouse, making it advantageous to install both sensors together. Modern modules integrate temperature and humidity sensors in a single module, simplifying the system by reducing the number and size of devices, which leads to decreased design complexity, power consumption, data transmission payload, and memory usage.

3.1.1.3. CO_2 sensors. Carbon dioxide (CO_2) is an essential component of plant photosynthesis. Plant leaves receive CO_2 from the atmosphere, roots absorb soil nutrients from the water, and light energy is required to complete plant photosynthesis. Temperature, humidity, sun irradiation, and plant transpiration all impact CO_2 concentration inside a greenhouse [56]. The CO_2 concentration within a greenhouse rises at night as a result of plant respiration and the burning of fuel if the greenhouse is heated with biofuel. However, CO_2 is scarce during the day because plants use it for photosynthesis. A plant absorbs CO_2 through its stomata; environmental conditions like temperature and humidity substantially influence stomatal opening. As a result, such environmental conditions, including CO_2, must be maintained optimally to guarantee that the plants absorb sufficient CO_2. Also, opening the greenhouse's ventilators and windows decreases the indoor CO_2 level [61]. Consequently, the selection of a suitable CO_2 sensor is an important issue. CO_2 sensors are classified into three broad groups based on operating principles [62] (see Fig. 8).

3.1.1.4. Light sensors. The sun's light is responsible for practically all life on Earth, powering photosynthesis, in which plants convert carbon dioxide and water into carbohydrates [63]. In the greenhouse, sunlight is the principal light and heat energy source. The materials used to cover a greenhouse influence the quantity of light allowed in and the structure and direction of the greenhouse [64]. Different plants respond differently to light, and the type of farming influences the amount of light intensity needed. Most greenhouse farms use sunlight as a light source; nevertheless, additional light at a specific band boosts production [65]. LED lighting is used in modern greenhouses because of its energy efficiency, durability, and robustness. Curtains, on the other hand, are employed in greenhouses to screen off excess light. Fig. 8 presents some of the most popular light sensors on the market [60].

3.1.1.5. Soil moisture sensors. This sensor measures the amount of water in the soil. Plants acquire necessary nutrients from the soil via their roots in soil-based farming. Therefore, maintaining an adequate water level in the soil is essential. Furthermore, excessive water might increase the plants' likelihood of developing or suffering from different diseases. As a result, maintaining the proper water level in the soil is critical. However, irrigation control systems are based on soil moisture sensors for water supply when plants need it while reducing water use, thus producing higher-quality crops and yields [56]. Soil moisture sensors primarily operate on two various principles: water tension-based sensors (Tensiometer, Granular Matrix Sensor) and soil water content-based sensors (Time Domain Reflectometry, Capacitive sensor) [66,67] (see Fig. 8).

3.1.2. Actuators

An actuator is a machine component responsible for moving or controlling a system component, such as opening or closing a valve. Individual actuators are linked for each environmental parameter, such as water level, humidity, temperature, CO2, and UV light. A control command and power supply are necessary for an actuator. Electric voltage, hydraulic or pneumatic pressure, and human power can all be utilized as low-energy control signals. Electric current, hydraulic fluid, and pneumatic pressure are possible main energy sources. The actuator adapts to the control signal by transforming the energy into mechanical motion [68]. Actuators for greenhouse farming include a nutrient container, a pump for water, fans, lights, and windows [Fig. 3]. They are employed to implement the user's command.

3.1.3. Microcontrollers

Microcontrollers are considered the core of a greenhouse cultivation system, with multiple sensors and actuators interconnected to create an accurate automated system. Microcontrollers are necessary to connect and communicate with other IoT systems and devices. They collect sensor data, process it, and transfer it to other devices or systems via wired or wireless communication protocols. Microcontrollers can also receive and decode commands and control signals from other devices that they can subsequently utilize for controlling the embedded device's activities and behaviors. Microcontrollers are appropriate IoT systems due to their small size, minimal energy consumption, and low cost. They can be programmed to do a variety of functions. They are also ideal for battery-powered electronic devices due to their low energy consumption. There are various microcontrollers on the market, each with its features and capabilities. Arduino, ESP8266, and Raspberry Pi are popular microcontrollers in IoT-based greenhouse farming applications.

3.1.3.1. Arduino. Arduino is an open-source physical computing system built on a simple microcontroller chip and an integrated development environment (Arduino IDE) that utilizes the Processing programming language, runs on the computer, and allows it to create and upload code to the chip [69]. Fig. 9 shows the Arduino UNO microcontroller. It contains 14 input or output pins, six analog input pins, a crystal oscillator with a frequency of 16 MHz, a power connector, and an ICSP header. The operating voltage is 5 V [70]. Arduino can detect and influence the surrounding environment by accepting input signals from numerous sensors and commanding actuators such as heaters and water pumps [71]. Rodriguez et al. employed Arduino as the center node to transmit information to a central big data store while monitoring and forecasting client applications [72].

3.1.3.2. NodeMCU (ESP8266). The ESP8266 is a low-cost Wi-Fi microchip having a full TCP/IP stack and microcontroller capability. Espressif Systems is the organization that introduced it, and it works based on the Arduino IDE compiler. It is a complicated device that incorporates some of the features of a standard Arduino microchip with the ability to connect to the Internet using its built-in Wi-Fi module [73]. ESP8266 microcontroller is shown in Fig. 10. Gutierrez et al. used an ESP8266 paired with an Arduino to provide a data communication system [74]. The Arduino receives data from different sensors and communicates it to the ESP8266 for the next connection. The results reveal that the system effectively monitors greenhouse farms in real-time.

3.1.3.3. Raspberry Pi. As indicated in Fig. 11, the Raspberry Pi board is a small, powerful, low-cost computer board announced in 2012. It is widely used in IoT applications. It includes a processor, RAM, graphics chip, and several ports and connectors for external devices. Some of these components are required, while others are optional. However, all Raspberry Pi types share the same CPU, the BCM2835, which is inexpensive, powerful, and consumes little power. The Raspberry Pi board functions similarly to a regular PC, needing a keyboard for command entry, a display device, and a power source. A flash memory card, typically used for digital cameras, is configured to appear like a hard drive to the Raspberry Pi processor. The micro-USB connector powers the device. Internet access can be obtained via Ethernet/LAN or USB dongle (Wi-Fi connectivity) [75]. Sensors in greenhouse farming support a link to a Raspberry Pi microprocessor and act as a data logger in the

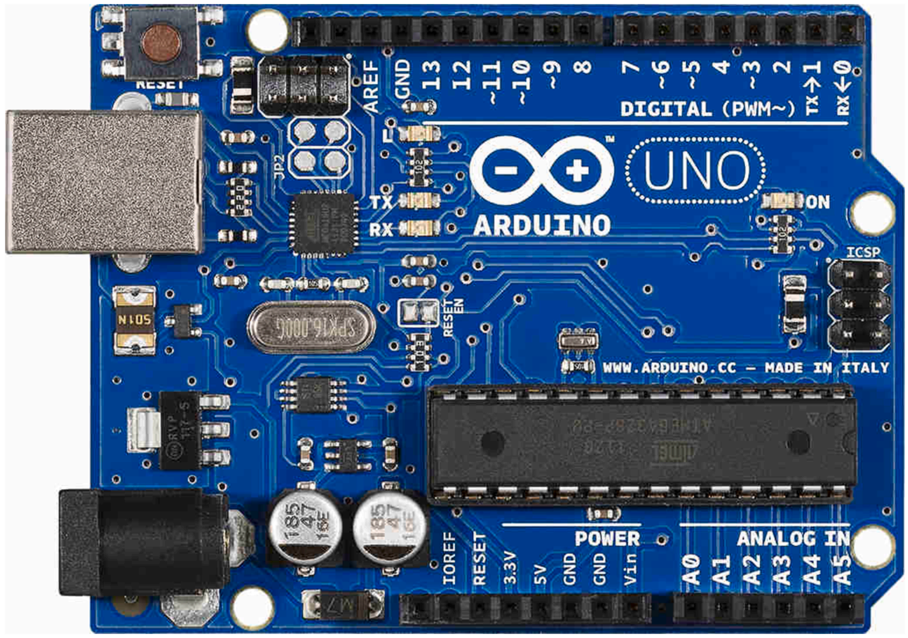

Fig. 9. Arduino UNO board.

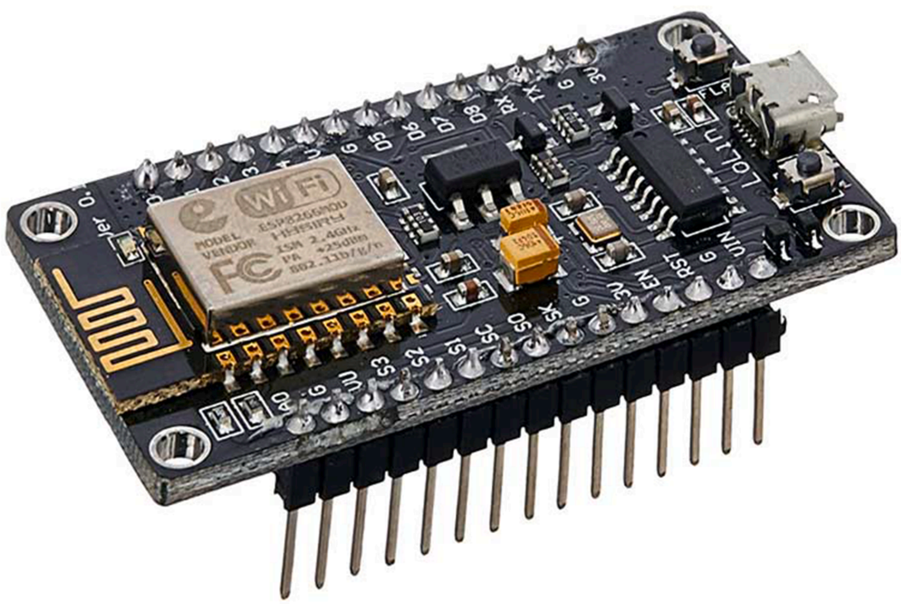

Fig. 10. NodeMCU (ESP8266).

cloud, making Raspberry Pie the optimal microcontroller for a greenhouse farming monitoring system [76].

Furthermore, as the Raspberry Pi is developed, newer models feature built-in WIFI and Bluetooth chips, making it simple to adapt applications to wireless mode. Mehra et al. [44] suggested an IoT-based hydroponics system that uses the Raspberry Pi 3 to incorporate data into a neural network model and make decisions to control the system. Liao et al. connected sensors to a cloud server using a Raspberry Pi 2 [77].

3.2. Communication protocols

Reliable, secure, firm, and fast communication are the most critical factors in smart greenhouse agriculture. Additionally, reliable connection is essential between objects in the greenhouse farm for timely crop reporting, monitoring, and controlling. IoT communication protocols can be quite useful in smart greenhouse farming to achieve this level of reliability. However, energy consumption, cost, and coverage must be considered before employing any communication protocol. As a result, numerous communication protocols and technologies are used for this purpose according to the application needs, scalability, and reliability. In the past few years, there has been significant advancement in IoT technologies and Wireless sensor networks (WSN) protocols.

The WSN protocols have become increasingly popular compared to wired transmission technologies due to their effective protocols, ease of maintenance, and cost efficiency compared to cable-based technologies [30,78]. These protocols facilitate wireless communication, remote sensing, and other applications by transmitting electromagnetic signals. The two main types of WSN are Wireless Underground Sensor Networks

Fig. 11. Raspberry Pi.

(WUSN) and Terrestrial WSN (TWSN). In IoT-based greenhouse farms, WUSNs are placed underground with sensor nodes that transmit data to a gateway node. This data can then be sent to the Internet and stored in distant databases to notify farmers via smartphones [30]. However, the drawback of the WUSNs is their limited capability for short-distance communication and the requirement for a large number of nodes.

In contrast, TWSNs consist of sensor nodes deployed on the ground to gather data about environmental factors such as temperature, humidity, soil moisture, CO2 levels, and pH in the greenhouse farm. Typically utilizing MEMS sensors, these nodes interact with each other to make smart decisions based on the gathered data [79]. Table 1 shows the most important WSN communication and transmission protocols in greenhouse farming. These protocols collect, encapsulate, and transport the greenhouse farm information.

3.2.1. *Standard protocols*

3.2.1.1. Wi-Fi. The Wi-Fi communication protocol is an effectively structured wireless local-area network protocol because it can handle the transfer of large files like audio and video as it has the highest transmission rate. It operates upon the IEEE 802.11b, IEEE 802.11 a, IEEE 802.11 ac standards, IEEE 802.11 g, and IEEE 802.11n standards [80]. A router, an antenna, and radio transmissions operate this network. Large, medium, and small greenhouse farms can easily create network connectivity using Wi-Fi connection mode to acquire the necessary data [81]. However, the power consumption of Wi-Fi equipment is high, the transmission distance is short, and the network's capacity is relatively low. A central base station can only connect 16–64 devices simultaneously [31].

3.2.1.2. ZigBee. ZigBee is an IEEE 802.15.4 wireless network communication protocol. The major benefits are low speed, minimal power consumption, and minimal cost. Also, it is used for many network nodes, supported for varied network structures, and is self-organized. Some base stations in automatic networking can be used even if damaged, and each node has the same state [77]. Zigbee technology replaces existing non-standard communication methods in many IoT-based greenhouse applications. This protocol can be integrated with three different types of devices, depending on the application requirements: routers, end nodes, and coordinators. Furthermore, Zigbee provides three topologies: star topology, mesh, and cluster tree [82]. ZigBee is frequently selected as the communication protocol for large, smart greenhouses because it can accommodate over 60,000 nodes in theory [31].

3.2.1.3. LoRa. LoRa (Long Range) is a wireless communication protocol that uses minimal power and transmits data over long distances. It is based on the IEEE 802.15.4 g standard [83,84]. The primary characteristics include minimal speed, minimal cost, support for many nodes, support for different networking architectures, ad hoc networks, and an automated repair mechanism. The theoretical maximum capacity of nodes in a LoRa network exceeds 60,000. The response time of LoRa is rapid, typically taking only tens of milliseconds to transition from sleep to an active state and just one second for nodes to connect with the network. Despite its fast response speed, the user base for LoRa is not as extensive as ZigBee because it is a relatively new technology. Exploring LoRa communication for agriculture is vital, including data capturing - from motion nodes like vehicles without requiring fixed gateways [85].

3.2.1.4. Sigfox. A Sigfox is a long-range, minimal data rate protocol that sends information acquired by a global positioning system (GPS) to a centralized server using low energy [86]. It is used to share data

Table 1
Comparison of current IoT communication protocols.

Communication Type	Frequency	Data Rates	Transmission Range	Energy Consumption	Module Cost
Wi-Fi	5–60 GHz	1 Mb/s–6.75 Gb/s	20–100 *m*	High	5–10 Dollars
ZigBee	2.4 GHz	20–250 kb/s	10–100 *m*	Low	2 Dollars
LoRa	868–900 MHz	0.3–50 kb/s	20 km	Very low	2 Dollars
Sigfox	908.42 MHz	10–1000b/s	30–50 km	Low	2 Dollars
Bluetooth	2.4 GHz	1–24 Mb/s	8–10 *m*	Very low	2–3 Dollars
RFID	860–960 MHz	40–160 kb/s	1–5 *m*	Low	1 Dollar
LTE	100 MHz	100 Mb/s	Over 1 km	High	Over 20 Dollars
5th generation mobile networks	1–6 GHz	1 Gb/s	Over 1 km	High	Over 100 Dollars
MQTT	2.4 GHz	250 kb/s	–	Low	–
CoAP	1.30–2.4 GHz	10–20 kb/s	–	Low	–

without maintaining and creating network connections. As a result, there will be no signal overhead, and the protocol will be perfect and concise [87]. The power consumption and cost of the devices are incredibly low, which makes it viable and practical for Sigfox network devices to transmit data over long transmission ranges. It includes an integrated network backbone and a base station in topology, allowing it to cover larger distances.

3.2.1.5. Bluetooth. Bluetooth is a minimal power and short-range wireless communication technology that connects small devices. It has many versions. This protocol is employed in various greenhouse farming applications because of its ease of use, minimal cost, and minimal power consumption. Taşkın et al. [88] developed a Bluetooth-enabled sensor node for IoT-based smart farming systems to monitor temperature and the surrounding light. Achour et al. [89] created a Bluetooth-based system for remote monitoring of the greenhouse.

3.2.1.6. RFID. Radio-Frequency Identification (RFID) uses radio waves to keep data collected on a machine safe and secure. The RFID approach includes RFID tags (both active and passive), readers, and hosts. The tags contain an identification number (ID) for greenhouse atmospheric items. The item is given an ID number so the reader can identify it and read data, which is then sent to the end host. The host serves as the RFID method's processing part [90]. RFID technology is utilized in various IoT applications such as smart shopping, healthcare management, national defense, and the agricultural sector [77].

3.2.1.7. LTE. Long Term Evolution (LTE) is a wireless network communication protocol that relies on Global System for Mobile Communication (GSM) technology. This protocol transmits data between mobile devices at high rates. [91]. It operates using an authorized frequency and prioritizes premium cellular services. IoT devices utilizing these technologies can link up through mobile networks [15]. Higher throughput and lower latency rates are encountered while uploading and downloading the data.

3.2.1.8. 5th generation mobile networks (5G). 5G is a new mobile revolution in the mobile phone market. The 5G utilizes a high-band spectrum for high rates and low latency. Because of its greater bandwidth, 5G can link billions of devices while providing large data capacity and faster than 10 Gbps. 5G will outperform current LTE standards in downloading and uploading rates by up to 100 times [92]. Precision agriculture is projected to benefit from the 5G network. The growth of 5G coverage benefits agricultural producers by allowing them to manage farms, livestock, and so on [93].

3.2.2. IoT protocols

3.2.2.1. MQTT. MQTT (Message-queuing-telemetry) is a bidirectional and asynchronous messaging protocol. It comprises three key components: a broker, a subscriber, and a publisher. IBM created it to support M2M connectivity and IoT technologies for flexibility, lower bandwidth utilization, and computational resources. The MQTT protocol is used by many greenhouse farming applications for various communication objectives [94,95]. Satpute et al. [96] designed a greenhouse monitoring system that uses IoT with MQTT protocol to monitor and control climate conditions within a greenhouse farm to ensure optimal crop development.

3.2.2.2. CoAP. CoAP (Constrained application protocol) is an application layer protocol for using internet devices with limited resources, including WSN nodes [97]. CoAP is a Representational State Transfer (REST)–based protocol that facilitates data transmission between client and server through HTTP [98]. This protocol can be split into two main components: the request/response and messaging layers. The messaging layer identifies duplicates and ensures dependable communication, while the request/response layer manages REST connections [52]. The CoAP protocol aims to facilitate RESTful interactions in greenhouse farming using low computation power and communication capabilities.

3.3. Data processing services

The primary goal of data processing is to gather and analyze the obtained data. Real-time, dynamic, and extensive production data is collected when monitoring agricultural production in greenhouse farms. By leveraging IoT technology, this production data can be stored and analyzed to some extent, enabling the identification of relevant data patterns. Cloud computing technology is primarily utilized for processing data, offering an effective solution for storing, computing, and processing large-scale agricultural production data. Various data services, including cloud computing, fog/edge computing, and artificial intelligence (AI), are integrated with IoT technologies and supported for the application layer, allowing greenhouse farming applications to implement a variety of smart management operations, including automated irrigation, autonomous environment-control systems, remote monitoring, fertilizing, and frost prevention [51].

3.3.1. Cloud computing

Cloud computing is an Internet-based storage system that utilizes centralized or distributed computing technology. It can utilize parallel and distributed computing together or separately and can be implemented virtually or physically in a data center [99]. It plays a crucial role in every IoT system. IoT devices lack utility without connectivity to the cloud. Data collected from individual IoT sensors becomes valuable when linked with other pertinent sensors. Cloud services provide huge storage by connecting large, virtualized servers to perform required functions. IoT can benefit from cloud computing capabilities and resources to overcome IoT limitations such as storage, processing, and communication [100]. A cloud-based IoT design for precision agriculture has been introduced [101] and emerged as a leading technology with wide-ranging applications across various industries, including farming. Farmers can utilize video, image, and short message services to access information about greenhouse farms inexpensively. In addition, cloud computing allows for the simultaneous management of large-scale intelligent computing systems [30]. Integrating IoT-based farming and cloud computing boosts the monitoring process, makes it easier to maintain, more understandable, and precisely solves greenhouse farming problems [102]. Farooq et al. [52] introduced a network platform based on cloud technology for an IoT-based greenhouse. This platform enables the greenhouse resource manager to handle numerous requests and manage resources effectively. Their platform encompasses three categories of cloud services: Software as a service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). The developed network can offer various data types for different uses within the greenhouse, including pest monitoring information, weather conditions, irrigation information, etc [52]. Hsu et al. [103] created a cloud integration system for analyzing large datasets and automating farm monitoring, even with limited network information. The developed system also enhances data processing speed, benefiting pest management in smart greenhouse farms [103]. Abdullah et al. [104] created an "Agri-System" incorporating cloud computing, IoT technology, and sensor data. The system's primary goal is to ensure that all environmental parameters are effectively controlled in smart greenhouse farms, using a fuzzy controller to reduce complexity [104].

3.3.2. Fog/Edge computing

Fog/Edge is a high-virtualization service offering conventional cloud computing services between end devices and cloud computing data centers, often placed on the network's edge [105]. That means Cloud computing includes infrastructure-level services that can grow to handle IoT storage and processing needs. However, some applications, including sensor monitoring, control, and analytic response, demand low latency. Hence, the delay imposed by transmitting data to the cloud servers and subsequently back to the application might significantly impact their performance. The Fog and Edge computing frameworks have been developed to alleviate this limitation. Cloud services are extended to the network's edge [106] to reduce latency and congestion. Wireless communication-capable sensors equipped with micro-controllers may be classified as edge computing devices. Precision herbicide application has gained popularity in field crop management. A mobile platform with a camera carries and applies the herbicide directly onto emerging weeds, ensuring precise targeting. The moving platform uses instant on-board image processing hardware and software to minimize delays caused by cloud-based image processing in larger fields [107]. The centralized cloud relies on the weed density data collected from the mobile IoT platform to predict future herbicide requirements and ensure sufficient stock levels. Edge computing involves positioning computing power at the device's sensors, providing processing capacity through low-power micro-controllers embedded in the devices. While their processing capabilities are more restricted, they can still be suitable for image processing tasks [108]. An IoT system based on Fog computing can make decisions quickly at the edge, reduce the quantity of data transmitted between the fog and the cloud, and reduce the amount of data the cloud processes [109].

3.3.3. AI

AI (Artificial Intelligence) technology helps multiple sectors, including agriculture, enhance efficiency and profitability. Plant diseases, inadequate storage control, pesticide management, weed concerns, and management of water are all agricultural challenges that AI can solve [110]. Data collected by various sensors is critical and must be managed and analyzed using one of the AI branches, such as machine learning (ML) and deep learning-based mechanisms, to predict forthcoming issues in greenhouse agriculture activities [111]. ML can predict and identify the correlation between factors to offer informed decisions or remedies for smart greenhouse agriculture. This technology has already been employed to design irrigation systems and predict occurrences of plant diseases [30]. Deep learning techniques are widely utilized in the realm of agricultural image processing. Trained models based on deep learning are accessible for identifying crop types, analyzing plant phenotyping, detecting fruits, flowers, and leaves, and identifying weeds for herbicide utilization [112].

In addition, AI and edge computing provide a range of advantages in IoT-based farming, particularly in situations where there is an impending danger of fire hazard caused by combustible liquids, moving machine parts (such as worn or misaligned components, damaged drive belts, and exposed electrical wiring), and the open burning of farming waste. For instance, AI frameworks played a crucial role in enhancing fire safety measures, addressing general hazards on farms, and automating systems [32]. Consequently, Artificial Intelligence and IoT - significantly contribute to modern farming by controlling and automating agriculture actions.

3.4. IoT-enabled greenhouse farming applications

The advancement of IoT technology enables objects to be remotely controlled. In a greenhouse, a farmer can remotely monitor essential environmental factors, including humidity, temperature, weather, light, water, soil moisture, fertilization, pests, and CO2. Table 2 shows the monitoring, controlling, tracking, and predicting applications of IoT in the greenhouse. In Table 2, we also performed a quality evaluation for IoT applications in a greenhouse by applying a questionnaire to assess the quality of the research papers collected.

QA1: Is the research work published in a reputable and ranked - journal? If the journal was ranked, the answer was yes (1); otherwise, the answer was no (0).

QA2: Is the research centered on greenhouse applications based on IoT, like monitoring, controlling, predicting, or tracking? If the research satisfied the requirements, the answer was yes (1); otherwise, the answer was no (0).

QA3: Has the research produced a clear solution for greenhouse agriculture with IoT technologies? The research assigned a score of (1) if the answer was yes and a score of (0) if the answer was no.

3.4.1. Monitoring

Greenhouse monitoring systems based on IoT can control and monitor the greenhouse farm by boosting light, enhancing photosynthesis, and raising plant growth rate. IoT systems can acquire real-time data permanently, reducing pesticide use, human input, and the consumption of resources and energy in greenhouse farms and increasing output production and quality [77]. Smart monitoring systems based on IoT technology play a crucial role in maintaining ideal conditions to enhance the quality of agricultural products. There has been a notable rise in the advancement of monitoring systems, particularly those that monitor environmental conditions like temperature, light, and humidity, which are vital for ensuring high-quality crops. Farmers can also utilize IoT-based disease monitoring systems to oversee numerous plant diseases on a large scale within greenhouses while minimizing labor expenses.

Furthermore, monitoring crop growth and production performance is integral to farm management. Monitoring plant growth only by analyzing specific pathogens may not provide accurate results. Digital forecasting methods that use IoT methods can be used for more accurate monitoring [52].

3.4.2. Controlling

Continuous control of greenhouse parameters like temperature, light intensity, soil PH, and CO2 is required to achieve high production of plants and vegetables. However, the control of weather variables is essential for promoting the optimal growth of plants. When implementing IoT-enabled greenhouse farming, it is important to consider factors such as constraints in the proposed smart solution, advancements in precision, and overall cost. Additionally, IoT-enabled irrigation control has the potential to enhance water resource utilization and attain effective outcomes. The prudent use of water in agricultural practices is vital for enhancing crop yields, cutting down expenses, and advancing sustainable methods [15]. Sensors can also automatically gather data for pest control, including identifying the presence of pests or detecting when a trap has been activated by capturing a pest [15]. According to the results, Yue et al. [147] introduced an advanced high-resolution model for intelligent pest detection, which significantly enhanced the recall rate.

3.4.3. Tracking

The Internet of Things development with Artificial intelligence, big data, satellite images, GPS, and drones allows agriculturists to track greenhouse farms remotely with less human work. Aside from that, the IoT-enabled system assists farmers in tracking machinery and undesired motion on the farm. Satyanarayana et al. [148] developed a plant health monitoring framework that tracks various soil types. ZigBee is incorporated with GPS and GPRS in the suggested architecture for tracking real-time data. When unusual activity occurs, GPRS connects to monitoring equipment and alerts the greenhouse farm owner. Although such a system has a high maintenance cost, it is incredibly useful due to its precise tracking ability.

Additionally, various models and algorithms have been suggested using IoT technology to monitor the growth stages of seedlings. González-Amarillo et al. [118] introduced a traceability model for tracking greenhouse farming products from initial planting to final production, which includes an automated internal environment control system based on temperature regulation.

Table 2
IoT Applications for smart greenhouse farming.

IoT-based Application						Quality Evaluation				
Author	Year	IoT-based Greenhouse Application	Application Domain	IoT Devices	Communication Technologies	Data Processing Services	*QA1*	*QA2*	*QA3*	*Total Score*
Liang et al. [81]	2018	- developed a dynamic and remote monitoring system for the greenhouse environment	- Monitoring	-Temperature, humidity, and light intensity sensors	- Wi-Fi - RS-485	- Cloud computing	1	1	1	3
Akhtar et al. [113]	2019	- Designed a user authentication scheme for using IoT technology to monitor greenhouse farming parameters	- Monitoring	-Temperature, humidity, light, pressure, and CO2 sensors	- WSNs	Not Available	0	1	1	2
Singh et al. [114]	2016	- Devised an Arduino-based controlled irrigation system	- Controlling	-Arduino and ESP8266 microcontrollers, -Water flow, soil, and temperature sensors - Actuators	- Wi-Fi	- Cloud computing	0	1	1	2
Ferentinos et al. [53]	2017	- Created a prototype WSN for assessing greenhouse climate and plant condition	- Monitoring	-Temperature and humidity sensors	- WSNs - Wi-Fi	Not Available	1	1	1	3
Rodríguez et al. [72]	2017	- Presented data monitoring and predicting system in precision farming in a rose greenhouse	- Monitoring - Predicting	-Temperature, humidity, soil moisture, and light sensors, -Arduino, Raspberry Pi	- WSNs - Zigbee	- Cloud computing-Fog computing	1	1	1	3
Sihombing et al. [115]	2018	- Automated hydroponics nutrition plants system has been developed to control the flow of nutrients of hydroponic plants	- Controlling	-Water level, temperature sensor, -ESP8266, Arduino microcontroller	- Wi-Fi	Not Available	1	1	1	3
Siddiqui et al. [116]	2017	- A smart greenhouse control system has been designed to grow healthier crops with higher yields in the fastest possible time	- Monitoring - Controlling	-Temperature, light, and moisture sensors - Arduino - Actuators	- Ethernet - Wi-Fi	Not Available	0	1	1	2
Chang et al. [117]	2021	- developed AI solutions to predict lettuce growing, harvest time, and quality in an IoT-based greenhouse system	- Predicting	- Growth and pest sensors	- Wi-Fi - WSN – 3G/4G	- AI	1	1	1	3
González et al. [118]	2018	- Developed a smart greenhouse traceability system for tracking and recordkeeping of seedlings	- Tracking	-Humidity, luminosity, temperature, and water level sensors - Actuators	- Wi-Fi	- Cloud computing	1	1	1	3
Azaza et al. [119]	2016	- An intelligent greenhouse fuzzy logic-enabled control system has been presented and improved using temperature and humidity correlation particular measures	- Controlling - Tracking	- Temperature - Humidity - CO2 -illuminance	- Zigbee - GSM/GPRS	Not Available	1	1	1	3
Alipio et al. [120]	2017	- Introduced a smart hydroponics farming system for automating crop growth through accurate inference in a Bayesian Network	- Monitoring - Controlling	- Light intensity, humidity, pH, water temperature, electrical conductivity sensor - Actuators -Raspberry Pi	- Serial interface	- AI - Cloud computing	0	1	1	2
Jiang et al. [121]	2019	- Created a farming cloud warehouse based on IoT and smart greenhouse agriculture technology to collect the environmental parameters	- Controlling	- Different sensing devices	- Zigbee - GPRS	-Cloud computing-AI	0	1	1	2
Liao et al. [77]	2017	- created an IoT-enabled environmental parameters monitoring system for greenhouse farming	- Monitoring	-Temperature, humidity, illumination sensor	- Wi-Fi - Zigbee	- Cloud computing	1	1	1	3
Subahi et al. [7]	2020	- A highly scalable IoT-based system has been introduced for monitoring and controlling greenhouse temperature	- Monitoring - Controlling - Predicting	-Temperature, humidity, and lighting sensor	- WSN - Wi-Fi	Not Available	1	1	1	3
Groener et al. [122]	2015	- Designed automated greenhouse farming control systems with a low-cost	- Controlling	-Humidity, temperature, and soil moisture	- Wi-Fi	Not Available	1	1	1	3
Zhao et al. [123]	2019	- Developed an IoT-based greenhouse agriculture frame to facilitate vegetable growth	- Monitoring - Controlling	-Temperature, light, CO2, humidity, and moisture sensors	- Zigbee	Not Available	0	1	1	2

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Table 2 (*continued*)

IoT-based Application						Quality Evaluation				
Author	**Year**	**IoT-based Greenhouse Application**	**Application Domain**	**IoT Devices**	**Communication Technologies**	**Data Processing Services**	***QA1***	***QA2***	***QA3***	***Total Score***
		environmental parameters monitoring process								
Achour et al. [124]	2018	- An effective method has been introduced to monitor the environmental parameters of greenhouse farming remotely	- Monitoring	-Temperature, humidity, light, and CO2 sensor	- Wi-Fi - Bluetooth	Not Available	0	1	1	2
Sofwan et al. [125]	2020	- Presented a smart device that is installed in the greenhouse to measure environmental parameters for optimal plant growth	- Monitoring	-Temperature, air humidity sensors	- MQTT	- Cloud computing	0	0	1	1
Abdallah et al. [126]	2018	- Presented an IoT-enabled control system for greenhouse farms	- Controlling	-Temperature, humidity, and soil moisture	- Wi-Fi – 3G/4G	Not Available	0	1	1	2
Carrasquilla et al. [127]	2020	- Designed an Electroconductivity sensor in greenhouse farming to assess drainage	- Monitoring	-Electrical conductivity (EC) sensor	- Wi-Fi – 4G	- Cloud computing	0	0	1	1
Wang et al. [128]	2021	-A smart greenhouse environment monitoring system has been designed to provide new power for smart agriculture	- Monitoring - Controlling	- Climate conditions	- Wi-Fi – 3G/4G	Not Available	0	1	1	2
Contreras et al. [129]	2023	-Proposed SAgric-IoT platform based on IoT to monitor environmental parameters as well as early detection of plant diseases while automatically controlling the irrigation and fertilization in greenhouses	- Monitoring - Controlling - Detection	- Temperature, soil moisture, and humidity sensor	- Wi-Fi - Zigbee	- Cloud computing-AI	1	1	1	3
Soheli et al. [130]	2022	- An intelligent greenhouse farming monitoring system based on IoT and AI has been created	- Monitoring	-Temperature, soil moisture, sunlight, and humidity sensor	- WSN	- Cloud computing-AI	1	1	1	3
Nemčík et al. [131]	2021	-Developed a novel approach based on IoT for building an indoor smart greenhouse system	- Monitoring	-Temperature, humidity, soil, and air quality	- MQTT	- Cloud computing	0	1	1	2
Kitpo et al. [132]	2019	- Created a system with a bot notification for predicting the growth stages of tomatoes in the greenhouse	- Monitoring - Predicting	-Temperature and humidity sensor	- Zigbee - Wi-Fi – 2G/3G/4G	- Cloud computing-AI	0	1	1	2
Lin et al. [133]	2018	- Developed a novel agriculture system based on IoT to revolutionize greenhouse cultivation	- Monitoring	- Environmental and pest sensor	- Ethernet - Wi-Fi – 3G/4G	Not Available	1	1	1	3
Huang [134]	2021	- An IoT-enabled design scheme has been created for the smart farming of flowers in a greenhouse	- Monitoring	- Temperature and humidity sensor	- Wi-Fi – 2G/3G/4G	Not Available	0	1	1	2
Šabić et al. [135]	2021	- Built an intelligent system to control greenhouse farming parameters for developing an optimal microclimatic condition	- Monitoring - Controlling	-microclimatic conditions	- GSM/GPRS	- Cloud computing	0	1	1	2
Quynh et al. [136]	2015	- A multi-route and single-path protocol has been created to improve the greenhouse's monitoring position	- Monitoring	- Temperature, light, pH, and humidity sensor	- WSN - IETF 6LoWPAN - IEEE 802.15.4	- Cloud computing	0	1	1	2
Zhang et al. [137]	2018	- Deployed a solar greenhouse smart control system to enhance production and save labor	- Controlling	-Multiple environmental sensors	- LoRa - GPRS	Not Available	0	1	1	2
Afzali et al. [138]	2021	- An optimal supplemental lighting system has been created to reduce the power cost in a greenhouse farm	- Predicting - Controlling	- Light sensor	- WSN	Not Available	1	1	1	3
Drakulić et al. [139]	2020	- An IoT-enabled remote monitoring and controlling system was designed to maintain optimal conditions while consuming low energy	- Monitoring - Controlling	- Temperature, light, water level, and CO2 sensor	- Wi-Fi	- Cloud computing	0	1	1	2
Rezvani et al. [140]	2020	- Incorporated a data fusion system for real-time monitoring of the microclimate parameter of	- Monitoring	- Vapor pressure, temperature, and humidity sensor	- LoRaWAN	- Cloud computing-Edge computing	1	1	1	3

(*continued on next page*)

Table 2 (*continued*)

IoT-based Application						Quality Evaluation				
Author	**Year**	**IoT-based Greenhouse Application**	**Application Domain**	**IoT Devices**	**Communication Technologies**	**Data Processing Services**	***QA1***	***QA2***	***QA3***	***Total Score***
		the greenhouse with tomato crop								
Shamshiri et al. [141]	2020	- Designed a customized wireless sensor for the evaluation of microclimate variables in two greenhouses	- Monitoring	- Weather, wind, temperature, and humidity	- Wi-Fi – 3G/4G/5G	- Cloud computing	1	1	1	3
Hernández et al. [142]	2022	- A scalable and practical IoT-enabled monitoring system has been designed with predictive capabilities for farming applications	- Monitoring - Predicting	- Temperature and humidity	LPWAN	- Cloud computing-AI	1	1	1	3
Tatas et al. [143]	2022	- Introduced a smart, low-cost controlling and monitoring approach base on IoT for hydroponics greenhouses	- Monitoring - Controlling	- Temperature and humidity	- WSN - Zigbee - GSM/GPRS	Not Available	1	1	1	3
Rabka et al. [144]	2022	- A solar-powered, low-cost, and low-energy consumption approach has been designed for remote monitoring of greenhouse farms	- Monitoring	- Soil moisture, CO2, light, temperature, humidity, and pressure sensor	- Wi-Fi – 4G/LTE	- Cloud computing	0	1	1	2
Sagheer et al. [145]	2020	- Created a multi-tier architecture based on the cloud and IoT for improving the greenhouse farming microclimate	- Controlling	- Temperature, PH, humidity, light, and gas sensor	- Wi-Fi	- Cloud computing	1	1	1	3
Castañeda et al. [146]	2020	- Designed a smart system for controlling anti-frost disaster irrigation for greenhouse farms	- Controlling	- Weather, wind speed, irrigation, and rain gauge sensor	- Wi-Fi	- AI	1	1	1	3

3.4.4. Predicting

Crop prediction models using IoT and ML determine plant growth through real-time observations. Kitpo et al. [132] designed an IoT-based system with a bot notification for predicting greenhouse tomato growth stages. Hence, solutions based on IoT and ML reduce greenhouse farmers' difficulties while increasing productivity by improving crop quality [149]. Also, predicting the occurrence of plant diseases is crucial for enhancing crop yield in greenhouse farms. Rodríguez et al. [72] presented a data monitoring and predicting system in precision farming in a rose greenhouse.

4. Challenges in greenhouse farms based on IoT

4.1. Technical challenges

4.1.1. Sensor diversity

Many types of sensors have diverse communication interfaces and incompatible protocols necessitating extensive software and hardware with the complexity of future expansion. The development and use of gateway middleware embedded in the core of IoT is still insufficient, with most of it still in the experimental phase.

4.1.2. Standardization of IoT technologies

In smart farming, addressing safety, security, and privacy is crucial. However, achieving this requires adherence to various standards. Data circulates among farmers, agriculturists, and technologists in smart farming with checks put in place at each stage. The main obstacle lies in determining which security measures should be employed to ensure data security and privacy. Therefore, standardization is critical in efficiently addressing these challenges [52].

4.1.3. Hardware and software costs

Researchers worldwide focus on reducing hardware and software costs in IoT implementations while maximizing system efficiency. Although the costs of IoT platforms have decreased significantly, top-quality sensors and actuators remain expensive [15]. Further reduction of costs is necessary, along with implementing an optimization model for minimizing service expenses.

4.1.4. Real-time monitoring

Greenhouse farms use millions of sensors and devices for real-time monitoring, control, tracking, and prediction. As a result, it is essential to create a streamlined network protocol to facilitate communication between servers and objects with minimal overhead. While numerous protocols have been developed for this purpose, many contribute to increased overhead during periods of heavy data traffic and elevate power requirements for the IoT architecture deployed in greenhouse farming [52].

4.1.5. Security and privacy

IoT is typically divided into three physical, network, and application layers. Although there is a great depth of research on individual layers, there is a relative lack of research and discourse on the entire architecture of IoT systems, which has led to issues such as unstable data transmission, challenges in data sharing, potential safety risks during transmission, as well as decreased accuracy and stability in positioning. All of which contribute to reduced timeliness of data transmission using IoT.

4.2. Resources management challenges

Higher energy expenditure in conventional greenhouses validates the necessity for practical energy solutions. Thermal heating requires 80 % of the energy consumed in conventional greenhouses, and non-based-Internet of Things adjustments performed throughout time, like replacing high-pressure sodium (HPS) bulbs with LED lighting, did not result in considerable power reductions [150]. According to Canakci et al. [151], the average power consumption was 10,459,688 MJ/ha, translating to 65,891.5–151,220.6$ annually. Due to the hefty price of artificial heating, smallholder farmers could not afford to invest in greenhouses. The energy restrictions validated the necessity for using Internet of Things technologies to improve energy efficiency. Based on IoT infrastructure, energy, water, and fertilizer preservation resulted in effective resource management via intelligent pesticide, fertilizer, and irrigation, leading to lower production costs [32].

4.2.1. Energy management

Smart sensors for power load structuring, smart sensors enabling renewable energy system optimization, and automated energy management are examples of emerging developments for optimal energy savings [152]. According to Yaci et al. [153], combining a crucial number of minimal-cost sensors and delivering steady energy to electronic devices is still one of the fundamental challenges for marketing IoT in smallholder and large-scale farms. Literature is scarce on the obvious benefits of the GSM network-based dual communication system that supplied users with real-time information for efficiently tracking, evaluating, and controlling energy flow [154]. Connecting wireless technologies with hardware such as sensors posed several challenges. Superior sensor performance comes at a cost in terms of power consumption [155]. The challenge was partially offset in Singh, Berkvens, and Weyn's [156] research by using the LoRa network, especially Low Power Wide Area Network (LPWAN) technology, integrated with new design methods for optimal wireless systems, MAC algorithms implementation, time synchronization, Machine Learning, and edge computing. Motlagh and Mohammadrezaei [152] observed that minimal-power communication protocols, including Bluetooth low energy (BLE), ZigBee, narrowband IoT (NB-IoT), LTE-M, LoRa, and Sigfox, might achieve optimal sensor performance. Deploying artificial lighting in greenhouse farms is critical because improved photosynthesis results from proper light source control. A parallel particle swarm technique was used for greater reductions in energy consumption to emphasize the energy-saving advantages connected with the proper positioning of LED bulbs for efficient photosynthesis [152]. As smart greenhouse farms need artificial illumination at night for efficient photosynthesis, the saving power from lighting has a cascading impact on greenhouse farming operations costs. Model Predictive Control methods like data-driven robust model predictive control (DDRMPC) were used to save even more energy for better temperature prediction and management. Instead, sequential quadratic programming and particle swarm algorithms [150] could provide automated temperature adjustment. In summary, using predictive model control in smart greenhouse farming can achieve near-zero energy expenditure [157].

4.2.2. Water management

It is unknown whether IoT technologies will address historical agricultural challenges. The need for effective approaches is justified, considering that pesticide overuse causes groundwater and soil toxicity, as well as human toxicity if tainted agricultural food is consumed [32]. According to Song et al. [158], pesticides impede the acetylcholinesterase (AChE) enzyme's cellular function, which regulates neurotransmitters like acetylcholine for CNS function. The exorbitant cost of clearing up tainted groundwater sources reinforces the need to reduce the risk of groundwater pollution. Most conventional pesticides are being demonstrated to contain endocrinology growth factors that affect endocrine system function [159]. The growing awareness of pesticides' long-term negative consequences has prompted the development of new systems, such as pest detection systems based on IoT [160] and smart pesticide systems based on robotics and IoT [161]. A major issue is that any proposed system has its benefits and drawbacks.

4.2.3. Communication service management

Effective communication service management is predicated on selecting the suitable communication protocol for long-distance and short-distance range M2M communication. Bluetooth Low Energy is one of the most popular short-range wireless communication protocols to transmit data over short distances- 0–30 m [154]. Some studies suggest that with BLE, the communication distance might be increased to 100 m [162] or over 200 m [153]. The inexpensive installation cost and ubiquitous availability of BLE across various categories of computing devices and Internet of Things infrastructure are significant benefits. Other significant advantages are minimal power consumption and fast data-rate rates of 125 kb/s – 2 Mb/s – 500 kb/s (long-range) [161]. Unlike Yaci et al. [153], Villa-Henriksen et al. [162] discovered that communication via Bluetooth in an IoT platform may achieve data transfer rates of up to 24 Mb/s, which is much greater than LoRaWAN's 0–50 Kb/s [162]. Besides variable data transfer rates, IoT systems have additional flaws, like a limited utility in end-to-end network communication because of a lack of technical awareness of its financial advantages. The phenomenon resulted in the strained use of technology [163]. The problem could have long-term consequences as Bluetooth and LoRaWAN connections have been deployed for a better connection with robots of agriculture, which automatically implement agricultural pesticides [161]. In some circumstances, Bluetooth was combined with IoT communication technologies like ZigBee and LAN to eliminate unneeded human involvement, enhance efficacy, and reduce contamination [164]. This was accomplished by incorporating humidity and temperature sensors inside smart greenhouses to improve productivity.

4.2.4. Construction materials

Since the materials of construction forecast cooling and heating requirements, the structural quality of construction materials considerably impacts resource management in greenhouse farms. Plastic, glass, and steel-reinforced concrete have traditionally been the preferred materials in agricultural construction [165]. However, corrosion risk and environmental degradation from rainfall, humidity, and sunlight remain substantial since typical structures are vulnerable to bacteria, acids, moisture, and other corrosion-causing causes in farms [155]. Incorporating nanomaterials like carbon nanotubes (CNTs), the Internet of Things, and graphene gives practical benefits compared to typical materials. According to laboratory-scale research, integrating 0.15 and 0.25 wt [166] of CNTs into concrete buildings increased flexural strength by 100 % compared to concrete structures without CNTs [167]. Graphene additions in concrete increased flexural and compressive rigidity by 80 % and 46 % [167]. The advancements make the material perfect for concrete constructions in flood-prone areas. Besides increased strength, technological advancements would make monitoring the effects of humidity and temperature on concrete structures easier by employing humidity and temperature sensors to monitor structural health. The Structural Health Monitoring (SHM) approach can be configured to transmit periodic updates related to the concrete structure's structural health based on clients' requirements. The simplicity of combining with external advancements, including smart devices, satellites, 4G/5G connection, cloud, or user applications, is another distinct benefit of IoT in SHM systems. Envira DS LOG, Nano-Envi MOTE, and Envira DS WEB are commercial IoT solutions for structural health monitoring [168].

5. Countries already applying IoT in greenhouse agriculture

The developed countries offer numerous new possibilities for farmers to address their challenges, particularly in greenhouse farming [33]. Garcia et al. [176] have developed many technical methods in farming worldwide. Table 3 summarizes IoT-enabled greenhouse farming efforts in various countries.

6. Future suggestions for using IoT in greenhouse farming

According to this review article of significant technologies, applications, and communication technologies, we will provide future research suggestions and critical advancements in these domains:

Table 3
IoT-based greenhouse farming efforts by some countries.

Country	Smart Greenhouse Farming Efforts
INDIA	- Farmers in India implement a controlled greenhouse farm to increase productivity by remotely accessing climatic conditions like soil moisture, temperature, humidity, and CO2 inside the greenhouse [169].
CHINA	- A wireless greenhouse farming system has been developed that is cost-effective and uses low power by autonomously controlling the greenhouse farming atmosphere [170]. - A miniature integrated multimodal sensor system in a greenhouse farm for monitoring pH, EC, and temperature [171].
ITALY	- They offered various energy-efficient greenhouse farming supplies, including producing energy through an environmentally friendly photovoltaic system [172].
RUSSIA	- Kulyasov et al. [173] designed a system that works with various agricultural items such as a smart field, greenhouse, and garden. This system allows various digital techniques to monitor and autonomously control atmospheric factors to increase production accurately [172].
KOREA	- Park et al. [174] expounded on critical aspects of greenhouse agriculture in Korea, including farm requirements, plant-growing methodologies, and pest control. The study identifies key hazards to greenhouse users as well as their level of satisfaction with greenhouse farming.
MALAYSIA	- Due to its equatorial location, Malaysia faced challenges cultivating sensitive crops such as strawberries. However, deploying IoT-based greenhouse farms makes it easy to cultivate plants of strawberry [175].

- A general architecture is required for all plants and crops, quality of service (QoS), implementation of explainable artificial intelligence (XAI) for crop growth monitoring, and pest control. XAI is critical for understanding and analyzing the reasons behind specific decisions [177]. XAI enables farmers to move away from traditional farming methods and better understand the factors influencing their outcomes. Machine learning (ML) algorithms also need much computer power and storage. As a result, lightweight AI and ML algorithms are required to build using novel automated strategies.
- Sensor development should focus on novel and creative sensitive materials, methods, technologies, and approaches with minimal cost and energy consumption. Aside from that, the deployment of sensors must be accelerated. There is a need to expedite the deployment of sensors. By widely introducing IoT sensors, it would be beneficial to establish a virtualized sensor system that allows farmers to remotely manage and monitor their greenhouse farms based on IoT technology.
- Getting large-scale and small-scale farmers to accept smart farming techniques in the greenhouse is the most difficult task. Furthermore, local farmers are apprehensive about using smart farming technologies based on IoT, citing cost, literacy, privacy, and security as important research gaps. Managing privacy and implementing transparent policies are vital to gaining farmers' trust. Devices with average computational power must provide farmers with cost-effective options.
- More research on greenhouse farming data and environmental parameters is required to use AI to model diseases for efficient plant growth. It is recommended that data analytics techniques must be developed to process massive amounts of greenhouse farming data at a faster rate.
- Leverage 5G communication technology and virtual reality to create a comprehensive network system integrating agriculture and farmers, enabling the digital twin of the entire production process and supporting intelligent decision-making, process monitoring, and multi-factor traceability.
- IoT in greenhouse farming has significantly increased cybersecurity incidents, including attacks, threats, and vulnerabilities. While intrusion detection systems (IDS) have been created to address these security issues by examining network traffic and identifying compromised devices, none offer tailored solutions for smart farming. Consequently, there is a need for further research into the development of machine learning-based IDS and specialized access control methods specifically designed for agricultural environments [33].

7. Conclusion

This survey presented the evolving technologies for IoT-based greenhouse agriculture. We presented an extensive discussion on patterns of IoT-based greenhouse farming. Additionally, we have discussed the components of an IoT-based greenhouse framework based on cloud/fog computing and AI, which serve as a backbone of IoT and assist farmers in increasing crop productivity. Also, this survey presented the IoT applications for smart greenhouse farming, including monitoring, controlling, tracking, and predicting applications. Furthermore, various IoT communication protocols, sensors, devices, and technologies are introduced. This article also presented resource management challenges in greenhouse farms, such as energy management, water management, communication service management, and structural materials. Also, the technical challenges existing in IoT-based greenhouse agriculture are analyzed. In addition, we considered the countries already using IoT in greenhouse farming. Lastly, future research suggestions in greenhouse farming based on IoT have been introduced. In conclusion, implementing IoT and associated technologies in greenhouse systems has the potential to usher in a new era of economic growth in agriculture, primarily due to its ability to provide precise measurements at any location and time, all while being cost-effective. Therefore, enhancing crop production, monitoring conditions of growth, such as humidity, temperature, and nutritional composition, and early detection of plant diseases through these technologies can provide a path to sustainability in agriculture.

Ethics statement

The authors declare that this work neither involves the use of human subjects nor the use of animal experiments.

Declaration of generative AI in scientific writing

The authors declare that they never used AI and AI-assisted technologies in the writing process of this work.

CRediT authorship contribution statement

Khalid M. Hosny: Conceptualization, Formal analysis, Supervision, Writing – review & editing, Methodology. **Walaa M. El-Hady:** Conceptualization, Methodology, Visualization, Writing – original draft, Software. **Farid M. Samy:** Resources, Validation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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