The Future Of Sustainable Agriculture: A Review Of IoT And Autonomous Control In Vertical Hydroponic Farming

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Abstract. *By 2050, the global population is expected to exceed 9.7 billion, increasing the demand for food production. Vertical hydroponic (VHF) systems, which enable hydroponically growing plants in space-constrained situations emerge as a promising solution to these difficulties. To address the limitations of traditional farming methods and the challenges faced in VHF, such as manual monitoring and inefficient resource utilization, this survey paper examines how IoT and ACS are integrated into VHF to enhance crop management. It discusses the advantages of this integration, including real-time monitoring, automation, and improved environmental control. Examples of IoT-ACS implementations in VHF, such as automated nutrient dosing systems and real-time root monitoring, are provided to illustrate the diverse applications of these technologies. This paper also presents the challenges such as connectivity issues and sensor calibration must be addressed for successful implementation. Finally, this article demonstrates how IoT and ACS have the potential to change agriculture and handle the growing demand for food production in a sustainable manner.*

Keywords

Autonomous control systems (ACS), Internet of Things (IoT), Vertical hydroponic (VHF).

1. Introduction

The global population is projected to reach 9.7 billion by 2050, peaking at almost 10.4 billion by the mid-2080s [1]. This massive population growth will greatly raise the demand for food production, especially in space-constrained urban areas, with an emphasis on sustainability and food security. Another concerning issue is that according to recent United Nations assessments, the world is currently off track to meet Sustainable Development Goal 2, Zero Hunger by 2030 as well as the global nutrition targets [2]. These issues highlight that the existing and traditional agricultural practices are unable to supply the food demand due to factors such as limitations of land, water, and other resources. One potential answer to this problem is to promote the concept of vertical cultivation, such as vertical hydroponic farming (VHF), which uses indoor farming systems within a controlled atmosphere where every single ecological component can be monitored and regulated [3].

VHF is a method of farming in which plants are grown in vertically stacked layers utilizing a soilless medium and nutrient-rich solution. This approach of farming allows the cultivation of plants in space-constrained areas including high-rise and indoor buildings [3]. Several other advantages of this approach over conventional farming include year-round consistency in production levels [4], smaller environmental footprint due to reduced transportation costs, pesticide, and fertilizer usage [5], and improved water usage [6]. However, the efficiency and productivity of these systems can be further improved by incorporating smart technologies such as Internet of Things (IoT) and autonomous control systems (ACS) into the vertical farming systems.

IoT refers to a network of physical objects or "things" embedded with sensors, software, and connectivity capabilities that enable them to collect and exchange data via the internet. IoT offers numerous applications across various domains, including agriculture, healthcare, transportation, manufacturing, smart cities, and energy management. In agriculture, IoT can be used to monitor soil moisture levels, track livestock, or optimize crop yields [7]. Conversely, ACS refers to the use of automation, artificial intelligence (AI), and robotics to manage and control numerous processes and operations without human intervention. ACS combines cutting-edge technologies such as AI, machine learning (ML), and robotics to enable autonomous decision-making, task completion, and environmental adaptation in systems and machines. In agriculture, ACS can automate certain farming tasks, such as irrigation and nutrient delivery, and plant disease detection and treatment.

The integration of IoT and ACS in VHF can provide numerous benefits, such as improved efficiency, production, and sustainability. Nonetheless, there are obstacles and constraints connected to the implementation of these systems. Thus, this paper aims to provide a comprehensive review of the role of IoT and ACS in vertical hydroponic farming. This paper will discuss the benefits and challenges of implementing these systems, as well as the prospects for further research in this area. Ultimately, this paper seeks to highlight the potential of IoT and ACS to revolutionize agriculture and address the growing demand for food production in a sustainable manner.

This review paper is organized as follows. Section 2. provides a background of VHF with a highlight on recent case studies. Section 3. discusses IoT implementation in VHF, while Section 4. focuses on ACS in VHF. Section 5. discusses the integration of IoT and ACS in VHF, with a thorough examination on the benefits and challenges of implementing these systems as well as their prospects. Finally, Section 6. concludes this review paper.

2. Vertical Hydroponic Farming (VHF)

The world currently requires more farmable lands to fulfill the huge food demands from the growing population, yet one-third arable land has been lost over the last four decades due to erosion and pollution [7]. Unfortunately, current industrial farming practices are degrading soil quality far quicker than nature can rebuild it. Furthermore, our planet is facing a significant strain on freshwater availability, with agriculture accounting for around 70% of water consumption due to unsustainable irrigation practices [8]. Other challenges to fulfill food demands include climate change, hazardous infectious diseases (such as the Covid-19 pandemic) and increasing urbanization. One of the solutions to overcome these challenges is through vertical farming.

The term "vertical farming" has several various definitions "depending on the size, density, amount of control, layout, building type, location, and purpose of use" [9]. In its most basic form, "vertical farming" can be characterized as the multilayered cultivation of plants to improve yield per surface area [9]. More specifically, vertical farming is a method of growing fruits, vegetables, and grains in vertically stacked layers using artificial lighting, controlled environmental conditions, and soilless growing media such as hydroponics or aeroponics. This farming strategy can boost crop output while consuming fewer resources and utilizing less ground surface. When vertical farming is paired with hydroponics, a farm of 100 square meters can produce the harvest equivalent to 1 acre of traditional farm while up to 95% less water and fertilizers and without the use of pesticides or herbicides [7, 10]. Additionally, Barbosa et al. [6] demonstrated that VHF of lettuces in Arizona reduced water consumption by 13 ± 2.7 times compared to conventional farming while increasing yield production by 11 ± 1.7 times.

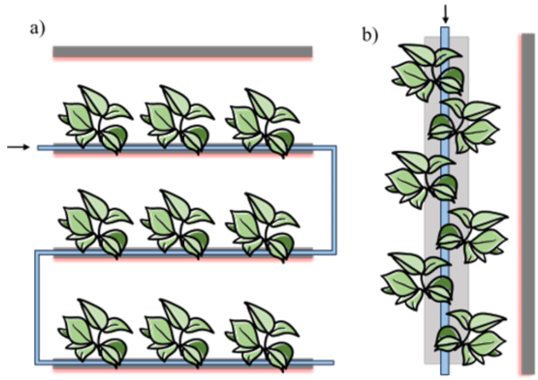

Fig. 1: Examples of VHF setups [5]; a) nutrient film technique (NFT); and b) deep irrigation system.

Fig. 1 shows the typical VHF setup, which can be categorized into nutrient film technique (NFT) and deep irrigation system. With NFT, light is supplied above each tray and water is pumped through the plant root channel. Nutrient water runs down the channel, into a reservoir, and back up to the top of the system. On the other hand, with deep irrigation system, the nutrient solution is dripped down the column. Water is drawn to the wicking material near the plant roots. Water that is not used by the plant flows through the channel and is recirculated back to the system.

Through VHF, crops can be grown in near optimal conditions using controlled environment agriculture (CEA). CEA, also used interchangeably with indoor farming, refers to the practice of replacing conventional features of traditional farming with artificial and controllable elements [11]. For example, LED lighting is often used to replace sunlight, while growth mediums such as water and coconut husks are used in place of soils. This soilless approach reduces the risk pest and weed invasion into the growth environment, while vertical racking system allows farmers to optimize their space and land usage [11]. Additionally, the controllable "sunlight" and climatic conditions ensure year-round farming and crop production that is unrestricted by seasons or environment.

Recent research in VHF varies from quantifying the energy consumption of VHF setups [12], feasibility of alternative growth mediums [13] and improving water quality and microbial life of VHF setups [9, 14], specific plant's yield potential in VHF [15–18], environmental, financial, and economic feasibility studies of VHF [19–21], and the effects of vertical farming on the environment [22, 23]. Table 1 summarizes recent VHF research in literature. Altogether, the literature indicates that VHF has tremendous potential to alleviate global food security concerns, improve crop yields, and reduce the environmental impact of agriculture. However, there are certain limitations, such as technical difficulty, costly initial capital expense, and energy consumption. More study is needed to optimize vertical farm design and operation, such as combining new technologies such as IoT and ACS.

3. The Internet of Things (IoT) in VHF

IoT is a network of interconnected devices that collect and exchange data to automate and optimize various processes. This technology is based on the combination of hardware, software, and communication protocols. More specifically, sensors incorporated in IoT devices collect data from the physical environment, such as temperature, humidity, motion, or location. This data is subsequently processed, analyzed, and sent to cloud-based platforms or local networks for storage, further analysis, and decision-making. In agriculture, IoT has the potential to revolutionize farming by allowing for real-time monitoring and control of the external environmental conditions, irrigation, and crop management. Fig. 2 shows the applications of IoT in farming, as presented by Ayaz et al. [7], in which the blue highlights emphasizing the applicability of IoT in VHF. This section will examine the existing literature on the application of IoT in VHF.

A study conducted by Chowdhury et al. (2020) [31] explored the integration of IoT in VHF testbed in Qatar. The researchers developed an automated IoT-based system that does not depend on the outdoor environment, while allowing remote monitoring and control of several parameters, including temperature, humidity, and nutrient levels. Fig. 3 shows the block diagram of the designed system. The study demonstrated that the designed system was able to improve the efficiency of the farming process by reducing water and energy. During peak summer, the system consumed 120.59 and 230.59 kWh, respectively, without and with air conditioning control, for a total system cost of 13.26 and 25.36 Qatari Riyal (QAR). This system was circulating roughly 104 k gallons of fertilizer solution weekly, however it only used 8-10 L of water. The proposed platform may be utilized to objectively optimize the indoor farming setup as well as automate some of the most labor-intensive maintenance tasks.

Similarly, Chand et al. [32] conducted a study of IoT-based VHF where the environmental parameters

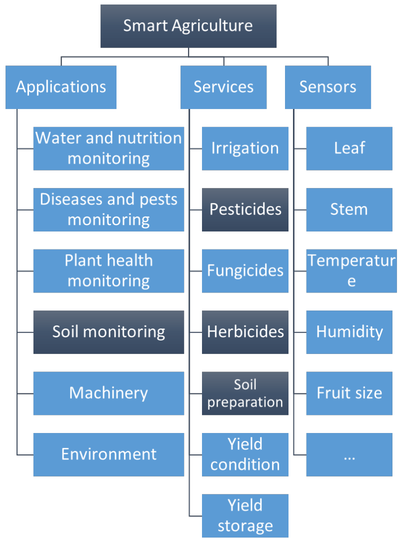

Fig. 2: IoT applications in smart agriculture [7], with blue highlights emphasizing VHF applicability.

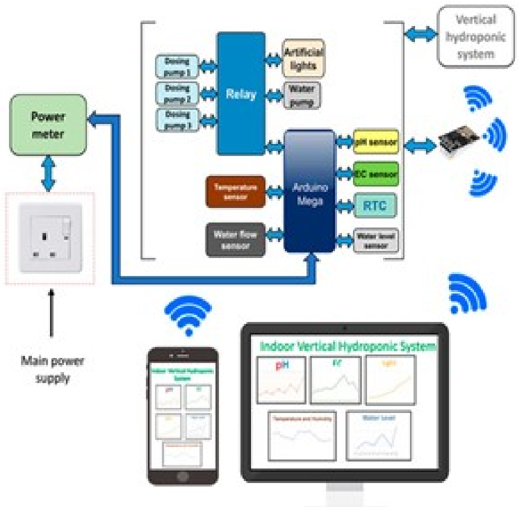

Fig. 3: Block diagram of the designed system by Chowdhury et al. [31].

Tab. 1: PV System parameters.

Author and Year	Focus	Description
Beacham et al. (2019) [25]	Categorization of vertical farming	The authors review the basic characteristics of vertical farming and emphasize how scientific examination of its potential is missing and will be needed to establish its practicality as a strategy to meaningfully aid world food production.
Cowan et al. (2022) [26]	Environmental sustainability of CEA systems (including VHF)	The authors outline existing information and gaps in knowledge about the environmental sustainability of CEA systems and examine whether these systems can support intense and fully sustainable agriculture on a global scale.
de Carbonnel et al. (2022) [27]	Understanding plant photobiology in VHF for RES incorporation	The authors of this review investigated how variable crop irradiation could accommodate the incorporation of renewable and fluctuating energy sources (such as wind) into vertical farming systems. The authors specifically examine the challenges of implementing renewable energy into vertical farming systems, as well as how light spectrum, intensity, and daylength can be altered to affect crop quality. The authors recommend that plant photobiology can be applied to increase energy efficiency in this ever-changing industry.
Baciu et al. (2023) [28]	Specific plant's feasibility/yield (mulberry)	The authors review the benefits of cultivating mulberry as well as providing an assessment on the suitability of vertical farming techniques to mulberry growth in a controlled setting, as well as its possibilities for a more sustainable and safer agricultural practice.
Asseng et al. (2020) [17]	Specific plant's feasibility/yield (wheat)	Wheat is arguably the most important food crop worldwide, with millions of hectares under cultivation. However, wheat yields in the field are typically low and they vary according to weather, soil, and crop management practices. In their study, the authors demonstrate that wheat yields cultivated in indoor vertical farms under optimal growth conditions would be "several hundred times higher than yields in the field" due to increased yields, additional harvests per year, and vertically stacked layers.
Moghimi and Asiabanpour (2023) [19]	Economic evaluation	The authors established a quantitative approach for assessing the economic viability of vertical farming systems in a competitive market context. The suggested framework highlights the key elements for evaluating vertical farming's economic and risk-aversion potential, and it employs a decision model to quantify the trade-off between the two alternative farming approaches. The model is used to assess the competitive economic promise of vertical farming in seven places in the United States with varying climate and economic conditions.
Yesil and Tatar (2020) [29]	Specific plant's feasibility (Barley fodder)	The authors reviewed and discussed the feasibility of cultivating barley fodder in a VHF setup. According to the review, the system's benefits, such as less water use (approximately 90%), no herbicides, pesticides, or fertilizer application compared to conventional production, would be more pronounced for barley fodder in vertical systems than for other conventional forage crop production systems.
Shahda and Megahed (2022) [20]	Environmental, economic, and social benefits of VHF in skyscrapers in post-pandemic era	The researchers examined how the COVID-19 epidemic affected skyscrapers and whether vertical farming could be used to lessen its effects. The study found that skyscraper-integrated vertical farming (SIVF) can create a closed ecosystem that preserves the environment by supporting food security, improving indoor environmental quality, enhancing psychological and physical health, saving energy, reducing greenhouse gas emissions and releasing oxygen, and supporting the local economy.
Wortman et al. (2016) [16]	Specific plant's feasibility/yield (Strawberries)	This study found the best strawberry cultivars and growing substrate and examined ways to replace synthetic fertilizer with organic nutrient sources in hydroponic strawberry production. Strawberry output was highest in perlite mixed with coco coir or vermiculite and fertilized with synthetic nutrients. Fertilizing with bio-based, liquid nutrients and vermicompost in soilless media lowered yield by 15%. Strawberry cultivar yield varied by year and place. Results help create best management methods for vertical, hydroponic, high tunnel strawberry production in the midwestern US, but more research is needed to understand nutrient dynamics and crop physiological response among tower levels.
Van Gerrewey et al. (2022) [9]	Vertical farming resilience (via microbial life introduction)	Plant growth-promoting rhizobacteria (PGPR) improves plant performance and resistance to biotic and abiotic stressors. In their study, the researchers give a brief history of vertical farming, explore its economic, environmental, social, and political implications, and explain progress in harnessing the rhizosphere microbiome in hydroponic production systems.
Yuan et al. [22]	Effects of VHF on environment (focusing on the natural ventilation in buildings)	The authors investigated how vertical farming affects ventilation performance, which is crucial for thermal comfort particularly in tropical and subtropical cities. According to the outcomes of the computational fluid dynamics model simulation, the block ratio of vegetables has a significant impact on the effectiveness of natural ventilation. By correctly changing the vegetable layout and species, the natural ventilation could also be enhanced while maintaining the same vegetable block ratio.
Dhawi (2023) [14]	VHF resilience (via microbial life introduction)	The authors discussed how plant growth-promoting microorganism (PGPM) processes can be used in hydroponics and vertical farming. For aquaponic and aeroponic systems, the study advises a synchronized PGPM treatment that includes a biostimulant extract in the hydroponic medium and pre-treating seeds or seedlings with a microbial solution.
Martin et al. (2019) [23]	VHF for sustainable food supply	This study evaluates residual material fluxes for vertical hydroponic farming in urban areas to enable a more circular, resilient, and sustainable urban food supply. Life cycle assessment is used to assess replacing conventional growing media and fertilizers with urban residual streams. The results suggest replacing conventional growing media appears to have significant environmental benefits.
Carotti et al. (2021) [30]	LED light needed for plant growth (lettuce)	The researchers investigated the influence of LEDs switching frequency (SF) on the productive and qualitative responses of lettuce, while considering resource efficiency. According to the findings, low SF boosted energy consumption efficiency by 40% when compared to high SF. However, high SF enhances lettuce leaves' antioxidant capacity. This study shows that various levels of SF can have a significant impact on crop nutritional characteristics as well as energy use efficiency

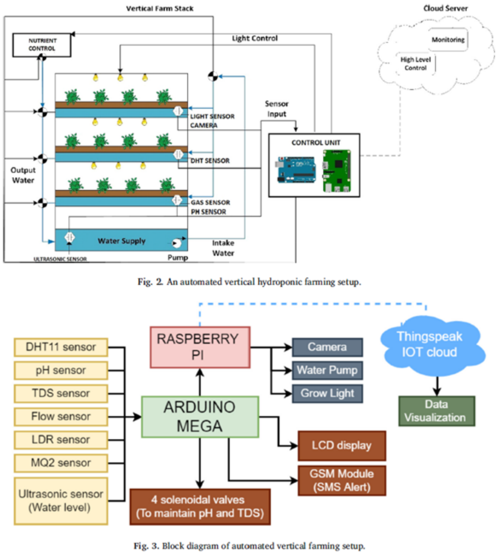

Fig. 4: IoT-based VHF with block diagram proposed by Kaur et al. [24].

of the setup, such as temperature and humidity, can be adjusted and monitored via a web server. The applications provided by the proposed system include water and nutrition monitoring, plant health monitoring, and environment monitoring. These applications are supported by sensors to detect pH, water level, temperature, humidity, total dissolved solids/electrical conductivity (TDS/EC), and light intensity (via light-dependent resistor (LDR) sensor). The data is then collected and transferred to the cloud for analysis. By incorporating IoT into the VHF setup, the authors demonstrated real-time monitoring and control of the VHF system.

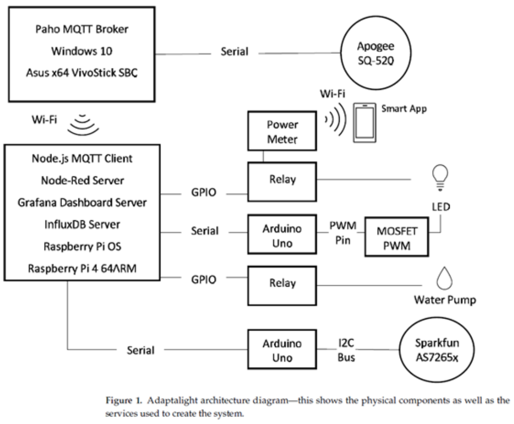

Fig. 5: Adaptalight architecture diagram [34].

While Kaur et al. [24] presented an IoT-based VHF setup to maintain an optimum plant growth parameters in the Punjab region. More specifically, the authors implemented IoT sensors to VHF setup as presented in Fig. 4. From the comparative analysis conducted between automated and manual setups, the study shows overall higher growth in the proposed automated setup, which can be attributed to the optimum growth environment. However, because of the usage of sensors and high electrical costs, the overall cost and energy consumption of an automated setup are substantially higher. Based on their findings, the authors proposed that an IoT-based setup be applied in industry or large-scale operations where cost might be neglected at the expense of skilled people required, time constraints, and human error.

Stevens et al. [33] designed an IoT spectroscopic nutrient monitoring system for VHF. The authors implemented an inexpensive IoT sensor (AS7265x) to effectively detect nitrogen concentration in nutrient solution for Micro Indoor Smart Hydroponics (MISH) system (small scale VHF), as opposed to the conventional methods of either measuring electrical conductivity (EC) or total dissolved solids (TDS) in the hydroponic solution. It should be noted that these conventional methods are incapable of distinguishing the concentrations of individual nutrients [33]. In two case studies of 40 L and 80 L MISH systems for growing lettuce over 30 days, the proposed system showed significant accuracy in monitoring nitrogen concentration changes when compared to the standard EC approach.

In another study, Stevens et al. [34] explored the potential of reducing the prohibitive cost of MISH system through harvesting ambient light. Commercially available Photosynthetic Active Radiation (PAR) meters measure the light spectrum required by plants, but they are costly. Thus, the authors presented Adaptalight, a MISH system built on commonly found IoT technology that harvests ambient light using an inexpensive AS7265x IoT sensor to measure PAR. Fig. 5 shows the architecture of the proposed system. Over the course of three months, a two-part experiment was carried out, with each phase lasting 21 days. The first phase assessed the IoT sensor's capacity to reliably measure PAR. Using the calibrated IoT sensor from phase one, phase two assessed the system's ability to gather ambient PAR light and provide appropriate yields. The results demonstrated that the proposed Adaptalight system was successful in conserving energy, gathering ambient PAR light, and providing yields with no significant changes from the control. Furthermore, the data suggests that the AS7265x sensor, when calibrated, is well suited to correctly measuring PAR light in MISH systems.

A summary of the discussed literature is presented in Table 2. Overall, the literature implies that IoT has the potential to significantly revolutionize agriculture by providing real-time monitoring and control of farming processes in VHF. IoT technology also enables innovative and cost-effective sensor applications as presented by [33,34], who demonstrated nutrient monitoring and ambient light harvesting for efficient energy consumption, respectively. According to the literature, IoT deployment in VHF can increase efficiency, sustainability, and productivity while reducing resource consumption. However, this technology alone is unable to monitor and control the intrinsic factors (e.g., plant health) of a VHF setup. Additionally, advanced features such as tasks automation are needed, which necessitate the integration of other technologies with IoT for a successful and efficient VHF implementation.

4. Autonomous Control Systems (ACS)

ACS refers to the concept of control systems that self-govern without external intervention over lengthy periods of time [35]. To accomplish this autonomy, ACS relies heavily on AI, ML, and robotics, as well as various other optimizing functions and feasibility programs. While the notion of ACS was considered a futuristic fiction around a century ago, with the advancement of new technologies and vast processing capacity, ACS is becoming a reality and increasingly prevalent in our current world. This is evident in innovations such as self-driving cars [36], robot vacuum cleaners that can navigate irregular spaces and objects to clean floors [37], autonomous high-rise window cleaning robots [38], and energy-saving smart windows that automatically tint to regulate light and heat in buildings [39]. In agriculture, the adoption of ACS has the potential to reduce labor costs, improve efficiency, and optimize resource usage [40]. This section will examine the existing literature on the use of ACS in VHF, with a particular emphasis on the implementation of AI and optimizing functions for VHF tasks automation.

One of the most significant parts of VHF is artificial lighting, which provides crops with an optimal amount of lighting and faster growing times. Although contemporary technology, such as LED lighting, consumes substantially less energy than systems from just 5 years ago, it is definitely not as efficient as using sunshine [40]. Additionally, some VHF systems require additional energy for tasks such as plant health monitoring, environment control (temperature and humidity), and other services and applications. The energy usage will grow exponentially as the size of the VHF system increases. Thus, there is several research dedicated to optimizing the energy efficiency of these VHF systems. For example, Avgoustaki and Xydis [41] focus on energy demand optimization of VHF based on partial equilibrium model. While Delorme and Santini [40] develop mathematical models and decision support tools to reduce the energy consumption of the automatic elevators servicing large-scale VHF structures.

ACS has also been implemented for quality inspection of VHF produces such as the study presented by Wongpatikaseree et al. [42] who explored the use of machine learning to assess the freshness of lettuce produced via hydroponic setups. While Kamala and Alex [43] implemented support vector machine (SVM) classifier in image processing to detect diseases in hydroponic apples. ML was also adopted by Kondaka et al. [44] in their design of a smart hydroponic system. More specifically, the researchers implemented random forest regression model in predicting the optimum EC/PPM of the hydroponic solution for plant growth based on the inputs of temperature, humidity, water temperature and number of days.

A study conducted by Rahadiyan et al. [45] focus on automated plant health inspection via non-destructive macronutrient identification and estimation in chili plants in a VHF setup by using computer vision technology. The study proposed a multi-layer perceptron (MLP) architecture, which is a feed forward artificial neural network (ANN), to identify and evaluate the conditions of the chili plants based on color, shape, and leaf texture. The proposed approach categorizes the health of the chili plants as healthy, potassium deficit, calcium deficit, magnesium deficit, or Sulphur deficit. The deployment of this technology will assist farmers in checking the condition of their plants, eliminating the need for tedious and manual inspection.

In the area of VHF nutrient solution, periodic readjustments of nutrient concentration in the hydroponic solution are required to continually offer a stable environment to plant roots because the interaction between plant and nutrient solution affects the rate of ions in the solution over time [46]. The traditional method involves repeating the process of giving a tiny amount of readymade concentrated nutrient solution while monitoring overall EC and pH of the tank. In order to automate the nutrient readjustments process, researchers in [46, 47] focus on the study of ion concentration of each chemical component in the nutrient solution. More specifically, Ban et al. [47] proposed a continuous network model based on the ordinary differential equation to describe the reactions in the solution, which is able to predict molar concentration of each chemical components and total dissolved solids with low error. While [46] developed a machine learning approach to adjust and remove interference in ion selective electrodes data for individual ions concentration in hydroponic solutions.

Table 3 summarizes the recent research on ACS in VHF, in which we highlight the focus area of the research, the method or model employed, as well as the task automation achieved.

Tab. 2: PV System parameters.

Author and Year	Description	Applications	Services	Sensors/Equipment	Measurements/Data Collected
Chand et al. (2022) [32]	Presented a study of IoT-based VHF where the environmental factors such as temperature and humidity of the setup can be controlled and monitored via a web server	- water and nutrition monitoring - plant health monitoring - environment monitoring	irrigation	- pH sensor - water level sensor - temperature and humidity sensor - TDS/EC meter - light-dependent resistor (LDR) sensor - Arduino Uno (connecting all sensors) - Wi-Fi Module	Temperature, humidity, pH, crop yield, plant health
Chowdhury et al. (2020) [31]	Designed an automated indoor VHF that does not depend on the outside climate and uses minimal human intervention. Tested in Qatar.	- water and nutrition monitoring - plant health monitoring - environment monitoring	irrigation	- artificial lights - Arduino Mega 2560 (for controlling other sensors) - Arduino Nano (for power measurements) - WiFi module ESP8266 - Submersible Water Pumps - Water flow sensor - water level sensor - pH sensor - EC sensor - Dosing pumps - Temperature and humidity sensor - 16 Channel relay - Real-time clock	pH, EC, temperature of the surroundings, light intensity, and water level
Kaur et al. (2023) [24]	Designed an IoT-enabled smart VHF system with a controlled environment for plant growth	- water and nutrition monitoring - plant health monitoring - environment monitoring		- artificial lights - Raspberry Pi - Camera - Water pump - GSM module for SMS alert - Water flow sensor - LDR - Temperature and humidity sensor - Ultrasonic sensor for water level - Toxic gas sensor - pH sensor - TDS sensor	Temperature and humidity, toxic gases (carbon dioxide concentration), light intensity, pH and TDS of nutrient solution, water flow in pipes, water level in tank
Stevens et al. (2023) [33]	Designed an inexpensive IoT spectroscopic nutrient monitoring system for VHF (detection of nitrogen concentration in hydroponics solution)	- Water and nutrient monitoring	- Yield condition	- SparkFun Triad Spectroscopy Sensor-AS7265x - Arduino Uno - Raspberry Pi 4 B (gateway for sensors) - Grow lights - Water pump - DFRobot analog EC sensor DFR0300 - DFRobot pH analog sensor V2 SEN0161-V2 - analog water-level sensor, and - DS1820 digital temperature sensor	pH, EC, temperature of the surroundings, spectrophotometric data, and water level
Stevens et al. (2022) [34]	Designed an inexpensive IoT-based VHF system for harvesting daylight	- Environment monitoring (light)	- Yield condition	- Power meter - Arduino Uno - Relay - MOSFET PWM - SparkFun A57265x	Channel spectral readings PAR light kwH

5. Integration of IoT and Autonomous Control Systems in Vertical Hydroponic Farming

As discussed in Section 3. , IoT has been utilized to monitor extrinsic factors and get relevant data from VHF setups; however, the difficulty with this strategy is that only the external factors are monitored. Through the introduction of ACS in VHF, tasks automation as well as the monitoring of intrinsic parameters for a successful cultivation of vertical farms are possible. This includes automated energy optimization of the VHF system based on the energy demand analysis, plant health monitoring via leaf and plant growth analysis, efficient nutrient management, as well as automated crop harvesting robotic arm. The integration of IoT and ACS in agriculture has the potential to transform farming even further by allowing real-time monitoring, automation, and control of environmental conditions, irrigation, efficient nutrient delivery, and crop management. This section will review the existing literature on the use of IoT and ACS in VHF, followed by a discussion on the future of VHF.

5.1. Examples of IoT-ACS Implementation in VHF

Researchers around the world are integrating IoT and ACS into VHF in various focus areas. For example, Gertphol et al. [51] deployed an IoT-based smart hydroponic lettuce farm for real-time monitoring and control. The environmental data collected from the IoT-based VHF setup was used to forecast lettuce yield via machine learning. Similarly, Samaranayake et al. [52] proposed a real-time VHF strawberry cultivation system that implements IoT, image processing and machine learning for remote monitoring, controlling of environmental factors and nutrition required for strawberry cultivation, and automated plant health inspection. While V. et al [53] focused on developing an automated irrigation system and plant growth prediction, and Musa et al. [54] implemented an IoT-based deep learning approach to automate plant disease diagnosis through image analysis of the plant leaf surface.

Arora et al. [55] proposed an automated IoT-based dosing system for nutrient supply and pH level screening in VHF setups, while Li et al. [56] introduced a self-adaptive IoT-based hydroponics care system. Kaur et al. [57] utilized SARIMA time series forecasting for Total Dissolved Solids (TDS) prediction in VHF, and De Los Santos et al. [58] developed a real-time lettuce root monitoring system. Vadivel et al. [59] implemented Hypaponics, an IoT and ML-based monitoring system, and Shrivastava et al. [60] integrated IoT sensors with big data analytics for continuous monitoring. Rathnayake et al. [61] enhanced VHF control with precise growth element management and customization for diverse plant species. These advancements underscore the global endeavor to optimize VHF efficiency and sustainability through IoT and ACS integration. Table 4 shows the examples of IoT-ACS implementation in VHF.

5.2. Challenges in the integration of IoT and ACS in VHF

The integration of IoT and ACS into VHF has a lot of advantages, including real-time monitoring, automation, and control of environmental conditions, as well as efficient irrigation and nutrient delivery. Through IoT sensors, VHF systems can collect data on crucial factors such as temperature, humidity, and nutrient levels, enabling ACS to adjust environmental parameters in real time to optimize plant growth. This level of precision ensures that crops receive the ideal conditions for their development, leading to higher yields and better quality produce compared to conventional farming methods.

Moreover, the incorporation of IoT and ACS technologies in VHF enhances overall crop management. By leveraging predictive analytics based on historical data, farmers can anticipate potential issues and proactively address them before they escalate, resulting in more resilient and sustainable farming practices.

Additionally, automation features streamline routine tasks such as irrigation scheduling and pest control, freeing up labor resources for more strategic activities. Overall, the integration of IoT and ACS into VHF not only revolutionizes farming practices but also holds promise for addressing key challenges in agriculture, such as food security and environmental sustainability, in the years to come.

However, there are several challenges that must be overcome for successful integration of these technologies into VHF. The challenges include connectivity and communication, sensor placement and calibration, data management and analysis, system scalability, energy efficiency, and security and privacy issues.

1) Connectivity and communication

To exchange data and commands, IoT devices and ACS require reliable and stable communication. The physical structure of VHF systems, where plants are stacked in numerous layers, might interfere with wireless signals, producing communication problems. Thus, it can be difficult to maintain strong and constant connec-

Tab. 3: PV System parameters.

Authors and Year	Description	Focus area	Method/Model	Task automation
Avgoustaki and Xydis (2021) [41]	Developed an energy demand optimization model of VHF based on partial equilibrium model. Energy consumption costs is reduced by employing electricity load shifting of LED lighting through the selection of the time of the day for darkness for plant growth and analysis on the energy market.	Energy optimization	Partial equilibrium model	LED lighting control
Delorme and Santini (2022) [40]	Developed mathematical models and decision support tools to lower the energy consumption of the automatic elevators servicing large-scale VHF structures	Energy optimization	Mixed-Integer Linear Programming and constraint programming model	Energy optimization for automated VHF
Rahadiyan et al. (2022) [45]	Developed a non-destructive macronutrient identification and estimation system in chili plants in a VHF setup by using computer vision technology	Macronutrient identification and estimation	MLP	Plant health inspection
Ban et al. (2019) [46]	Developed a machine learning approach to adjust and remove interference in ion selective electrodes data for individual ions concentration in hydroponic solutions.	Hydroponic nutrient solution	Quadratic regressions	Nutritional balance in hydroponic solutions
Lauguico et al. (2019) [48]	Designed a VHF crop-harvesting robotic arm using inverse kinematics	Design of robot for harvesting crops	Inverse kinematics	Harvesting crops
Wongpatikaseree et al. (2018) [42]	Explored machine learning methods for assessment if the freshness in hydroponic produce	Quality of produce (lettuce)	Decision tree, Naïve Bayes, MLP, deep neural network	Product quality inspection
Kamala and Alex (2021) [43]	Implemented machine learning image processing for detection of diseases in apples	Disease detection/Quality of produce (apples)	SVM	Product quality inspection
Kondaka et al. (2023) [44]	Proposed an automated VHF system that is controlled using machine learning analysis	Design of an automated VHF system	Random forest regression model	Control of VHF environment
Ban et al. (2019) [47]	Proposed a continuous network model of VHF nutrient solution system, which predicts the molar concentration of each chemical component in the solution accurately. Furthermore, the suggested model can compute the number of chemical compounds required to make a desired nutrient solution.	Hydroponic nutrient solution	Ordinary differential equation	Nutritional balance in hydroponic solutions
Aquino et al. (2022) [49]	Utilized computational intelligence and computer vision for the early detection of discoloration in lettuce leaves	Disease detection	Support vector machine (SVM)	Plant health inspection
Verma and Gawade (2021) [50]	Proposed a flexible framework for predicting and analyzing nutrients uptake for plant growth (tomato) in hydroponics system.	Hydroponic nutrient solution	Classical machine learning models	Nutritional balance in hydroponic solutions

Tab. 4: PV System parameters.

Authors and Year	Description	Focus area	Method/Model	Task automation
Gertphol et al. (2018) [51]	Deployed an IoT-based smart hydroponic lettuce farm to collect environmental data and control the farm's operation in real time. The large dataset from data collection was used to create regression models using machine learning techniques to forecast lettuce yield (target variables are total fresh weight, nitrate content, number of leaves, and leaf area)	Yield forecasting	Linear regressions, SVR, MLR, and ANN and the best ones were selected for each week prediction	Amount and intensity of light, humidity, temperature, weekly measurement of plant growth.
V et al. (2020) [53]	Proposed a smart irrigation system for VHF, which employed IoT for data collection and control, while machine learning is employed for plant growth prediction	Automated irrigation system and plant growth prediction	Random forest	pH, temperature, humidity, EC, water level
Musa et al. (2021) [54]	Implemented an IoT-based deep learning approach to automate plant disease diagnosis (through image analysis of the plant leaf surface)	Plant disease detection	Deep CNN	Image of leaf (captured via Raspberry Pi Camera module)
Samaranayake et al. (2022) [52]	Proposed a design for a closed environment with automatic monitoring and controlling of environmental factors and nutrition required for strawberry cultivation, with the capability of remote live monitoring and analysis of each plant using IoT, image processing, and machine learning.	Live monitoring, control, and analysis (strawberry plants)	Fuzzy logic and CNN	Image of plant (to identify growth stages of plant), air quality, temperature, humidity, and light intensity
Arora et al. (2021) [55]	Proposed an automated IoT-based dosing system that supplies nutrients and screens the pH level, water level, and supplement fixation in a VHF setup.	Automated nutrient delivery	Deep neural networks	Temperature, humidity, pH, nutrient, carbon dioxide level, light intensity)
Li et al. (2021) [56]	Introduced a self-adaptive IoT-based hydroponics care system that adapts its daily plant care plan by forecasting future growing environments and evaluating humans' daily routines	Maintaining and controlling plant growth conditions	multivariable linear regression	Light, water level, pH, EC/TDS, historical sensor data
Kaur et al. (2022) [57]	Presented a TDS prediction system for VHF using the seasonal autoregressive integrated moving average (SARIMA) time series forecasting model	Prediction and control of nutrient solution's concentration	SARIMA	TDS, pH
De Los Santos et al. (2022) [58]	Developed an automated real-time lettuce root monitoring system for detecting root rot and changing water temperature to avoid extreme heat that damages the root system	Disease detection/Plant health monitoring	Decision tree	Image of root, temperature
Vadivel et al. (2019) [59]	Developed Hypaponics, an IoT and ML-based monitoring system for vertical farming (included agriculture, hydroponics, aquaculture, and poultry in their setup)	Prediction of plant growth and health	Linear regression	Temperature and humidity, pH, soil moisture, water temperature
Shrivastava et al. (2023) [60]	Integrated IoT sensors with big data analytics to monitor crop's status, nutrition level, water level and plant's health continuously.	Automated irrigation system and plant growth monitoring	Big data analytics	Temperature, pH, EC, ultrasonic, moisture, water level and water flow
Rathnayake et al. (2023) [61]	Developed an indoor VHF with precise control over essential growth elements, customization options for different plant species, and independence from external environmental factors.	Prediction of plant growth and health	ANOVA	pH, total dissolved solids (TDS), temperature, and humidity sensors

tivity throughout the system. Additionally, other issues include the selection of suitable communication technology that provides the best coverage and reliability at a reasonable cost. For example, Tolentino et al. [62] explored implementing the LoRaWAN technology, which enables long-range and low-power data transmission over a wide area network, in a smart VHF setup. While Zhang and Zhang [63] proposed a data-driven control method for planting temperature that connects to the server via 5G module.

2) Sensor placement and calibration

A smart VHF setup is highly reliant on the capabilities of sensors for monitoring various parameters such as ambient and hydroponic solution temperature, humidity, pH levels, nutrient levels, and light system. Monitoring these parameters requires accurate sensor placement. In a VHF system, arranging sensors in each layer to capture representative data can be challenging. Additionally, the calibration of sensors may vary across different layers due to variations in environmental conditions, affecting the accuracy of measurements. An example of a sensor placement study in agriculture is presented by Khujamatov et al. [64]. More specifically, the researchers presented a simulation of 5G-based IoT sensor placement in an agricultural field to determine the current state of the soil. Although this study is focused on soil-based smart agriculture, the research can be expanded to sensor placement in VHF.

3) Data management and analysis

The integration of IoT devices creates a large volume of data. It can be difficult to manage and analyze this data, especially when working with various sensors and control systems. To draw valuable insights and make informed decisions, efficient data management strategies such as data storage, processing, and real-time analytics must be employed. This includes using edge computing [65] for minimized latencies and enhanced efficiency in smart VHF setups, and employing big data analytics to enhance acquiring, storing, and analyzing data from vertical farming activities [66].

4) System scalability

VHF systems frequently have numerous tiers or levels, and increasing production capacity may necessitate expanding the system or adding new layers. Integrating IoT and control systems into a scalable architecture that can handle system growth can be a difficult undertaking. It is difficult to ensure smooth integration of additional layers and devices while maintaining system stability and performance. In a study conducted by Meshram et al. [67], the researchers evaluated various wireless IoT network protocols for scaling micro VHF to macro setups. In a simulation, the researchers evaluated the packet drop, energy efficiency, and network latency by increasing the number of sensors and sinks for a given volume of a confined space.

5) Energy Efficiency

VHF is an energy intensive crop production system [68], especially with the integration of IoT devices and ACS. It is challenging to balance the energy requirements of the system while optimizing plant growth and maintaining cost-effectiveness. Implementing energy-efficient designs, utilizing renewable energy sources, and adopting smart scheduling algorithms can help address this challenge. Examples of investigation in energy efficiency of ACS-based VHF have been presented by [40, 41], which can be extended to VHF integrated with other advanced technologies. While [69] studied agro-photovoltaic system, a system that "promotes the co-location of crop production and electricity generation using photovoltaic technology".

6) Security and privacy

Another issue to be considered is the security and privacy of IoT devices and ACS. IoT devices are vulnerable to cyber-attacks. Thus, system security is crucial to preventing unauthorized access, data breaches, or control system manipulation. It is critical to safeguard sensitive data linked to crop growth, user information, and system operations is essential. To address these issues, robust security protocols, encryption, access control mechanisms, and regular system updates are required. Additionally, another issue that needs to be considered is the publishing of smart agriculture data to support the expansion of research, while maintaining data privacy and confidentiality. An example of data publishing research is presented by Song et al. [70], who proposed a Flexible Privacy-Preserving Data Publishing (FPDP) scheme that balances the data publishing aspects of smart agriculture and data privacy.

5.3. VHF Prospects

VHF provides exciting prospects for the future of agriculture. This agricultural practice offers the potential to increase food production with a smaller footprint compared to traditional farming methods. VHF enhances land efficiency by exploiting vertical space, allowing farmers to grow more crops in a smaller area. This scalability can aid in addressing the worldwide challenge of feeding a growing population, particularly in urban areas with limited land availability.

VHF also enables localized food production, bringing farmers closer to urban centers and shortening the distance between production and consumption. This results in fresher products with lower transportation costs and carbon emissions. VHF can reduce resource usage and environmental effect by using sustainable techniques like water and nutrient recycling. Furthermore, when compared to traditional soil-based agriculture, hydroponic systems used in VHF utilize substantially less water [71]. The closed-loop technology recirculates water, decreasing waste while also allowing precise control over water flow to plants, maximizing water efficiency.

As previously pointed out, VHF can leverage advancements in IoT and ACS to optimize crop cultivation. IoT sensors and control systems can monitor and adjust environmental factors, nutrient levels, and irrigation schedules automatically. AI algorithms can analyze data to optimize resource utilization, detect crop diseases, and enhance overall productivity. Additionally, the integration of VHF with technologies such as blockchain [72] may improve the overall VHF system. For example, blockchain technology can be used to provide a transparent and immutable record of each stage of the VHF supply chain, ensuring food safety and quality while promoting trust in the supply chain.

VHF systems also allow for the cultivation of a diverse range of crops, including uncommon and exotic species that would not be feasible in regular farming approaches. Furthermore, VHF enables the adjustment of environmental parameters to improve nutritional profiles, such as boosting nutrient density or enhancing flavor attributes, in order to meet consumer demand for healthier and tastier products.

These prospects demonstrate VHF's potential to change agriculture by providing sustainable, locally sourced food, lowering environmental impact, and enhancing agricultural output. VHF is positioned to play a significant role in the future of food production as technology, research, and adoption continue to progress.

6. Conclusion

The global population is projected to reach 9.7 billion by 2050, raising the demand for food production. Due to land, water, and resource constraints, traditional farming operations cannot meet the exponential food demand. VHF systems, which allow for the growing of plants hydroponically in space-constrained environments such as high-rise and inside structures, could be a potential answer to these challenges. Additionally, the efficiency and productivity of these systems can be further improved by incorporating smart technologies such as IoT and ACS. The integration of IoT and ACS in VHF can provide numerous benefits, such as improved efficiency, production, and sustainability. Nonetheless, there are obstacles and constraints connected with the implementation of these systems. Thus, this paper provided a comprehensive review of the role of IoT and ACS in VHF. We also discussed the benefits and challenges of implementing these systems. Ultimately, this paper highlighted the potential of IoT and ACS to revolutionize agriculture and address the growing demand for food production in a sustainable manner.

As VHF continues to evolve, future research directions are poised to address key challenges and unlock new opportunities in the field. One critical area of focus is scalability, where efforts will be directed towards developing VHF systems that can accommodate larger production volumes while maintaining efficiency and sustainability. This involves exploring innovative design strategies, such as vertical stacking and modular construction, to optimize space utilization and maximize yield per square meter. Additionally, sustainable practices will be prioritized to promote wider adoption of VHF technologies. Researchers will investigate methods to minimize energy consumption, reduce waste, and mitigate environmental impact, ensuring that VHF remains an environmentally responsible alternative to traditional farming methods.

Furthermore, the integration of other advanced technologies, such as blockchain, holds immense potential to revolutionize VHF operations. Blockchain technology can enhance transparency and traceability throughout the supply chain, enabling consumers to track the journey of their produce from farm to table. This not only fosters trust and confidence in VHF products but also provides valuable insights for quality control and regulatory compliance. Moreover, future research will focus on expanding the range of crops cultivated in VHF systems. By optimizing growing conditions and genetic traits, scientists aim to diversify the types of crops that can be successfully grown indoors, thus addressing global food security challenges and meeting the diverse dietary needs of consumers. Overall, these future directions underscore the ongoing innovation and potential for VHF to reshape the future of agriculture in a sustainable and impactful manner.

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Author Contributions

K.H.M.A developed the conceptualization, investigation, formal analysis, resources, original draft preparation, data curation and visualization. N.A.M.R contributed to the review and editing, supervision, and project administration. A.A contributed to the final manuscript and funding acquisition.

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