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ADVANCEMENTS IN IOT-ENABLED VERTICAL FARMING: ENHANCING FOOD SECURITY AND ENVIRONMENTAL SUSTAINABILITY – A REVIEW

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ABSTRACT

Vertical farming, when combined with Internet of Things (IoT) technologies, represents one of the most promising approaches to addressing the interconnected challenges of urbanization, climate change, food insecurity, and sustainable resource management, offering an agricultural model that is both technologically advanced and environmentally conscious. In essence, vertical farming refers to the cultivation of plants in vertically stacked layers, often housed in skyscrapers, warehouses, greenhouses, or shipping containers, where environmental conditions such as light, humidity, temperature, water, and nutrient supply are carefully controlled to optimize plant growth and yield. Unlike traditional soil-based agriculture, vertical farming predominantly relies on soilless techniques like hydroponics, aeroponics, and aquaponics, which allow plants to thrive in nutrient-rich water solutions or air-mist systems with minimal dependence on arable land. The integration of IoT into this model elevates the efficiency and precision of production by enabling continuous monitoring, automation, and data-driven decision making. IoT devices such as sensors, actuators, cameras, and drones are deployed to gather real-time data on crucial variables including soil moisture (where applicable), pH levels, electrical conductivity of nutrient solutions, ambient temperature, humidity, carbon dioxide concentration, and light intensity. This information is transmitted to centralized cloud platforms where it is analyzed using advanced algorithms and sometimes integrated with artificial intelligence and machine learning models to predict plant growth patterns, identify stress conditions, detect diseases at early stages, and recommend corrective actions. Automated systems, triggered by IoT feedback, can adjust irrigation schedules, control fertigation (the delivery of nutrients dissolved in water), regulate artificial lighting systems that mimic natural sunlight, and optimize HVAC (heating, ventilation, and air conditioning) systems to maintain ideal microclimates. Such automation minimizes human intervention, reduces labor costs, and ensures that crops are grown in consistent, predictable environments that are less vulnerable to the uncertainties of external weather and climate variability. Moreover, IoT-enabled vertical farms enhance resource efficiency by drastically reducing water usage through recirculating systems that recycle and reuse up to 95% of irrigation water, while precisely measured nutrient delivery minimizes wastage and runoff that often pollutes natural ecosystems in traditional farming. The controlled environment reduces or eliminates the need for chemical pesticides, thereby producing cleaner and safer crops with higher nutritional quality, while also reducing post-harvest losses since farms can be located closer to urban consumers, cutting down transportation time and maintaining freshness. The role of IoT extends beyond simple

monitoring, as predictive analytics powered by big data can anticipate crop yields, forecast resource needs, and even suggest planting schedules to match consumer demand, making the entire production cycle more market-responsive and less wasteful. Integration with blockchain technologies further ensures food traceability, giving consumers transparent information about where and how their food was produced, thereby building trust in urban agriculture supply chains

Keywords: Vertical farming, Food security, Sensors, Crop yield, Minimal resources utilization, Crop yield

Introduction

The rapid growth of urban populations and the decline of arable land, there is a need to improve the food security necessitate sustainable alternatives to conventional agriculture. In 2022, the FAO reported a concerning regression in achieving the second sustainable development goal when the number of undernourished individuals increased (FAO 2022b). This issue is especially pronounced in developing countries, whereas high-income nations are primarily constrained by their reliance on complex food supply chains, whereas the global population is expected to reach at least 9 billion by the year 2050, requiring up to 70% more food and a demanding food production system and the food chain to become fully sustainable King *et al.,* (2017). Ensuring sustainable nutrition and achieving food security have become global priorities, highlighted as core themes in the United Nations Sustainable Development Goals (UN, 2015). Even through a number of challenges we faced towards the global food security such as climate change, Disease and pathogens, growing populations and paradigm shift in consumers preference towards the food. Vertical farming is promising solution for agricultural food security by enabling the good yield by utilizing the available resources in efficiently and also climate resilient. As a novel plant production system, vertical farming (VF) enables year-round, high-quality fruit and vegetable cultivation. This localized approach is vital for feeding the growing populations of modern cities Sharathkumar *et al.,* (2020) However, challenges such as high energy demands, system optimization, and cost-effectiveness remain critical barriers to large-scale adoption but this approach reduces the 90% of water use and shortens the food supply chain and ensures the year around cultivation. VF faces challenges in simultaneously monitoring multiple growth indicators like temperature, nutrients insufficiency, humidity and light intensity can be addressed through modern technologies like IoT – based syatem. VF combined with IoT possible to develop a sustainable, resources efficient and climatic resilient food production system Rathor *et al.,* (2024) These approaches hold the capacity to reshape agriculture by boosting operational efficiency, reducing input wastage, and ensuring both improved productivity and environmental sustainability. This study examines the recent advancement in VF along with IoT technologies

Objectives

- To present the overview of IoT technologies and their role in vertical farming
- To assess how IoT integration enhance the resources efficiency, crop yield and operational sustainability.
- To identify the technical, economical, and infrastructural challenges limiting the IoT adaptation in vertical farming.
- To explore the future opportunities for IoT-enabled vertical farming.

Concepts and Evolution of Vertical Farming

Vertical farming is the practice of cultivating crops in vertically stacked layers within controlled environments such as warehouses, skyscrapers, or shipping containers. This method maximizes space utilization, optimizes resource use, and creates ideal growing conditions, enabling higher crop yields, reduced water consumption, and continuous year-round production along with minimal space utilization compared to conventional farming methods. Vertical farming can help to reduce the dependency on long supply chain and imports and also contribute global food security by enabling the production of fresh and nutritional food in urban areas Mishra *et al.,* (2023)

IoT Integration in Vertical Farming

IoT-enabled vertical farming was designed to get the data from the sensors and collected in as microcontroller and send it to IoT platform and it helps to store, analyse and preview the data to the user in private or public interface or through the mobile applications, For this required several parameters, including pH, EC, ambient temperature, and container water level, are maintained and adjusted by different sensors that are connected to the microcontroller, then the system work automatically and independently without the need for human intervention. These systems include the main power system, power meter sensing and control system, wifi module, online database and also in comprises with different sections nutrients container (to supply the required amount of nutrients to the system) which is the ideal container made up of plastic material to avoid the chemical reactions, Water pumps help to pump the sufficient water to the system continuously, Artificial lighting is crucial factor for plant photosynthesis and plant does not required the full amount of sunlight in the spectrum, it only takes in between the range of 400 to 700 nm (Photosynthetically active radiation), pH and EC are measured continuously. The suitable pH 5.0 to 7.5 high amount of pH in nutrient solution leads to high chance to toxic to plants thereby pH and EC sensors, water flow sensors, water level sensor were tested and calibrated and connected to microcontroller to maintain the pH, EC, water flow rate water level in the system Chowdhury *et al.,* (2020).

Fig. 1 IoT based hydroponic system (vertical farming)

Technical Challenges Faced in Vertical Farming

Vertical Farming (VF) is an agricultural technique involving large-scale food production in high-rise buildings that enables fast growth and planned production by controlling environmental conditions and nutrient solutions to crops based on hydroponics. VF produce more agricultural output when compare to other farming techniques with small land holding but these techniques face many practical application problems. In many countries like US, Singapore, UAE, China, Holland, South Korea, Japan, Kanada practicing this farming technique and produce the product in most effective with that feasibility for various climate and geological area (topography). In this technique there is no pressure of climate on the crop due to climate change because all the crops are grown in controlled climate condition. Kalantari *et al.,* (2017)

- Artificial light like LEDs is necessary for photosynthesis which is consider as the main sources of energy Germer *et al.,* (2011)
- In addition to adding brightness, lighting produces heat, which can interfere with air conditioning systems, especially in the summer, accurate control and monitoring of temperature are necessary to ensure the right humidity and ventilation for optimal indoor plant development, which raises energy expenses.
- A major technical challenge in vertical farming is meeting high water demand, pumping system and Efficient transport of large water volumes to upper floors is essential for irrigation and the system must also supply nutrients consistently, requiring standardized fluid provision across all levels. Kalantari *et al.,* (2017)

Advantage of VF

- Growing the plants inside that keeps surrounding air cool through the process of evapotranspiration, when the plant takes the water from the soil it transferred to its body and leaves and eventually released into the air which consequently reduce the room temperature and provide the air conditioning up to 20% and cut down the electricity by 23% Specht *et al.,* (2014)
- Vertical farming improves the psychological and spiritual health of peoples the effects seed the positive thinking, metal stability, lowering the stress and improve self-confidence Safikhani *et al.,* (2014).
- Rather than discharging wastewater into rivers, it can be repurposed for irrigation in vertical farms. In this system, gray or black water is treated and recycled, eliminating the need for drainage while ensuring safe reuse within the farm Thomaier *et al.,* (2015)
- As land becomes increasingly scarce in both urban and rural areas, vertical farming (VF) does not aim to acquire additional land. Instead, it focuses on utilizing existing unused spaces within cities.
- Vertical farming had more advantages over Traditional farming which include more efficiency, adaptability, more economical and environmental benefits Kalantari *et al.,* (2017)

Disadvantages of VI

- Limited crop varieties grown in vertical farming are not suitable for all crops
- High initial investment and potential challenge: natural pollination
- The system must be regularly operated and maintained
- Initial investments are high
- High consumption of power for artificial lightning, Mist pumping

Conclusion

A promising answer to many of the problems facing contemporary agriculture is vertical farming. It promotes increased crop yields, effective use of water and nutrients, and less dependence on land and climate conditions by making controlled-environment production possible. Its sustainability and resource efficiency are further improved by the incorporation of technology like automated systems, water recycling, and artificial lighting. Along with its positive effects on the environment, vertical farming also helps people's mental health, energy efficiency, and air quality. Vertical farming provides a useful, flexible, and environmentally friendly way to meet the rising need for food as urban areas continue to increase and land becomes scarce.

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