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Sustainable Optimization of Vegetable Production in Hydroculture Environments

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Abstract:

Rapid population growth, climate change and the loss of arable land are creating major challenges for global food security. Traditional soil-based farming is no longer sufficient to meet the food and nutritional needs of the growing populations. Hydroculture system, especially hydroponics, have emerged as sustainable alternatives that use water instead of soil to grow crops. These systems allow better control of growing conditions, efficient use of water and nutrients and higher crop yields. Recent development in Agriculture such as the Internet of things (IoT), artificial intelligence (AI), Machine learning (ML) and deep learning (DL). have further improved hydroculture systems. These technologies enable real-time monitoring, automated nutrient management and better decision making. This review paper discusses recent advancement in hydroculture technologies for vegetable production, focusing on system type, nutrient optimization, sensor-based automation and AI-based control method. The use of intelligent nutrient dosing system nd data driven models is emphasized as an effective approach to increase productivity, improve suitability and enhance crop quality while reducing resource waste.

Keywords: Hydroponics, Hydroculture, vegetable production, IoT, Artificial intelligence, Biostimulants.

Introduction:

The global population is growing rapidly and is expected to reach about 9.6 billion by 2050.At the same time, urbanization and industrial development are reducing the amount of land available for framing (Rahmann *et al.,* 2019). These changes are placing increasing pressure on agricultural system to produce enough healthy and nutritious food in sustainable way (Lindgren *et al.,* 2018). Food security is not only about having enough food, but also about ensuring access to foods that provide the nutrient needed for healthy growth and development (Walls *et al.,* 2019). Although agriculture productivity has improved, malnutrition and micronutrient deficiencies are still serious global problems,escipecially among children under five years of age (Wakeel *et al.,* 2018). Condition such as anaemia and vitamin A deficiency to affect millions of people worldwide. This situation highlight the need for new farming approaches that can increase both crop yield and nutritional quality (Khoshgoftarmanesh *et al.,* 2010).

To address these challenges, agriculture has entered a new phase known as agriculture 4.0.this approach uses modern technologies such as automation, robotics, artificial intelligence and digital management system to improve food production(Araújo *et al.,* 2021). One important development is soilless cultivation, which allow plants to grow without soil(Balliu *et al.,* 2021). These system provide better control over plant nutrition and growing condition while reducing dependence on traditional farmland (Singh & Singh, 2017).

Overview of Hydroponics systems:

Hydroculture is a method of growing plants with little or no soil, where nutrient is supplied directly through water or mist. There are three main types of hydroculture system: Hydroponics, aeroponics and aquaponics(Mehdizadeh & Moghaddam, 2023). Hydroponics is the most commonly used system because it is simple to operate, efficient and easy to expand(Rajaseger *et al.,* 2023).

In hydroponics system, plant root grow in a nutrient rich water solution, allowing plants to absorb essential nutrient directly. Aeroponics supplies nutrient as a fine mist to plants roots that suspended in air, which increase oxygen availability and support faster growth(Kirmani *et al.,* 2025).Aquaponics combines fish farming with hydroponics by using nutrient-rich water fish tanks to feed plants (Delaide *et al.,* 2017).

Several hydroponics techniques are widely used, including the Nutrient Film Technique (NFT),Deep Water culture (DWC),wick system and drip irrigation system(Gillani *et al.,* 2023).NFT is especially popular for growing leafy vegetable because it uses water and nutrients efficiently and works well in vertical farming setups(Carrasco *et al.,* 2024). These hydroculture system are for urban areas, rooftop and small spaces where traditional soil-based farming if difficult (Caputo, 2022).

Benefits of Hydroculture for Vegetable Production:

Hydroculture system offers numerous advantages over conventional agriculture.one of the most significant benefits is the efficient use of water and nutrients(Pomoni *et al.,* 2023). Hydroponics can reduce water consumption by up to 90% compared to soil- based cultivation making it ideal for regions facing water scarcity (Hamdaoui *et al.,* 2025).

Additionally, hydroculture allows for faster plant growth and higher yield due to continuous nutrient availability and optimized environmental condition(Rajaseger *et al.,* 2023). The controlled environment minimizes pest infestation and soil-borne disease, reducing the need for chemical pesticides(Panth *et al.,* 2020).

Studies have also shown that soilless system can sufficiently reduce heavy metal accumulation in crop, enhancing food safety and quality(Sathyanarayana *et al.,* 2021).Vertical farming integration further improves space utilization, enhancing high density production in urban settings (Fei *et al.,* 2025). This contributes to shorter supply chains, reduced transportation costs and lower carbon emission aligning hydroculture with sustainability goals (Rowan, 2023).

Role of IoT in Hydroculture Automation:

The efficiency of hydroculture system depends heavily on the precise monitoring and control of environmental parameters such as Ph, electrical conductivity(EC), Temperature, humidity, dissolved oxygen and total dissolved solids (Nagothu *et al.,* 2024). IoT-based sensor networks play a crucial role in enabling real-time data collection and remote system management.

Smart sensor connected to microcontrollers and clouded platforms allow growers to monitor system performance via smartphone or computers(Thilakarathne *et al.,* 2023). Automated actuators can adjust nutrient dosing, water flow, lighting and temperature based on sensor feedback, reducing labor requirements and human error(Kaya, 2025).

However, sensor accuracy remains a challenge, particularly due to ionic interference in nutrient solution. Plants absorb nutrient at varying rates, leading to imbalance that can distort sensor readings(Ameer *et al.,* 2024).Addressing these in accuracies is essential for maintain optimal conditions and preventing deficiencies or toxicities(McBurney *et al.,* 2021).

Artificial Intelligence for Nutrient Optimization:

Artificial intelligence has emerged as a powerful tool for enhancing hydroculture system performance(Diaz-Delgado *et al.,* 2025). Machine learning and deep learning algorithms can analyze large datasets generated by IoT sensor to identify patterns, predict plant growth and optimize nutrient dosing strategies(Islam *et al.,* 2023).

ML models have demonstrated high accuracy in estimating macronutrient concentration particularly nitrogen(N), phosphorus(P), and Potassium (K) even in complex system such as aquaponics(Dhal *et al.,* 2022).these models can compensate for sensor noise and ionic interference by recalibrating data and predicting nutrient uptake trends(Wang *et al.,* 2024).

Deep learning approaches, including neural networks have shown promise in optimizing lighting schedules, forecasting yield and detecting early signs of plant stressor disease. By Enabling adaptive data-driven decision-making, AI significantly improves resource efficiency while maintain or enhancing crop quality(Ajith *et al.,* 2025).

Intelligent Dosing Devices and Sustainability:

Intelligent nutrient dosing devices integrate sensor data with AI algorithms to deliver precise nutrient concentration tailored to specific crop requirements and growth stages(Sharma & Shivandu, 2024). This targeted approach minimizes nutrient waste, reduces operational costs and prevents environment contamination (Szogi *et al.,* 2015).

The combination of intelligent dosing IoT automation and AI-driven analytics contributes to the long term sustainability of Hydroculture system(Roy & Kumari, 2025). Improved efficiency not only enhances productivity but also supports circular economy principle by optimizing resource use and reducing inputs(Elroi *et al.,* 2023).

Future Perspectives and Challenges:

Despite its advantages widespread adoption of hydroculture faces challenges such as high initial investment costs technical complexity and the need for skilled operators(Kishore *et al.,* 2021). Future research should focus on developing low cost sensor user-friendly control system and robust AI models adapted to diverse crops and environment (Dhanaraj *et al.,* 2025).

Further integration of renewable energy sources and Biostimulants may also enhance system resilience and sustainability. As technology continues to advance hydroculture system are expected to play critical role in ensuring global food security(Mešić *et al.,* 2024).

Hydroculture system represents a transformative approach to vegetable production addressing key challenges related to land scarcity, water use and food quality(Diaz-Delgado *et al.,* 2025). The integration of IoT ,artificial intelligence and intelligent nutrient dosing has significantly improved system efficiency, productivity and sustainability(Sharma & Shivandu, 2024).

This review highlights the potential of data-driven hydroculture management as a viable solution for future food production particularly in urban and resource limited environments(Lakhiar *et al.,* 2025). Continued research and technologies innovation will be essential to maximize the benefits of hydroculture and support global nutritional needs (Glencross *et al.,* 2023).

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