# SMART HYDROPONICS: ADVANCING TOWARDS FUTURISTIC SUSTAINABLE AGRICULTURE

**Abstract**

Hydroponics has witnessed significant advancements over the past few years, with ongoing research and technological innovations leading to increased crop yield, improved resource efficiency, and enhanced automation. Advanced monitoring and control systems, utilizing Internet of Things (IoT) and artificial intelligence (AI), allow for precise nutrient delivery, optimal lighting, and real-time data analysis, optimizing plant growth. Furthermore, vertical farming and rooftop hydroponics have gained traction, enabling the utilization of urban spaces efficiently and reducing transportation-related carbon emissions. Hydroponics, a revolutionary soilless farming technique, has emerged as a promising solution to address global food security and environmental challenges. This abstract explores the future trends of hydroponics by analysing recent advancements, identifying potential challenges, and highlighting sustainable solutions.

**Keywords:** hydroponics; vertical farming; genetic diversity; Internet of Things (IoT); artificial intelligence; urban food security

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## I. INTRODUCTION

Apart from its productivity, hydroponic cultivation stands out as one of the most resource-efficient methods of crop production in the evolving landscape of agriculture. It finds extensive application in both developed and developing nations for food production. Over time, the cost of hydroponic farming diminishes since it doesn't demand extensive land, a large workforce, or sophisticated agricultural technologies for monitoring crop performance. Given its capacity to efficiently utilize limited resources such as time and space, hydroponic agriculture holds significant potential for mitigating the challenges faced by our agricultural system. [1].

A significant benefit of hydroponic farming lies in its capability to cultivate crops under nearly perfect conditions, employing controlled environment agriculture (CEA) technologies. Crops grown hydroponically and indoors can thrive irrespective of location, season, weather, land availability, or soil quality. [2]

Hydroponic farming shows great promise in mitigating the challenges facing our agricultural system. A key advantage of hydroponics lies in its ability to cultivate crops under optimal conditions through controlled environment agriculture (CEA) technologies. Regardless of global location, season, or environmental factors, hydroponic farming enables year-round crop production indoors, without dependence on climate, available farmland, or soil quality. In regions grappling with severe droughts and poor soil conditions, like sub-Saharan Africa where access to leafy green vegetables is often limited, hydroponics has the potential to provide fresh, locally-sourced food options.

**Table 1: Difference between Hydroponics and Conventional Farming**

| Hydroponics | Conventional Farming |
|---|---|
| Higher yield | Less yield |
| Less space | More space |
| Less water | Demands substantial irrigation water |
| Excellent utilization of nutrients | Lower nutrient utilization efficiency |
| Environmentally friendly agriculture | Not sustainable |
| Not dependent on seasons | Not seasonally agonistic |
| Resistant to climate variations | Venerable |

## II. HYDROPONICS SYSTEM TYPES

There are several different types of hydroponics systems available based on how simple they are to put up; seven of them are frequently used commercially. These are the systems:

1. **Wick System:** Wick systems represent the simplest form of hydroponic systems, as they operate without the need for aerators, pumps, or electrical power. In this setup, plants are cultivated directly on absorbent materials such as perlite or vermiculite. Prior to submersion in the nutrient solution, the plants are enveloped by nylon wicks. This method is particularly suitable for cultivating small herbs and plants with lower water requirements.

2. **Deep Water Culture:** A straightforward hydroponic method called a "deep water culture system" submerges the plant right into the nutrient solution. This method pumps oxygen into the nutritive medium using a diffuser or air stone. The standout advantage of this method is that it ensures that plant roots have direct access to the nutrient medium, making nutrient absorption by plants straightforward and stimulating rapid growth. This system is suitable irrespective of the facility's scale.

3. **Nutrient Film Technology:** The nutrients are supplied at the base of the crop using this system, which is used to grow high value crops like lettuce. The nutrients are circulated through tubes arranged side by side in rows and connected to a central reservoir tank of nutrient solutions. To increase the effectiveness of resource usage in this system, the slope, length, and flow rates are set appropriately [3].

4. **Flood and Drain (Ebb and Flow):** In this system, electricity and water pumps with timers are needed to circulate nutrient solution. Plants are grown in beds made of growth mediums like rock wool or perlite, and timers and monitors are used to prevent the solution from overflowing. The water automatically drains out of the bed and is recirculated back through the pump when the optimal nutrient solution is circulated. This method is effective for both root and leafy vegetables.

5. **Drip System:** Drip systems offer versatility by allowing adjustments to their configuration based on the specific crops being cultivated. Nutrient solutions are delivered to the plant's root system through the use of pumps and small tubes. Drip emitters are positioned at the extremities of these tubes to regulate the quantity of solution dispensed, with flow rates adaptable to the plant's requirements. Any type of crop can be cultivated in this system because it is flexible enough to be changed according to the plants.

6. **Dutch Bucket System:** This method is well-suited for cultivating vines and larger plants because they are placed in buckets connected to tubes or drip emitters, which deliver the nutrient solution directly in droplets at the plant's base. Normally, 2-3 plants are arranged in rows within a single bucket that is equipped with these delivery tubes, making it particularly ideal for growing fruits and vegetables.

7. **Vertical Hydroponics System:** When plants are grown in vertical stacks or towers, it becomes possible to arrange numerous plants within a single structure, significantly reducing the space requirements. All these plants receive their nutrients through a unified system of delivery tubes. Cultivating plants within greenhouse structures is highly efficient, as it reduces land usage by 99 percent and conserves up to 90 percent of irrigation water. Additionally, because the crops are grown in controlled environments, the risk of pest and disease infestations is minimal.

## III. MANAGEMENT OF NUTRIENTS

1. **Essential Nutrients:** Plants require 17 essential nutrients to properly function, crucial for their growth and development. Take magnesium, for example; it plays a vital role in chlorophyll, a pigment responsible for absorbing the light energy needed in

photosynthesis. Most plants appear green because they reflect green wavelengths, and at the heart of the chlorophyll molecule lies magnesium.

These essential nutrients fall into two main categories: macronutrients and micronutrients, both playing pivotal roles in plant growth. Macronutrients encompass calcium, magnesium, phosphorus, potassium, sulfur, oxygen, and nitrogen. Micronutrients, on the other hand, include iron, manganese, zinc, boron, molybdenum, chlorine, copper, and nickel. The distinction between macro- and micronutrients depends on the quantity required by plants; more of the former are needed compared to the latter [4].

While carbon, hydrogen, and oxygen are sourced from air and water, hydroponics systems acquire the remaining nutrients from the soil, nutrient solutions, or aggregate media.

2. **pH:** When discussing plant nutrition, it's essential to consider pH. In hydroponics, our primary focus is on the pH of the water utilized to create nutrient solutions and to water the plants. pH, concerning nutrient availability for plants, indicates the level of acidity or hydrogen ion concentration. It is measured on a scale ranging from 0 (most acidic) to 14 (most alkaline), with 7 representing neutrality. This scale operates logarithmically, meaning that each unit change signifies a tenfold difference. For instance, a pH of 7 is 100 times more alkaline than 5 and ten times more alkaline than 6.

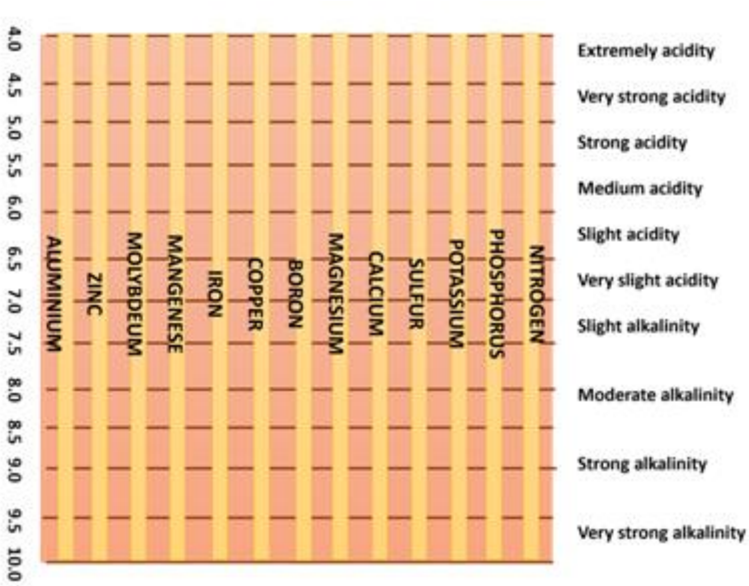


**Figure 1:** The Chart illustrates how pH levels relate to the Accessibility of Nutrients.

3. **Conduction of Electricity:** The term "EC" stands for "Electrical Conductivity," and it is used in hydroponics to assess the density of nutrients in water. While examining your water's pH level informs you of the balance of nutrients, EC provides information on the quantity of nutrients present.

Due to the absence of minerals, pure water has no electrical conductivity. Water can conduct electricity once minerals (i.e., in the form of liquid nutrition) have been added to it because of the dissolved salts. By measuring electrical conductivity (EC), which increases with salt concentration, you may determine how much nutrition is present in the water. Milli Siemens per centimeter (mS/cm) is a unit of measurement for the EC level.

It is essential to maintain the proper EC level for healthy plant growth because both an inadequate and excessive supply of nutrients can be harmful to plants. Inadequate nutrient availability can result in stunted growth and low yields, whereas an excess of nutrients can poison plants and harm their roots.

4. **Maintenance:** We'll start by talking about pH and EC readings. You should keep an eye on your nutrient solution more regularly when your system is still quite new. Test your nutrient solution regularly or more frequently in the beginning. As your system matures, you'll develop a better sense of it, allowing you to decrease the frequency of testing. Eventually, you can reduce your testing to just once every few days. The only exception to this is when you introduce additional nutrient solution to your reservoir; in such cases, you must test pH and EC levels each time to maintain consistent levels. Smaller hydroponic systems require more frequent testing because fluctuations in EC and pH are more noticeable with nutrient additions and water evaporation. There are various options for conducting pH and EC tests, including electronic meters, test strips, and drop test kits.

   In your record log, create separate columns to document each pH and EC reading, along with the corresponding date of measurement. When you reach a stable level in your system, you should observe little volatility. Each time you test TDS, temperature, or humidity, follow the same steps. Again, they should be pretty stable; if there is a substantial fluctuation in a reading, there may be a problem with your hydroponic system or fertilizer reservoir.

   Unless you alter your lighting schedule, the photoperiod data you log will remain constant. Your plants' photoperiod will alter in accordance with their stage of development so you can provide the right amount of lighting at each step.

## IV. FUTURE OF HYDROPONICS

1. **Potential of Vertical Farming and Controlled Environment Agriculture:** The concept of vertical farming was introduced as a means to maximize agricultural space by constructing upwards. Essentially, this approach involves erecting multi-story high-rise buildings on the same land plot, effectively expanding the usable area for crop cultivation. One approach involves using a single tall greenhouse structure with multiple vertical crop racks, which is an extension of hydroponic farming techniques utilized in traditional greenhouses. This method addresses soil-related challenges, such as the need for fertilizers, pesticides, and herbicides. By being closer to consumers, it can reduce transportation costs, enable year-round production aligned with demand, and optimize plant growth conditions by adjusting factors like temperature, humidity, and lighting.

   Compared to outdoor farming, controlled environment indoor farming in such facilities uses significantly less water due to reduced evaporation and efficient gray water recycling. As a result, widespread adoption is expected to commence in smaller, highly urbanized nations like Israel, Japan, and the Netherlands, as well as in arid and drought-prone regions, including parts of the Middle East and Africa. Vertical farming is particularly appealing in regions like China, which have high demand for Controlled Growth Environment (CGG) food due to severe pollution and soil depletion [5].

Vertical farming offers numerous benefits that may be enticing to policymakers, including year-round crop production, significantly increased yields (often sixfold or more depending on the crop), resilience against droughts, floods, and pests, efficient water recycling, ecosystem restoration, reduced pathogen risks, energy generation through methane production from compost, reduced reliance on fossil fuels (no need for tractors, farm machinery, or long-distance shipping), and the creation of new job opportunities. Additionally, the closed environment concept may find applicability in space exploration for potential use in other planetary habitats.

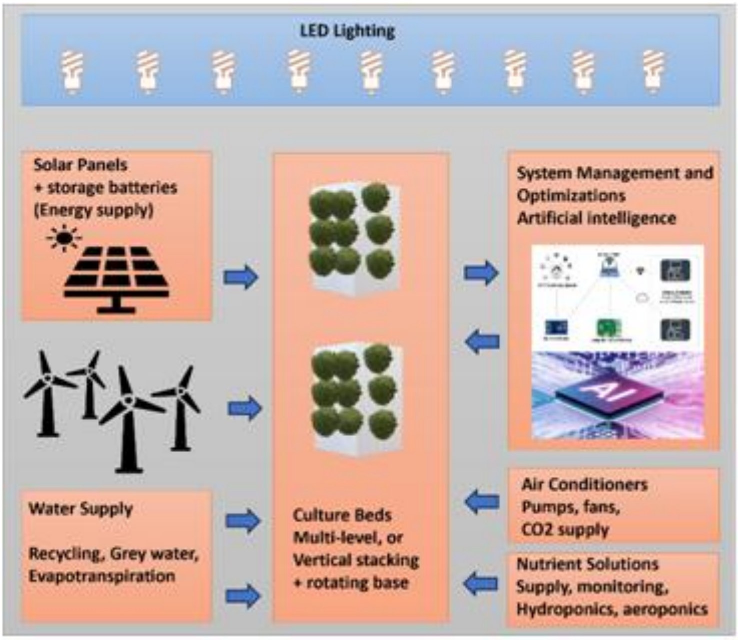


**Figure 2:** Elements within a vertical farm and how they work together.

2. **Integration of AI and Machine Learning:** The utilization of AI (Artificial Intelligence) and machine learning has brought about a complete transformation in the way crops are cultivated and managed in hydroponics. Hydroponic systems may be automated, tracked, and controlled with extreme precision using AI and machine learning algorithms, which boosts production and sustainability.

The creation of intelligent sensors and monitoring systems is one of the main uses of AI and machine learning in hydroponics. The sensors track a number of variables, including temperature, humidity, light intensity, pH levels, and nutrient concentrations. Real-time data processing by AI algorithms enables producers to make well-informed judgments and take the appropriate steps to improve plant development circumstances.

Predictive analytics for hydroponics heavily rely on machine learning methods. Machine learning models can produce precise predictions and suggestions by examining previous data on crop growth, environmental factors, and nutrient levels. This knowledge aids growers in making the best decisions possible about things like nutrient dosing, irrigation schedules, and lighting conditions, maximizing crop yields and reducing resource waste.

Remote hydroponic setup monitoring and control are also made possible by AI-powered devices. On their mobile devices, growers may access real-time data and alarms, enabling them to monitor and change system parameters even while they are not on the field. By spotting trends and anomalies in the data, machine learning algorithms can provide early warnings for potential problems like nutrient deficits, illnesses, or pests. By allowing for prompt interventions, this proactive strategy lowers crop losses and boosts the effectiveness of the entire system. [6]

Furthermore, AI and machine learning have aided in the creation of complex agricultural growth models. To simulate and forecast crop behavior, these models take into account a variety of environmental variables, plant features, and growth stages. Growers may explore and perfect their hydroponic systems without having to go through a lot of trial and error by modeling various scenarios and optimizing growth factors. As a result, hydroponic farming operations become more profitable by saving time and resources.

It is crucial to remember that hydroponics' use of AI and machine learning is still in its infancy. These technologies and their uses in hydroponic farming will be further developed through ongoing research and development as well as practical application, opening the door for more effective, sustainable, and fruitful agricultural systems.

3. **Nutrient Management Innovation:** A more precise and focused administration of nutrients will be possible because to developments in sensor technology and data processing. Plant health indicators, nutrient levels, and ambient variables will all be continuously monitored by sensors integrated into the hydroponic system.

Real-time AI algorithms will process this data, enabling dynamic fertilizer distribution modifications, optimizing plant growth, and reducing waste. Integrated nutrient sensing systems will provide plants with real-time feedback on nutrient availability and uptake. This data will be instrumental in adjusting nutrient formulations and dosing schedules to maintain optimal nutrient ratios and prevent imbalances or shortages [7].

It will be prioritized more in future hydroponic systems to shut the loop on nutrient recycling. The development of effective techniques for collecting, handling, and recycling nutrient solutions will be pursued. With less fertilizer waste and less dependency on outside resources, hydroponics is more ecologically friendly and environmentally sustainable.

Innovative nutrient distribution methods will be influenced by natural systems. To improve nutrient uptake effectiveness and overall plant health, ideas such root zone microbiome manipulation, bioactive chemicals, and symbiotic interactions will be investigated. The smooth connectivity and data sharing between numerous components would be made possible by the integration of hydroponic systems with IoT technology. Real-time monitoring, control, and optimization of nutrient distribution will be made possible by IoT-enabled devices and AI algorithms, increasing productivity and efficiency. [11]

4. **Genetic Engineering and Crop Improvement:** An exciting future development in hydroponics is the use of genetic engineering and crop modification, which has the potential to increase crop features, boost yields, and solve a number of agricultural problems.

   The deliberate change of an organism's genetic makeup through biotechnology methods is known as genetic engineering. Genetic engineering can be used in the context of hydroponics to enhance plant properties necessary for hydroponic production, such as nutrient uptake effectiveness, disease resistance, and environmental adaptability. With the help of this technique, certain genes from other organisms can be inserted into plants' genomes or altered to produce desired effects. [8]

   Growth rates and crop yields can be accelerated by genetic engineering by improving a plant's capacity to absorb and utilize nutrients from the hydroponic solution. Crops grown hydroponically can be given disease-resistant genes, which lowers the likelihood of pathogen outbreaks and reduces the need for chemical pesticides.

   Genetic engineering has improved crop performance in difficult growing conditions by conferring resistance to various environmental stresses, such as high salinity or extreme temperatures, and can be used to increase the nutritional value of crops grown in hydroponic systems by increasing the levels of vital nutrients like vitamins, minerals, and antioxidants. Alternatively, genetically modified crops with improved resource use efficiency can flourish in hydroponic systems with less water and nutrient inputs, making them more sustainable.

   The potential for crop enhancement in hydroponics will dramatically increase if genetic engineering and biotechnology advances continue. Researchers are constantly experimenting with new methods, such as genome editing tools like CRISPR-Cas9, which allow for targeted and precise alterations to plant genomes. [9]

   Additionally, continuing genetic engineering research strives to maximize the potential of hydroponic non-traditional crops. These crops can be modified to survive in different hydroponic conditions by modifying certain qualities, expanding the variety of crops that can be effectively produced using this technique.

5. **Integration of Hydroponics with other Agriculture Practices:** A symbiotic system called aquaponics combines hydroponics and aquaculture (fish farming). In these systems, hydroponically grown plants are fertilized with nutrient-rich water from fish tanks while the plants clean the fish's drinking water. This integrated strategy improves resource efficiency and nutrient cycling, resulting in a closed-loop system that uses fewer resources and produces less waste. [10]

 

Interest in fusing hydroponics with organic agricultural practices is rising as the market for organic produce continues to expand. The development of organic hydroponic systems, which supply consumers with pesticide-free, ecologically friendly produce, can be facilitated by innovations in the formulation of organic nutrients and sustainable business methods.

The creation of hybrid farming techniques that combine aspects of hydroponics and conventional soil-based farming may be a trend in the future. For example, combining hydroponics with greenhouse or open-field farming can create more controlled growth environments, lengthen growing seasons, and increase crop output overall.

In deteriorated or nutrient-depleted locations, hydroponics can be utilized as a method to encourage soil restoration and conservation. Growing cover crops or particular hydroponic plants with deep root systems can enhance soil structure, reduce erosion, and restore nutrient levels. Opportunities for nutrient cycling and a circular economy can be created by combining hydroponics with other agricultural techniques. garbage that is nutrient-rich from one system can be used as inputs for another, lowering the requirement for outside inputs and generating less garbage.

With the help of hydroponics, it is possible to create controlled, ideal growing conditions for a variety of plant species with various environmental needs. Farmers can increase their resistance to pests, illnesses, and climate change by using a variety of crops in hydroponic systems.

Research and innovation in the area will probably increase as a result of interactions between hydroponics and other agricultural techniques. New growth methods, crop types, and sustainable farming approaches will be developed through cooperation between conventional farming methods and hydroponic technology.

## V. DISCUSSION

The future of hydroponics offers an enticing vision for the future of agriculture, to sum up. Hydroponics is emerging as a practical and sustainable alternative to fulfill the rising demand for food as we grapple with issues like the expanding global population, climate change, and the scarcity of arable land. Hydroponic systems are expected to undergo a revolution as a result of the integration of cutting-edge technologies like AI, machine learning, and IoT, which will improve fertilizer supply, automate procedures, and use resources more effectively.

The ability of hydroponics to grow a variety of crops, including unusual and specialist types, presents tremendous opportunities for agricultural adaptation and innovation. Growers may respond to individual crop needs, generate higher yields, and produce nutrient-rich foods by fine-tuning nutrient formulas and growth conditions.

In the future of hydroponics, urban agriculture and vertical farming will become increasingly important. By reducing travel times and increasing access to fresh fruit for nearby populations, these approaches bring farming closer to urban areas. Hybrid systems that integrate hydroponics into conventional agriculture can boost output, lengthen growing seasons, and encourage cooperation across various agricultural practices.

The advancement of hydroponics will be fueled by research and innovation. New and improved growing methods, cutting-edge crop varieties, and ground-breaking technology will continue to push the limits of hydroponics.

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