

Precision Hydroponics: Innovations for Resource Efficiency and Sustainable Crop Production – A Review

Mrs. S Preethijohnevilin
Department of Agricultural
Engineering
Dhanalakshmi Srinivasan College of
Engineering,
Coimbatore, India.
preethi.je@dsce.ac.in

Dinesh V
Department of Agricultural
Engineering
Dhanalakshmi Srinivasan College of
Engineering,
Coimbatore, India.
dinesh.v23@dsce.ac.in

Desika G
Department of Agricultural
Engineering
Dhanalakshmi Srinivasan College of
Engineering,
Coimbatore, India.
desika.g23@dsce.ac.in

Dhanush Kannan S
Department of Agricultural
Engineering
Dhanalakshmi Srinivasan College of
Engineering,
Coimbatore, India.
Dhanushkannan.s23@dsce.ac.in

Nandhana A
Department of Agricultural
Engineering
Dhanalakshmi Srinivasan College of
Engineering,
Coimbatore, India.
nandhana.a23@dsce.ac.in

Abstract - Precision hydroponics is an emerging approach in soilless agriculture that integrates advanced technologies to improve resource efficiency and ensure sustainable crop production. This review highlights recent innovations such as Internet of Things (IoT)-based sensors, artificial intelligence (AI), and automated control systems that enable precise monitoring and regulation of critical growth parameters including pH, electrical conductivity, temperature, humidity, and light intensity. By utilizing closed-loop and recirculating systems, precision hydroponics significantly reduces water usage—up to 80–90% compared to conventional farming—while minimizing nutrient losses and environmental pollution. The adoption of vertical farming structures and climate-controlled environments further enhances land-use efficiency and enables year-round production, particularly in urban and peri-urban areas. Additionally,

integration with renewable energy sources and smart fertigation systems contributes to lowering the carbon footprint and operational costs over time. Despite its advantages, challenges such as high initial investment, energy dependency, and the requirement for technical expertise remain barriers to widespread adoption. However, ongoing developments in low-cost sensors, data analytics, and user-friendly automation platforms are making these systems increasingly accessible to farmers. Overall, precision hydroponics presents a promising solution to address global food security concerns by optimizing input use, increasing crop yield and quality, and reducing environmental impact under changing climatic conditions.

Keywords: Precision hydroponics, sustainable agriculture, IoT, artificial intelligence, resource efficiency, vertical

farming, smart irrigation, controlled environment agriculture.

I. INTRODUCTION

The increasing global population and mounting environmental pressures on conventional agriculture highlight an urgent need for innovative and sustainable food production methods. While traditional farming often faces challenges like water scarcity, soil degradation, and climate change impacts, alternative approaches are emerging to address future food security. One such promising pathway is hydroponics.

1.1 What is Hydroponics

Hydroponics is defined as "the growing of plants without soil using mineral nutrient solutions in water." It is a method where plants are cultivated in controlled settings, receiving their essential nutrients directly from a water-based solution rather than from traditional soil. This established branch of agronomy offers a means to grow food independently of soil, making it particularly relevant for individuals in urban environments or areas with limited arableland.

1.2 A Brief History of Soilless Cultivation

While the recent "northern gardening boom" and the development of northern greenhouses have drawn significant attention, the concept and practice of soilless cultivation are not new. For nearly a century, and possibly longer, both indigenous and non-indigenous residents, along with small groups of scientists and settlers, experimented with

various crops in Arctic and sub-Arctic regions. This historical context indicates that the idea of growing food without traditional soil has roots much deeper than contemporary advancements suggest, showcasing an ongoing human endeavor to adapt and innovate food production in challenging environments.

1.3 Advantages of Hydroponics

Hydroponics offers numerous compelling advantages over conventional soil-based horticulture. Firstly, it eliminates the need for soil entirely, which broadens the possibilities for cultivation to areas where traditional farming is impractical, such as flats, inner-city areas, or regions with problematic soil, light, or temperature conditions (e.g., Finland, allowing year-round growth). Secondly, hydroponic systems are highly water-efficient, as water remains within the system and can be reused, leading to lower water requirements. Thirdly, growers gain complete control over nutrient levels, ensuring precise delivery and potentially lower nutrition requirements while preventing nutrient pollution in the environment. This controlled environment also contributes to stable and high yields. Furthermore, hydroponics simplifies pest and disease management due to the mobility of containers, reduces pesticide damage, promotes healthier plant growth, and ultimately results in food that is better for consumption. Beyond these individual benefits, hydroponics can "sustain much higher yields with fewer inputs," making it a crucial tool for meeting rising food demands.

1.4 Disadvantages and Challenges of Hydroponics

Despite its numerous advantages, the widespread adoption of hydroponics

faces several disadvantages and challenges. One significant barrier is the cost: current hydroponics controllers, essential for monitoring critical factors like pH, EC (electrical conductivity), and water temperature, are often expensive. Additionally, a lack of readily available open-source hardware and software for these controllers limits accessibility for the average person. Furthermore, large-scale adoption of hydroponics requires overcoming challenges related to technological expertise, access to affordable equipment, availability of necessary inputs, and high energy demands. To maximize the potential of such systems and promote wider uptake, significant investment is required, particularly in research and technical assistance for farmers, as current investment levels are not meeting this need. Targeted research is also crucial to enhance efficiency, crop quality, and profitability, and to assess potential environmental tradeoffs.

II. UNDERSTANDING PLANT ESSENTIALS

This comprehensive guide articulates the **fundamental requirements for plant growth in hydroponic systems**. It details the 16–17 **essential plant nutrient elements** (macronutrients: N, P, K, Ca, Mg, S; micronutrients: Fe, Mn, Zn, B, Mo, Cu, Cl, Ni) and their roles, chemical forms, and deficiency/excess symptoms. The book further explores water quality, pH control (ideally 5.8–6.5), and composition of nutrient solutions for different crops (e.g., tomatoes: 200mg/L N, 50mg/L P, 360mg/L K, 185mg/L Ca). Essential nutrients are provided in ionic

forms through precisely made solutions, and plant health is ensured by regular monitoring, adjusting concentrations, and recognizing nutrient antagonisms. The guide emphasizes balancing nutrient delivery with environmental control, supporting both commercial and hobby-scale hydroponics, and stresses **regular diagnostic testing of water, solutions, and plant tissue** for optimal growth.

Representative experimental values from the book include:

- **Nitrogen:** 100–200mg/L (optimal in solution)
- **Phosphorus:** 10–20mg/L (lower than typical soil applications)
- **Potassium:** 100–200mg/L
- **Calcium:** 150–200mg/L
- **Micronutrients** (e.g., Fe: 2–12mg/L, Zn: 0.05–0.1mg/L)
- **Optimal EC for tomatoes grown in rockwool:** 2.0–3.0µS/cm, pH 5.5–6.0

This experimental protocol outlines **stepwise hydroponic cultivation for Arabidopsis and similar species**, highlighting the key essentials: strictly controlled nutrient solutions, oxygen supply via aeration, and sterile conditions to minimize disease. It demonstrates how **homogeneous nutrient delivery** allows for precise manipulation of plant nutritional status and toxic element exposure. Roots and shoots can be harvested separately for biochemical analysis.

2.1 Light Requirements for Plant Growth

(“Evaluation of IoT-Based Grow Light Automation on Hydroponic Plant Growth”)

This study evaluates an IoT-automated LED grow light system for bok choy hydroponics compared to natural sunlight. The automated system uses an RTC module to control LED lighting, with temperature and humidity continually monitored and recorded via IoT. Over a 30-day period, plants under LED grow lights showed increased growth metrics: average fresh weight (23.6g), number of leaves (11.2), and plant height (18.1cm), versus sunlight-exposed plants (20.2g, 9.3 leaves, 17.1cm). Statistical analysis (t-test) confirmed that LED lights significantly improved fresh weight and leaf growth rate, but not plant height. This highlights that controlled LED lighting optimizes specific growth parameters in hydroponic systems, especially for enhancing biomass and foliage.

("Controlled Environment with Artificial Lighting for Hydroponic Production Systems")

This research describes the use of a controlled environment room with artificial lighting, air-conditioner, chiller, and humidifier for hydroponic melon (*Cucumis melo*) cultivation. Air temperature was maintained at 23–26°C, humidity at 60–80%, and light intensity varied diurnally up to 20,000 lux to mimic natural patterns. Environmental factors such as pH (5–6), electrical conductivity (2–3 mS/cm), and dissolved oxygen were also controlled. The system successfully supported plant growth from seedling to 45 days, but low light intensity led to elongated internodes and smaller leaves, indicating a need for higher irradiance for optimal morphology. The findings emphasize the importance of not only providing sufficient light duration but also maintaining adequate light intensity and

spectrum to ensure robust plant growth in artificial systems.

2.2 pH and EC: Critical Parameters

(Predictive Neural Network Modeling of pH and EC in Deep-Trough Hydroponics)

This study developed a neural network model to predict pH and EC changes in lettuce hydroponics, incorporating variables such as air/solution temperature, relative humidity, light, and plant age. The system operated within target ranges: pH 5.8, EC 1150–1250 $\mu\text{S/cm}$, day/night temperatures of 24°C/19°C, and relative humidity 30–70%. The best-performing neural network (1 hidden layer, 9 nodes) predicted pH and EC at the next 20-minute interval with RMS errors of 0.0072 (pH) and 3.7 $\mu\text{S/cm}$ (EC), demonstrating high precision. The approach enables accurate, real-time prediction and control of pH and EC, essential for stable crop performance in hydroponic systems.

Simultaneous pH and EC Control in Hydroponics through Real-Time Ammonium/Nitrate Ratio Manipulation

This research introduced a control strategy where both pH and EC in kale hydroponics were managed by adjusting the ammonium-to-nitrate ratio, thus eliminating the need for direct acid/base dosing. Experimental runs consistently held pH within ± 0.5 of set point (6.1) and EC within 2–3 mS/cm. Maximum relative plant growth rates ranged between 0.20–0.21 day^{-1} , with shoot yields of 83–86% leaf mass. The approach produced comparable or better nutritional outcomes (notably increased protein and chlorophyll content) relative to conventional nitrate-

only systems, validating pH and EC as critical, controllable variables for robust plant health and yield.

III. TYPES OF HYDROPONIC SYSTEMS

Hydroponic systems enable soil-less cultivation of plants using nutrient solutions. They are broadly categorized as **solid substrate systems** and **substrate-free systems**. Solid substrates include fibrous materials (peat, coconut coir, stone wool) and granular media (perlite, expanded clay), offering root support, water retention, and nutrient availability. Substrate-free systems such as the Nutrient Film Technique (NFT), Deep Flow Technique (DFT), and aeroponics circulate nutrient solutions directly to the plants' roots without media. NFT is widely used, delivering a thin nutrient film in shallow channels, suitable for quick-growing crops but vulnerable to pump failure. Aeroponics suspends roots in misted air, optimizing oxygen but needing sophisticated management. Closed-loop hydroponics systems recycle nutrient solutions to reduce waste, whereas open-loop systems discharge excess. Selection depends on crop type, environmental control, space, and economic factors.

3.1 Wick system

The wick system is a passive hydroponic technique where the nutrient solution is drawn to the plant roots via a wick, eliminating the need for pumps or electricity. It is simple, low-cost, and suitable for small-scale or home-based growing. Studies with pak choi (*Brassica chinensis* L.) and lettuce (*Lactuca sativa* L.) demonstrated that nutrient

composition, especially the use of AB mix nutrients, significantly affects plant growth in the wick system. Optimal nutrient concentrations improved parameters such as plant height, number of leaves, leaf area, fresh and dry weight, and harvest index. Although easy to manage, the wick system's nutrient delivery can be slower than active systems, affecting growth rates.

3.2 EBB and flow (flood and drain)

Ebb and Flow (Flood and Drain) systems intermittently flood plant roots with nutrient solution, then drain it back into a reservoir, creating wet/dry cycles that improve oxygenation and nutrient uptake. The flood cycle duration and frequency are carefully controlled to optimize growth and resource efficiency. One study developed a water pump control system using Arduino and a tidal (on/off) timing method, effectively extending pump operation in solar-powered setups by running pumps 5 minutes on and 15 minutes off to conserve battery power. This control allows 24-hour nutrient flow without continuous energy consumption. Another study introduced a Shallow Aggregate Ebb-and-Flow (SAEF) system using expanded clay aggregate with varying substrate depths (19, 38, 57 mm) and irrigation frequencies (1 to 8 hours). Optimal results came from 38 mm aggregate depth and 2-hour irrigation frequency, yielding fresh shoot mass of 214.47 g and dry mass of 9.01 g after 30 days, comparable or superior to conventional NFT and Deep Flow systems.

3.3 Drip systems (recovery and non-recovery)

Drip irrigation systems deliver nutrient solutions directly to plant roots

through controlled dripping, enhancing water and nutrient efficiency. Recovery (closed-loop) systems collect and recycle excess nutrient solution, minimizing waste and environmental impact, while non-recovery (open-loop) systems allow runoff, leading to potential nutrient loss. The studies focus on automating drip fertigation with big data and IoT for precise control, and on the effectiveness of drip fertigation methods in substrates like polyester fiber and rockwool. Drip fertigation improves nutrient availability at the root zone by maintaining capillary water continuity, enhancing stomatal density, photosynthetic rates, and plant growth over bottom fertigation. Automation via sensors and cloud data further optimizes irrigation and nutrient delivery.

3.4 Aeroponics and Fogponics

Drip irrigation systems deliver nutrient solutions directly to plant roots through controlled dripping, enhancing water and nutrient efficiency. Recovery (closed-loop) systems collect and recycle excess nutrient solution, minimizing waste and environmental impact, while non-recovery (open-loop) systems allow runoff, leading to potential nutrient loss. The studies focus on automating drip fertigation with big data and IoT for precise control, and on the effectiveness of drip fertigation methods in substrates like polyester fiber and rockwool. Drip fertigation improves nutrient availability at the root zone by maintaining capillary water continuity, enhancing stomatal density, photosynthetic rates, and plant growth over bottom fertigation. Automation via sensors and cloud data further optimizes irrigation and nutrient delivery.

IV. ESSENTIAL COMPONENTS AND EQUIPMENT

Hydroponic systems require precise control and monitoring of environmental and solution parameters for effective plant growth. Core components include sensors for pH, electrical conductivity (EC), temperature (air and water), and light intensity. The use of Arduino-based microcontrollers paired with modules such as DS18B20 temperature sensors, DHT11 humidity/temperature sensors, Atlas Scientific pH and EC probes, and real-time clock (RTC) modules enable automated data acquisition and control. Equipment like submersible pumps, supply tubing, growing media (e.g., coco coir), and grow lights (LEDs, fluorescent lamps) support nutrient delivery and optimal plant development. User interfaces are often provided by touchscreens. Additionally, wireless communication modules (e.g., 433 MHz transmitters/receivers) facilitate remote control of pumps, lights, and heaters. Regular calibration of sensors is essential for maintaining accuracy.

4.1 Growing mediums (substrates)

Growing mediums in hydroponics provide physical root support, water retention, aeration, and nutrient delivery but differ widely in composition and sustainability. The 2011 study on *Gypsophila* compared sawdust, river sand, and vermiculite across three hydroponic systems (elevated tray, ground lay, bag culture). Sawdust supported the highest vegetative growth, number of shoots, flower stem length, and quality due to its superior water and nutrient holding

capacity and aeration, while sand performed poorest. Bag culture with sawdust was optimal for flower yield and quality. More recently, keratin-cellulose composite substrates, developed via freeze-drying of biowastes (human hair keratin and wood pulp cellulose), offer a sustainable, biodegradable alternative with high porosity (>90%), excellent water retention (up to 40× weight), and mechanical resilience. These substrates enable controlled nutrient release through keratin degradation and micronutrient binding, supporting improved seedling growth (Bok Choy, Arugula). The innovative substrates outperform traditional phenolic foam in biomass and root development, offering an eco-friendly medium for advanced hydroponics.

4.2 Nutrient solutions and fertilizers

Provides a comprehensive overview of nutrient solutions used in hydroponic systems, emphasizing the precise balance of essential (N, P, K, Ca, Mg, S) and micronutrients to optimize plant growth. It details how pH affects nutrient availability, notes ideal electrical conductivity (EC) values (typically 1.5–2.5 dS/m), and demonstrates that temperature and oxygenation of the solution significantly influence nutrient uptake and plant productivity. Various standard nutrient solution formulas and fertilizer sources are directly compared, highlighting the need for correct ionic ratios. Experimental data (e.g., Hoagland solution: N 210 mg/L, P 31 mg/L, K 234 mg/L, Ca 160 mg/L) and case studies illustrate best practices and the role of careful nutrient management in sustainable hydroponic cultivation.

The second file reviews organic nutrient solutions for hydroponics,

focusing on the substitution of chemical fertilizers with organic liquid fertilizers produced from agricultural residues, industrial waste, and animal byproducts through fermentation. It summarizes experiences with sources like vermicompost tea, fish waste, seaweed, and plant extracts. The review acknowledges the challenges, such as rapid pH fluctuations and ensuring nutrient solubility, and stresses regular monitoring to avoid phytotoxicity. Numerous studies cited indicate that crops grown with organic solutions—when well-managed—show comparable growth to those using chemical fertilizers, supporting the environmental and health benefits of organic hydroponics.

Experimental values found within both files highlight:

- Standard inorganic solution (Hoagland): N 210 mg/L, P 31 mg/L, K 234 mg/L, Ca 160 mg/L, optimal pH 5.5–6.5, target EC 1.5–2.5 dS/m.
- Organic solutions: Effective sources include vermicompost teas, fish-based fertilizers, and plant extracts; growth results for lettuce, tomato, and pakcoy have shown equivalence to chemical systems in several metrics when pH and nutrient levels are well-controlled

4.3 Reservoirs and Pumps

The first paper details an automated reservoir temperature monitoring and controlling system for hydroponics using a 150 L reservoir and a 65-watt submersible pump supplying nutrient solution at 1–2 L/min per growing tube. The system maintains reservoir temperatures between 24°C and 30°C by activating a water chiller and mixer, improving lettuce growth (yield:

4.78 kg total). Sensor calibration ensured accuracy (equation $y = x + 0.37$). The system effectively automates nutrient solution management in hydroponics, optimizing plant growth while reducing labor.

The second paper describes a vertical hydroponics system with dual reservoirs for clean and used nutrient solution, employing submersible pumps with a flow rate of 221.22 L/h to circulate nutrients through rectangular PVC channels. Two motorized ball valves regulate water flow between layers. The energy consumption is reduced by ~38% compared to traditional NFT systems. Sensors monitor EC, pH, and temperature to maintain nutrient quality, with data transmitted via Arduino and **NodeMCU for remote monitoring**. Experimental highlights include: Flow rates: 1–2 L/min per tube (first study); 221.22 L/h pump rate (second) Reservoir volume: 150 L (first); dual reservoirs (second) Temperature maintained: 24–30°C (first) Energy consumption: 0.2616 kWh/day monitoring system vs. 0.424 kWh/day NFT system(second) Lettuce yield: 4.78 kg total (first).

4.4 Air Pumps and Airstones

The documents emphasize the critical role of air pumps and airstones in hydroponic systems, mainly for oxygenating nutrient solutions to maintain root health and promote plant growth. Air pumps drive aeration through airstones, creating fine bubbles that increase dissolved oxygen (DO) levels. Optimal DO levels prevent root hypoxia and improve nutrient uptake. Studies indicate that low power submersible air pumps with flow rates around 1–2 L/min are common in small-scale systems. Aeration systems are often integrated with

reservoirs (e.g., 150 L) and monitored for temperature and oxygenation to optimize conditions. The airstones' porosity and bubble size affect oxygen diffusion efficacy.

Together, air pumps and airstones provide essential oxygenation for healthy hydroponic growth, requiring careful selection and monitoring to balance energy use and plant oxygen demand.

V. SETTING UP YOUR HYDROPONIC SYSTEM

The documents outline hydroponic setup essentials, emphasizing controlled-environment agriculture (CEA) combined with nutrient solution culture. Key components include site selection with appropriate light (high PAR in southwestern US deserts), temperature regulation, water quality (low soluble salts, pH control), pest management, and structural design (high greenhouses, ventilation). Optimal root aeration and nutrient delivery (e.g., drip, nutrient film technique) maximize yields (up to 12.8 kg tomatoes/plant in 6 months). Advanced control systems integrate sensors and automated pumps for precise pH, EC, temperature, and lighting regulation. The Arduino-based hydroponic controller enables affordable monitoring and management to ensure stable nutrient conditions and plant health. This foundation aids growers in building an efficient, productive, and manageable hydroponic system.

5.1 Choosing the right system for your needs

The choice of a hydroponic system depends on crop type, space, budget, and

desired yield. Systems range from simple hydroponic planters (ideal for herbs and small leafy greens) to aeroponic Aerospring gardens or PVC pipe systems for larger-scale rapid cropping. Aeroponics maximize oxygen delivery to roots and boost growth up to 10 times soil yields but require more precise control and reliable pumps. PVC systems (4" or 6" pipe diameters) offer durability and scalability—4" suits smaller indoor crops, while 6" supports bigger plants with larger roots outdoors. Key considerations include oxygenation, nutrient delivery, root health, and ease of automation.

5.2 Site Selection and Environmental Considerations

The documents highlight key factors for successful hydroponic and controlled environment agriculture (CEA) site selection. High photosynthetically active radiation (PAR) is crucial, favoring southwestern US deserts, where winter PAR can reach 63–195 mol·m⁻² compared to northern states with much lower values (e.g., New York ~6–44 mol·m⁻²). Temperature regulation is essential, with optimal greenhouse elevation in southern Arizona recommended between 1250–1675 m to minimize cooling and heating needs. Water quality parameters, including low soluble salts, pH, and absence of harmful elements, are vital. Pest presence, especially whitefly vectors of viruses, should be minimal. Modern structures emphasize good ventilation and energy conservation, often using polyethylene glazing with infrared retention films.

5.3 Initial System Preparation and Sterilization

The documents highlight sterilization as critical for successful

hydroponic setup to minimize microbial contamination that can hinder plant growth. Effective seed surface sterilization for large crops (wheat, barley) involves sequential washes: 70% ethanol, bleach (20%), hydrogen peroxide, followed by a 50°C heat treatment, reducing contamination while slightly lowering germination. The sterile hydroponic system uses fully enclosed polypropylene chambers enabling long-term culture with regular nutrient changes and filtered aeration. Nutrient solutions and air are filtered through 0.22–0.45 µm sterile syringe filters. UV sterilization of nutrient solutions removes bacteria but may generate harmful radicals inhibiting growth; submicronic filtration is safer.

VI. NUTRIENT MANAGEMENT AND WATER QUALITY

Effective nutrient management in hydroponics focuses on optimizing the composition, concentration, and monitoring of nutrient solutions to maximize crop yield and resource efficiency. Maintaining an optimal pH range of 5.5–6.5 and electrical conductivity (EC) typically between 1.5–2.5 dS/m ensures nutrient solubility and availability. Closed-loop systems improve nutrient and water use efficiencies by recirculating solutions, but require regular monitoring to prevent ion imbalances and salinity buildup. Nitrogen—especially nitrate form (NO₃⁻)—is a key macronutrient to manage precisely for yield and quality. Advanced techniques include ion-selective electrodes and IoT-based sensors for real-time monitoring,

reducing fertilizer use and minimizing environmental impact.

6.1 pH Adjustment and Monitoring

The studies present automated systems for precise pH monitoring and control in hydroponic nutrient solutions to optimize plant growth. Using pH sensors integrated with microcontrollers (Arduino Mega 2560 and ESP8266), these systems continuously measure pH and actuate peristaltic pumps to add acid/base solutions, maintaining an optimal pH range of 6.0–6.8 for lettuce. Calibration yields a linear sensor response (e.g., $y = 0.91x + 0.91$). Fuzzy logic-based IoT control enhances precision by adjusting pH in real-time alongside nutrient dosing. Automated control improved lettuce growth, achieving yields of 4.78 kg (total) and increased leaf size versus manual methods.

6.2 Water Source Considerations (Tap vs. RO Water)

Hydroponic systems require high-quality water for optimal plant growth. Tap water often contains variable levels of dissolved salts (e.g., calcium, magnesium, potassium), chlorine, and organic matter that can accumulate over time, affecting nutrient balance and potentially leading to salt buildup and microbial growth in reservoirs. Conversely, Reverse Osmosis (RO) treated water significantly reduces total dissolved solids (TDS) and contaminants including calcium (~159 mg/L in tap vs. ~4 mg/L post-RO), potassium (~144 mg/L vs. ~27 mg/L), magnesium (~29 mg/L vs. ~4 mg/L), phosphorus (~53 mg/L vs. ~1 mg/L), nitrogen (~5 mg/L vs. ~3 mg/L), and total organic carbon (~14 mg/L vs. ~2 mg/L). RO water enhances control over nutrient

solution composition, reducing risks of toxicity and improving overall water quality for hydroponics. However, RO systems require higher energy input and investment costs. Facilities may balance cost, water quality, and treatment energy to select the appropriate water source. This analysis advises growers to consider the trade-offs between water quality and treatment costs when selecting tap or RO water sources for hydroponics.

VII. PLANT SELECTION AND PROPAGATION

The document emphasizes careful plant selection and propagation as foundational for successful hydroponic systems. Popular crops include tomatoes, cucumbers, lettuce, herbs, peppers, and strawberries, often using cultivars bred specifically for controlled environments. Propagation primarily starts from disease-free, uniform hybrid seeds to ensure consistent crop quality and yield. Seed germination occurs typically in plug trays with inert or organic media like rockwool or coconut coir, maintaining optimal moisture and aeration. Vegetative grafting (e.g., splice grafting for tomatoes) enhances vigor and disease resistance. Environmental control for propagation involves high humidity, moderate temperatures, and indirect lighting to maximize seedling health and transplant success. This structured approach ensures vigorous, healthy transplants that optimize growth and yield in hydroponic systems.

7.1 Starting Seeds in Hydroponics

Starting seeds in hydroponics emphasizes controlled, sterile conditions to

ensure uniform, vigorous seedlings free from soil-borne pathogens. Seedlings are often germinated on inert media such as rockwool, coco coir, or foam plugs that provide moisture retention and aeration. Optimal seed germination requires maintaining ideal moisture, temperature (usually 20–28°C), and humidity. Nutrient solutions with low electrical conductivity (0.5–1.5 mS/cm) and pH around 5.5–6.0 support early seedling growth. A well-managed hydroponic setup allows rapid root development and transplantation readiness. Disease-free propagation using such methods significantly improves transplant success and crop uniformity.

7.2 Transplanting Seedlings

The research focuses on developing a simplified transplanting manipulator for hydroponic leafy vegetable plug-seedlings grown in coco-peat substrate. Using four 301-stainless steel fingers with a rectangular cross-section (3 mm × 0.8 mm), the manipulator employs a single vertical-drive air cylinder to simultaneously insert and shrink the fingers, increasing friction and lifting force on the seedling substrate block. Shrinking distance (3.2 mm) and high root distribution rate (~90%) significantly improve transplanting success rate (up to 96.67%) while maintaining substrate integrity. Excessive shrinkage can disrupt the substrate, lowering success rate. The system proved effective for 16-day-old seedlings with moisture at 81%.

7.3 Cloning and Cuttings

The alfalfa study developed a hydroponic cutting system using stem segments (top, middle, bottom) with modified ½ Hoagland nutrient solutions supplemented by HB-101. Bottom stem

segments showed best rooting (up to 98.33% rooting rate), root length (~12.72 cm), and stem height (~20.95 cm) after 21 days. Lower nutrient concentrations (HM + 1/2000 HB-101) optimized root induction. The Eucalyptus review advances micro- and mini-cuttings for commercial cloning, improving rooting speed, quality, and uniformity over traditional stem-cuttings. Hydroponic mini-hedges enable high juvenile vigor, nutrient control, and yields up to 41,480 propagules/m²/year. Micro-cuttings avoid growth regulators, enhance root architecture (taproot-like), and reduce costs.

VIII. COMMON PESTS, DISEASES, AND DISORDERS

The documents describe integrated pest and disease management in hydroponic greenhouses, focusing on tomatoes. The JAPIEST intelligent system identifies key pests (aphids, whiteflies, mites, nematodes, caterpillars) and diseases (bacterial spots and cancers, fungal infections like *Alternaria solani*, *Fusarium* wilt, and viral diseases like TMV, TYLCV). Environmental variables such as humidity, temperature, and vapor pressure deficit (VPD) influence pest outbreaks and disease incidence. Root pathogens (*Pythium*, *Phytophthora*, *Fusarium*) spread rapidly in nutrient solutions, emphasizing prevention via pathogen-free seedlings and sanitation. Disorders arise from autotoxic root exudate accumulation in closed systems.

8.1 Identifying Common Hydroponic Pests

The study focuses on pest identification and management challenges

in hydroponic vegetable systems, specifically at Celebes Hydroponics Bengkulu. Common pests affecting a variety of hydroponic vegetables like pakcoy, kale, lettuce, and spinach include aphids, whiteflies, thrips, caterpillars, grasshoppers, leaf miners, and fungal pathogens. The complexity arises due to overlapping symptoms among different pests, making diagnosis difficult without expert input. An expert system using Certainty Factor and Dempster-Shafer methods was developed to assist non-expert staff in timely and accurate pest identification based on observable symptoms, improving intervention speed and efficacy.

8.2 Organic and Chemical Pest Control

The attachments discuss pest control strategies in hydroponic systems, comparing organic (biopesticides, botanical extracts) and chemical methods for managing common pests like aphids and spider mites on crops such as cucumber. Organic controls include botanical pesticides derived from custard apple seed extract, matrine (from *Sophora flavescens*), neem (azadirachtin), and spintoram. These biopesticides showed high efficacy, with custard apple extract achieving up to 95–97% reduction in aphids and spider mites, matrine and neem showing significant yet slightly lower efficacy, and spintoram effective especially over longer durations. Chemical controls are more traditional but risk resistance and environmental impact. Organic biopesticides provide eco-friendly alternatives compatible with IPM.

This evidence supports the use of organic biopesticides as sustainable effective controls in hydroponic pest management programs.

8.3 Recognizing Nutrient Deficiencies and Toxicities

Nutrient deficiencies and toxicities in hydroponic systems arise from improper nutrient solution composition or imbalances during plant growth stages. Deficiencies commonly occur when essential macronutrients (N, P, K, Ca, Mg) and micronutrients (Fe, Mn, Zn, Cu, B) are too low, leading to visible symptoms such as chlorosis, necrosis, stunted growth, or poor fruit quality. Toxicities often result from excess ions like potassium or calcium accumulating in solution, inhibiting uptake of others (e.g., excess K suppresses Ca uptake, causing blossom end rot). Accurate pH and electrical conductivity (EC) management is critical to prevent nutrient lockout. This integrated understanding helps growers identify deficiency or toxicity early, guiding nutrient solution adjustments to maximize hydroponic crop health and yield.

IX. MAINTENANCE AND TROUBLESHOOTING

Maintenance of a hydroponic system includes regular sensor calibration, equipment inspection, and timely replacement to ensure optimal plant growth and system reliability. Troubleshooting challenges encountered during testing covered sensor failures (e.g., ultrasonic water level sensor corrosion), inaccuracy (pH and EC probes), and component malfunctions (peristaltic pumps). Strategies involved sensor recalibration with chemical kits, hardware replacements, software debugging, and code optimization. Preventive measures include protective sensor placement, regular cleaning, diluting acids for pH

control, and having backup components on hand. Automated alerts and calibrated sensors improve system autonomy, reducing user intervention and minimizing crop loss risks.

9.1 Routine System Checks

Routine system checks are essential for maintaining hydroponic system stability, crop health, and food safety. Regular inspection includes sensor calibration (pH, EC, temperature), equipment function (pumps, aerators, lighting), and sanitation protocols (cleaning rafts, reservoirs, and airstones). Monitoring nutrient solution parameters frequently (pH: 5.5–6.5; EC: 1.5–2.5 dS/m) prevents deficiencies and toxicities. Microbial load assessments and sanitation reviews reduce contamination risks. Record-keeping of maintenance actions supports traceability under FSMA guidelines. Automated alerts for sensor drift and pump malfunction enhance response time and reduce labor.

9.2 Troubleshooting Common Issues (Pump failure, pH swings)

The primary challenges in hydroponic system troubleshooting include pump failures impacting nutrient delivery and erratic pH swings that disrupt nutrient uptake. Pump malfunctions, e.g., stepper motor misalignment or physical blockages, can cause non-uniform nutrient dosing and crop stress. pH swings occur due to sensor drift, temperature fluctuations, or improper dosing response. Automated control systems employing real-time ion-selective electrodes mitigate these issues by continuously measuring key ions (nitrate, potassium, calcium) and pH, triggering precise nutrient injection. Calibration and sensor drift remain critical concerns; robust sensor calibration and frequent

checks improve reliability. Maintenance includes inspection for pump mechanical integrity and software error handling to prevent overdosing during sensor faults.

This integrated troubleshooting approach reduces human errors, maintains nutrient stability, and enhances system resilience against common mechanical and sensor-related issues.

9.4 Seasonal Adjustments and Winterizing

Seasonal adjustments in hydroponics focus on modifying system parameters to cope with environmental changes, especially during winter. Strategies include insulating reservoirs, using water heaters to maintain nutrient solution temperatures between 18–24°C, and reducing light intensity or supplementing with artificial lighting to compensate for shorter daylengths and lower natural PAR. Winterizing procedures emphasize preventing root zone chilling, minimizing temperature fluctuations, and reducing pathogen risks heightened by cooler, humid conditions. Adjustments to nutrient concentration and pH stabilize nutrient availability. Automated sensors and controls help maintain stable environments. Case studies demonstrate yield preservation when maintaining root zone temperatures and adjusting photoperiod and nutrient supply during cold months.

X. ADVANCED HYDROPONIC TECHNIQUES AND FUTURE TRENDS

Recent advancements in hydroponics integrate smart technologies such as IoT, AI, cloud computing, and automated

sensor systems for precise monitoring and control of environmental factors (pH, EC, temperature, light). Novel systems like Micro Indoor Smart Hydroponics (MISH) incorporate spectroscopic sensors for real-time nutrient profiling, outperforming traditional EC-only methods. Vertical farming and aeroponics are expanding, emphasizing space efficiency, water savings (up to 90%), and year-round production. AI-driven systems utilize neural networks and fuzzy logic for dynamic adjustment of nutrient delivery and climate control. Future trends include increased automation, data analytics, and sustainable urban agriculture, targeting 30% food sustainability by 2030 using limited arable land.

10.1 Automation and Monitoring Systems

The discussed systems integrate IoT and embedded microcontrollers (Arduino Mega, NodeMCU ESP8266) to automate real-time monitoring and control of hydroponic parameters such as nutrient solution pH, electrical conductivity (EC), temperature, and water level. Sensor data are collected and transmitted via MQTT protocols to cloud platforms (Ubidots, Node-RED) for visualization, remote supervision, and alerting. Automated nutrient dosing pumps and motorized valves adjust nutrient concentrations and flow rates dynamically, optimizing plant growth and reducing resource use. User interfaces (mobile apps, web dashboards) enable easy management, while sensor calibration and error handling ensure data accuracy and system reliability. This automation framework enhances scalability, precision, and sustainability in vertical hydroponic farming through

integrated monitoring and adaptive control.

10.2 Aquaponics and Permaculture Integration

Aquaponics and permaculture integration combines sustainable food production with ecological design principles. Aquaponics provides a closed-loop system where fish waste supplies nutrients for plants, while plants purify water for aquatic life, enhancing resource efficiency and reducing waste. Permaculture complements this by emphasizing biodiversity, water conservation, and soil health through system design mimicking natural ecosystems, promoting resilience and sustainability. Integrating aquaponics on green walls or vertical farms, as in building-integrated living systems, further enhances urban sustainability, biodiversity, and energy savings (up to 47%). Both systems prioritize minimal external inputs, water savings (~80%), and improved yields, supporting climate-smart, regenerative urban agriculture.

10.3 Future of Hydroponics and Sustainable Food Production

Hydroponics is poised to play a transformative role in sustainable food production, especially against the backdrop of urbanization, water scarcity, land degradation, and changing climate. Advanced hydroponic, vertical farming, and controlled environment agriculture (CEA) technologies maximize productivity per unit area, drastically reduce water use (by 85–90%), and enable year-round, pesticide-free crop yields even in non-arable or urban spaces. Future systems leverage automation, IoT, renewable energy, precision nutrient delivery, AI, and

robotic controls for optimal resource use and real-time crop management, increasing resilience and minimizing environmental impact. Rapidly growing startups and urban farms in India demonstrate scalable models, integrating local supply chains to deliver fresh, safe, and contaminant-free produce and mitigate food safety risks observed in conventionally grown vegetables.

This evidence establishes hydroponics as a cornerstone technology for future urban and peri-urban food security, boosting productivity, conserving resources, and ensuring safe, high-quality produce while supporting climate adaptation and sustainability goals.

REFERENCES

- [1]. H. M. Resh, *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower*, 7th ed. Boca Raton, FL, USA: CRC Press, 2013.
- [2]. J. B. Jones, *Hydroponics: A Practical Guide for the Soilless Grower*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2016.
- [3]. M. Raviv and J. H. Lieth, *Soilless Culture: Theory and Practice*. Amsterdam, Netherlands: Elsevier, 2008.
- [4]. D. R. Hoagland and D. I. Arnon, *The Water-Culture Method for Growing Plants Without Soil*. California Agricultural Experiment Station Circular 347, 1950.
- [5]. D. Savvas and N. Gruda, "Application of soilless culture technologies in the modern greenhouse industry," *Eur. J. Hortic. Sci.*, vol. 83, no. 5, pp. 280–293, 2018.
- [6]. G. L. Barbosa *et al.*, "Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs conventional agricultural methods," *Int. J. Environ. Res. Public Health*, vol. 12, no. 6, pp. 6879–6891, 2015.
- [7]. C. Treftz and S. T. Omaye, "Hydroponics: Potential for augmenting sustainable food production in non-arable regions," *Nutr. Food Sci.*, vol. 46, no. 5, pp. 672–684, 2016.
- [8]. A. Graber and R. Junge, "Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production," *Desalination*, vol. 246, no. 1–3, pp. 147–156, 2009.
- [9]. J. E. Rakocy, M. P. Masser, and T. M. Losordo, *Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture*. Southern Regional Aquaculture Center, 2006.
- [10]. C. F. Sace *et al.*, "Hydroponics: A review on modern agriculture technology," *Int. J. Res. Eng. Technol.*, vol. 4, no. 6, pp. 1–4, 2015.
- [11]. N. Sharma, S. Acharya, K. Kumar, N. Singh, and O. P. Chaurasia, "Hydroponics as an advanced technique for vegetable production," *J. Soil Water Conserv.*, vol. 17, no. 4, pp. 364–371, 2018.
- [12]. D. Toulaitos, I. C. Dodd, and M. McAinsh, "Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics," *Food Energy Secur.*, vol. 5, no. 3, pp. 184–191, 2016.
- [13]. K. Benke and B. Tomkins, "Future food-production systems: Vertical farming and controlled-

- environment agriculture,” *Sustainability: Sci. Pract. Policy*, vol. 13, no. 1, pp. 13–26, 2017.
- [14]. F. Kalantari, O. M. Tahir, R. A. Joni, and E. Fatemi, “Opportunities and challenges in sustainability of vertical farming,” *J. Landscape Ecol.*, vol. 11, no. 1, pp. 35–60, 2017.
- [15]. T. Kozai, G. Niu, and M. Takagaki, *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. San Diego, CA, USA: Academic Press, 2016.
- [16]. A. AlShrouf, “Hydroponics, aeroponics and aquaponics as compared with conventional farming,” *Am. Sci. Res. J. Eng. Technol. Sci.*, vol. 27, no. 1, pp. 247–255, 2017.
- [17]. E. Pantanella *et al.*, “Aquaponics vs hydroponics: Production and water use efficiency of lettuce,” *Acta Horticulturae*, vol. 927, pp. 887–893, 2012.
- [18]. M. A. Nichols and N. Savidov, “Aquaponics: A nutrient and water efficient production system,” *Acta Horticulturae*, vol. 947, pp. 129–132, 2012.
- [19]. M. Dorais, “Greenhouse vegetable production,” *Horticultural Reviews*, vol. 28, pp. 239–319, 2003.
- [20]. C. Sonneveld and W. Voogt, *Plant Nutrition of Greenhouse Crops*. Dordrecht, Netherlands: Springer, 2009.
- [21]. L. Morgan, *Hydroponic Crop Production: A Practical Guide to Growing Vegetables, Herbs and Flowers*. Suntec International Hydroponic Consultants, 2018.
- [22]. M. H. Jensen and A. J. Malter, *Protected Agriculture: A Global Review*. World Bank Technical Paper, 1995.
- [23]. P. Adams, “Nutritional control in hydroponics,” *Acta Horticulturae*, vol. 578, pp. 211–261, 2002.
- [24]. D. Savvas, “Hydroponics: A modern technology supporting the application of integrated crop management,” *Eur. J. Plant Sci. Biotechnol.*, vol. 7, pp. 1–12, 2003.
- [25]. P. Bradley and C. Marulanda, “Simplified hydroponics to reduce global hunger,” *Acta Horticulturae*, vol. 554, pp. 289–296, 2001.
- [26]. S. Singh and B. Singh, “Smart hydroponic farming using IoT technology,” *Int. J. Eng. Res. Technol.*, vol. 8, no. 7, pp. 101–106, 2019.
- [27]. K. Kularbphetpong *et al.*, “Automated hydroponics system using IoT technology,” *J. Phys.: Conf. Ser.*, vol. 1144, 2019.
- [28]. R. R. Shamshiri *et al.*, “Advances in greenhouse automation and controlled environment agriculture,” *Comput. Electron. Agric.*, vol. 153, pp. 1–17, 2018.
- [29]. K. Specht *et al.*, “Urban agriculture of the future: An overview of sustainability aspects of food production in cities,” *Sustainability*, vol. 6, no. 10, pp. 6223–6242, 2014.
- [30]. A. M. Beacham, L. H. Vickers, and J. M. Monaghan, “Vertical farming: A summary of approaches to growing skywards,” *J. Hort. Sci. Biotechnol.*, vol. 94, no. 3, pp. 277–283, 2019.