***Review Article***

**Optimizing Hydroponic Crop Production: A multifaceted approach to EC, pH and Nutrient Management**

**ABSTRACT**

Hydroponics isthe practice of growing crops without soil, which relies on careful calibration of pH, EC (electrical conductivity) and nutrient availability to promote plant growth and yield. In hydroponics, pH is an important factor governing how nutrient availability is affected. Ideal pH range for most of the crops is 5.5-6.5. pH is important to determine acidity and alkalinity of a solution and it further affects nutrient absorption. pH management is different in Deep water Culture, Nutrient Film Technique and System of Flooded tubes. Modern techniques like microcontroller and sensors are being used to monitor hydroponic solution. Optimum pH is important for nutrient uptake and proper nutrient ratio influence uptake of another nutrient.EC or dissolved amounts of salts, measures the concentration of nutrients available for the plants. There are various nutrient recipes for the crops that are being added to the system in dosage of gram/litre. Higher EC can be managed by diluting the solution. Falling EC levels can be adjusted by adding the nutrient solution. An increase in EC value can be beneficial for the fruit quality but may result in yield reduction. Real time sensors are used nowadays for monitoring of EC and pH. In hydroponics there is less contamination, low water consumption, higher yield and no need of herbicides or pesticides but initial cost is high and regular monitoring is important.

**Keywords:** Hydroponics, pH optimization, nutrient management, electrical conductivity

**INTRODUCTION**

One of most productive plant growth method using soilless cultivation approach is hydroponics that enables a high degree of control over the nutrient status, pH and electrical conductivity (EC) of the systems provides. All of which take precedence in the management of plant health inherently to each and every increase yield for available nutrient use(Son *et al.,* 2020; Shubham *et al.,* 2024a). pH and EC are the key variables as they directly govern nutrient uptake, ion solubility and the responsiveness of all plant metabolism. Maintaining the appropriate pH and EC in a hydroponic system is extremely important since this way plants get the necessary nutrients at a percentage that they can actually uptake. pH is a measure of acidity or alkalinity of the solution it measures at the time of its measurement only from a 0 to 14, 7 being neutral(Aliac and Maravillas, 2018). Nutrition occurs only between a pH level of nutrient solution absorbs the nutrients and allows them to be absorbed as such to avoid a deficiency or toxicity. Factors that dictate the amount of nutrients that are absorbed from the soil in which a crop is planted pH is one such factor and minor variations lead to nutrient lockout or symptoms of deficiency/toxicity(Cho *et al.,* 2017). For instance, different pH management will be required by different hydroponics system as system has an inherent pH fluctuation apart from one another Some cultures systems (DWC) can deviate widely in pH, as the system is directly-rooted in its buffering functions of nutrients (LagesBarbosa *et al.,* 2015). Nutrient Film Technique (NFT) pH is usually lowered with phosphoric acid or citric acid and the pH buffered so as to avoid large fluctuation in pre-buffered nutrient solutions (Graves, 1983). For example, ebb and flow (caused by substrates such as coco coir and rockwool) has pH stability (substrates term buffering but it should regularly be flushed out to not change pH (Raviv *et al.,* 2019). More efficient automated pH, in modern hydroponics with microcontrollers and pH sensors going through the right control. The systems that automate pH perturbations are used control these pumps *i.e*. changing on and off cycles to dispense pH-adjusting chemicals (Saaid *et al.,* 2015). Many such systems are constructed on hydroponic solution that is continuously recirculate and pH level movements being monitored, adjusting accordingly in real time (Rico, 2020). The advance of this has improved nutrient absorption efficiency and avoided pH-related pathological progress (Mehboob *et al.,* 2019).

In hydroponics, all major components of a nutrient are in solution and the availability of nutrients is related to EC which is an express of concentration of all dissolved ions. Sustainable nutrient management allows growers to fine-tune the efficiency of uptake where plants reach optimal growth yield (Jones, 2016). EC levels moving away from the recommended EC indicate stress in relation to nutrient availability, EC too high caused osmotic stress and ion toxicities; low EC is linked with insufficient plant nutrition hampering health and growth (Sulaiman *et al.,* 2025) EC requirements of crops need to be different for every stage up to October 2023. 1.2-2.0 mS/cm in leafy greens and EC levels of 2.5-3.5 mS/cm for crops such as tomatoes & peppers (Dutta *et al.,* 2023); the initial vegetative stages require lower EC values are to establish roots and EC for fruiting or reproductive stages need to ≥ 1.30 EC to increase both chlorophyll fluorescence, stem diameter, nutrient uptake (Dutta *et al.,*2023). The EC of the crop has been well-established is depend on its relationship with plant growth, where optimal ECs lead some treatments especially in vegetative stages (Wongsorn*et al.,* 2024; Amalfitano *et al.,* 2017). Low EC’s of ~0.3-1.1dS/m is typical with Aquaponics and other hydroponics due to nutrient dilution of fish effluent demanding the need for augmenting potassium as well as iron. Hydroponic technique prevents plants from soil borne diseases and there is no chance of insect pest attack. Plants in hydroponic require less time to grow and production is more. Human labour can be reduced by automation and there is year around production. (Sharma *et al.,* 2018). Hydroponics require less space and waste production is very less (Olness *et al.,* 2005)

**KEY COMPONENTS INVOLVED IN HYDROPONIC SYSTEM**

Hydroponic system is a technique of raising plants in soil-less medium by using mineral nutrient solutions. Most commonly used hydroponic system for growing leafy vegetables are DFT (deep flow technique) and NFT (nutrient film technique). In DFT system, nutrient solution is circulated and supplied to the plants when the water levels in the culture bed goes lower than the set value and it is again circulated and supplied to the bare roots of the plants at regular intervals in a culture bed with a slope of 1/100. Nutrient solution which are not absorbed by plants are recycled back to the reservoir in recirculation systems. NFT system and modified DFT system which are similar to ebb and flow system are commonly used by plant factories(Son *et al.,* 2020).

1. **Hydroponic system:** Selection of a proper hydroponic system according to plant growth is very crucial. Commonly used hydroponic systems are NFT (Nutrient Film Technique) and Dutch Butch System which is also known as Bato Bucket System.
2. **Nutrients:**17 elements are considered essential for nutrient management in hydroponics and their appropriate amount effects plant health (Son*et al.,* 2020; Salam *et al.,* 2024). Nutrients can be micronutrients (Fe, Mn, Zn, Cu, B and Mo) and macronutrients (N, P, K, Ca, Mg and S).
3. **Soil reaction (pH):** pH is related to uptake of many nutrients by the means of plant roots. In Hydroponic system maintaining neutral pH is a hectic task (Spinu *et al.,* 1997). pH meter has electrode tip in the end for sensing changes in pH. Nowadays software is being used to monitor the pH and make changes in it (Domingues *et al.,* 2012).Table 1 shows the pH management in different crops. Phosphoric acid, potassium hydroxide and calcium hydroxide are used for lowering and raising the pH (Saxena & Bassi, 2013; Shubham *et al*., 2024b).
4. **Electrical Conductivity:**EC value representsnutrient concentration in the solution which indicates the concentration of dissolved salts and available ions in the nutrient solution. Optimal values for leafy vegetables and fruit bearing crops.
5. **Hygiene maintenance:** Proper hygiene maintenance in lab is crucial for ensuring healthy plant growth, reduced pest infestations andpreventing disease outspread.

**CONCEPT OF pH:**

pH is a scale used to determine the acidity or alkalinity of a solution at the moment of measurement. It ranges from 0 to 14, with 7 being the neutral range. The pH level of a nutrient solution affects how easily nutrients are absorbed, so it's important to keep it within the ideal range. The pH of nutrient solutions for soilless cultivation should be maintained between 5 and 6, with 5.5 being the typical value (Singh & Dunn, 2016).Table 1 depicts different pH management techniques.

**Table 1. pH management in different crops**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Crops** | **Optimal Range of pH** | **Effects of Low pH** | **Effects of High pH** | **pH Adjustment** | **References** |
| Tomato | 5.5-6.5 | Calcium deficiency leading to blossom-end rot | Poor phosphorus availability | pH down: Phosphoric acid; pH up: Potassium hydroxide | (Kang *et al.,* 2011; Resh, 2022; Sonneveld& Voogt, 2009) |
| Lettuce | 5.5-6.5 | Calcium and magnesium deficiencies affecting cell wall formation; Magnesium toxicity | Iron and phosphorus deficiency | pH down: Phosphoric acid; pH up: Potassium hydroxide | (Resh, 2022; Sonneveld& Voogt, 2009) |
| Spinach | 5.5-6.5 | Calcium deficiency leading to weak structure | Iron deficiency leading to chlorosis | pH down: Phosphoric acid; pH up: Potassium hydroxide | (Resh, 2022) |
| Strawberry | 5.8-6.2 | Blossom-end rot and calcium deficiency | Iron chlorosis | pH down: Phosphoric acid; pH up: Potassium hydroxide | (Yafuso & Boldt, 2024) |
| Saffron | 6.0-8.0 | Ammonium-based nitrogen accumulation | Phosphorus availability best at neutral to alkaline pH | pH down: Phosphoric acid; pH up: Potassium hydroxide | (Kour *et al.,* 2022; Naseri *et al.,* 2025; Dewir*et al.,* 2022) |
| Cabbage& Cauliflower | 6.0-6.2 | Leaf necrosis and stunted growth due to increased iron and manganese solubility | Reduces availability of iron, manganese and phosphorus: over stunted growth | pH down: Phosphoric acid; pH up: Potassium hydroxide | (Resh, 2022; Sonneveld& Voogt, 2009) |
| Brush beans | 6.0-7.0 | Reduced leaf number and weak stems | Poor growth and low yield |

|  |
| --- |
|  |

|  |
| --- |
| pH down: Phosphoric acid; pH up: Potassium hydroxide |

 | (Hopkinson & Harris, 2019) |

**Table 2. Some of the important pH management techniques**

|  |  |  |
| --- | --- | --- |
| **Variation in pH** | **Methods/ Techniques** | **References** |
| Lowering pH | Phosphoric acid which releases phosphorus helps in lowering pH. Organic acids such as citric acid. | (Dorais, 2019; Trejo & Gómez, 2012) |
| Raising pH | Potassium hydroxide, dissociates in water to release hydroxide.Calcium hydroxide dissolve slowly in water and calcium is important for cell wall structure and root development.Other agents used are sodium bicarbonate and calcium carbonate | (Saxena & Bassi, 2013) |
| Buffering solutions | Buffering solutions stabilize pH and minimize fluctuations (Calcium carbonate, potassium hydroxide and sodium bicarbonate) | (Jones, 2016) |
| pH cycling | pH interplay between nutrient uptake and chemical equilibrium of solution. | (Sonneveld & Voogt, 2009) |

There are many techniques or systems that allow hydroponic customization. Some system holds large amount of water while other hold less amount of water. These systems can be selected based on crops, budget and area (Yuvaraj & Subramanian, 2020). In most crops closed hydroponics system is utilized very less as compared to system, but yield is higher in closed loop system as seen in crops like lettuce (Abd-Elmoniem*et al.,* 2006).Table 3 explains about pH management in various hydroponic system.

**Table 3. pH management in different hydroponic systems**

|  |  |  |  |
| --- | --- | --- | --- |
| **Various Hydroponic System** | **pH variation** | **pH Adjustment techniques** | **Reference** |
| Deep Water Culture (DWC) | PH fluctuation is frequent because of roots immersed in water. | By serving as a buffer and avoiding abrupt changes, nutrients aid in pH stabilization. | (LagesBarbosa *et al.,* 2015; Jones, 2016) |
| Nutrient Film Technique (NFT) | Regular pH monitoring is essential. | Phosphoric acid or citric acid can be used to reduce pH and pre-buffered solution help to keep pH. | (Graves, 1983) |
| System of flooded tubes | pH becomes stable due to the buffering effect | Flushing the growing medium, such as coco coir, rock wool, clay pellets, or perlite, helps maintain pH | (Raviv *et al.,* 2019) |

**AUTOMATION IN pH CONTROL SYSTEM IN HYDROPONICS**

Nowadays microcontrollers activate the motors to liberate the pH adjusting solution. In some scenario there is pump to take out the hydroponic solution and that is further collected for pH checking in a container and recirculated back again (Saaid *et al.,* 2015). pH sensors detect the basicity or acidity of the solution. LCD screens are also installed sometimes to show the reading. If pH is below 6 sensors send signal to activate the pumps to disperse the solution to adjust pH (Rico, 2020).Fig. 1 depicts the working of automatic pH monitoring system (Mehboob *et al.,* 2019).

**Fig. 1. Working of automation pH monitoring system**

**NUTRIENT MANAGEMENT IN HYDROPONICS**

Hydroponic systems have nutrients dissolved nutrients in it. Grower can control the nutrients uptake to have efficient plant yield. Nutrient uptake is influenced by EC *i.e*.dissolved salts. Nutrient toxicity can be caused due to high EC because of osmotic stress in plants, whereas, due to low EC whereas yellowing of leaves is caused (Jones, 2016).Table 4 depicts the macro and micro nutrients in hydroponics.

$$Mass \left(mg\right)=\frac{Required concentration \left(ppm\right)×Volume (L)}{Amount of nutrient in salt}$$

**Table 4. Macronutrients and micro nutrients in hydroponics**

|  |  |  |  |
| --- | --- | --- | --- |
| **Crops** | **Macronutrients** | **Micronutrients** | **References** |
| Lettuce | Nitrate (NO3-), Phosphorus required for root growth, Mg for production of chlorophyll | Fe to prevent chlorosis, Cu for enzyme activity & other micronutrients are B, Mo and Mn | (Sublett *et al.,* 2018) |
| Tomatoes | Moderate level of nitrogen, P for fruiting, Mg for fruit development | Fe, Cu, B and Mo | (Adams *et al.,* 1992) |
| Cucumber | Ca to prevent blossom-end rot, P for flowering, S for protein synthesis. | B for pollination, Fe, Zn Mo for nitrogen fixation | (Zhang *et al.,* 2023) |
| Berries | N carefully to prevent excessive growth, Sulphur in moderate amount. | Fe, Cu, Zn | (Caruso *et al.,* 2011) |
| Spinach | Potassium for plant vigour, adequate calcium for tip burn | Mo for nitrate reduction, boron for cell wall formation. | (Maneejantra *et al.,* 2016) |
| Saffron | Phosphorus and potassium for corm development, nitrogen for overall growth. | Fe, Mn, Zn, Cu and Mo | (Dewir *et al.,* 2022) |
| Cabbage and cauliflower | Nitrogen is required for head formation, potassium for head firmness. | Fe, Mn and Zn | (Abdel & Ali, 2016) |

**NUTRIENT SOLUTION MANAGEMENT AND SUSTAINABILITY**

In recirculating system water loss is minimum and along with-it nutrient loss is also minimized. Maintaining the pH between 5.5-6.5, typically ensures the optimal nutrient uptake. Table 5 includes the general nutrient recipe for most of the plants. Nutrient ratio should also be proper to allow proper uptake of nutrients. Table 6shows some nutrient recipes for growing leafy vegetables.Sustainability refers to minimal environmental impact and reducesthe waste. In traditional farming, fertilizer seeps down in soil and pollute environment(Resh, 2022). The periodic addition of fresh nutrients helps in maintaining the proper hydroponic balance. Automated monitoring system allows real time monitoring and adjustment and because of it less nutrients are required. Hydroponic system often uses drip irrigation or aeroponics to minimize the water loss (Savvas &Neocleous, 2019).Table 7 explains some nutrient recipes for growing fruit bearing crops.

**Table 5. Nutrient recipes for most of the crops**

|  |  |  |
| --- | --- | --- |
| **S.No.** | **Nutrients** | **Dose****(g/lt water)** |
|  | Calcium Nitrate (CaNO3) | 15-20 |
|  | Potassium Nitrate (KNO3) | 5-10 |
|  | Magnesium Sulfate (MgSO4) | 5-8 |
|  | Monopotassium Phosphate (KH2PO4) | 2-5 |
|  | Iron (Fe) | 2-4 ppm |
|  | Manganese (Mn) | 0.5-1 ppm |
|  | Boron (B) | 0.3-0.5 ppm |
|  | Zinc (Zn) | 0.2-0.5 ppm |
|  | Copper (Cu) | 0.05-0.2 ppm |
|  | Molybdenum (Mo) | 0.05 ppm |

**Table 6. Nutrient recipe for growing leafy vegetables**

|  |  |  |
| --- | --- | --- |
| **S.No.** | **Nutrients** | **Dose (g/lt water)** |
|  | Calcium Nitrate (CaNO3) | 1.5 | 1.7 | 2 | 1.5 | 6.7 | 1.7 |
|  | Potassium Nitrate (KNO3) | 0.5 | 0.6 | 0.8 | 0.5 | 2.4 | 0.6 |
|  | Magnesium Sulfate (MgSO4) | 0.5 | 0.7 | 0.6 | 0.5 | 2.3 | 0.6 |
|  | Monopotassium Phosphate (KH2PO4) | 0.25 | 0.3 | 0.3 | 0.3 | 1.2 | 0.6 |
|  | Micronutrient Mix (Iron, Zinc, Copper, etc.) | 0.1 | 0.1 | 0.1 | 0.1 | 0.4 | 0.1 |

**Table 7.Nutrient recipe for growing fruit bearing crops**

|  |  |  |
| --- | --- | --- |
| **S.No.** | **Nutrients** | **Dose(g/lt water)** |
|  | Calcium Nitrate (CaNO3) | 1.8 | 2 | 1.7 | 1.7 |
|  | Potassium Nitrate (KNO3) | 1.2 | 1 | 1 | 1 |
|  | Magnesium Sulfate (MgSO4) | 0.7 | 0.6 | 0.6 | 0.7 |
|  | Monopotassium Phosphate (KH2PO4) | 0.8 | 0.5 | 0.5 | 0.6 |
|  | Micronutrient Mix (Iron, Zinc, Copper, etc.) | 0.1 | 0.1 | 0.1 | 0.1 |

**FACTORS INFLUENCING UPTAKE OF NUTRIENTS**

Nutrient uptake is influenced by various factors for maximizing plant growth. pH range of 5.5-6.5 is crucial for nutrient uptake and EC also influence water absorption along with nutrient absorption. Temperature directly links with metabolism and influence nutrient uptake as hot temperature can damage root system. Light intensity influence photosynthesis and then nutrient demand(Yan *et al.,* 2012). Aeration in hydroponic solution is important for proper ion exchange and proper growth of the plant. Root morphology and microbial interaction with roots also influence nutrients uptake. Factors like air circulation and humidity influence how much water a plant transpires which consequently affects nutrient movement within the plant. Moreover, the nutrient solution circulation and the type of growing medium, or growing medium absence, may impact the uptake efficiency and nutrient availability from the hydroponic system design. To improve nutrient uptake and increase crop yields, more automated systems which control pH, EC, and temperature, are being used for better micromanagement of nutrient solutions (Hochmuth & Sideman, 2022).

**MANAGEMENT OF ELECTRICAL CONDUCTIVITY IN HYDROPONICS**

Electrical conductivity (EC) is a key factor in hydroponic crop production which indicates the concentration of dissolved salts and available ions in the nutrient solution. Careful management of EC is essential for optimizing hydroponic crop production as it regulates plant growth, development and crop yield overall of the crop (Sulaiman *et al.,* 2025). Optimal EC range can be affected by many factors such as crop species, growth stage and environmental conditions. The ideal EC levels range between 1.5 to 2.5 mS/cm but changes may be required to meet the specific crop requirements (Wortman, 2015). High EC levels can in general improve the nutrient availability and uptake however, extremely high EC can inhibit nutrient absorption due to increase in osmotic pressure. On the other hand, lower EC levels may lead to nutrient deficiencies which results in reduced yield and poor plant health. Aquaponic culture which combines aquaponics and hydroponics typically operates with a lower EC level of 0.3 to 1.1 dS/m due to variations in nutrient sources. Table 8 shows the EC ranges and effects of EC on crop growth. As aquaponic system derives nutrients from fish effluent it requires extra supplementation of elements like potassium and iron to avoid nutrient deficiencies meanwhile, hydroponic systems derive its nutrient through synthetic sources like nutrient solutions (Pantanella, 2012; Ritambara*et al.,* 2024).

**Table 8.Effect of EC ranges on crop growth**

|  |  |  |
| --- | --- | --- |
| **Features** | **Information** | **References** |
| Optimal EC for fruit bearing crops | 2.5-3.5 mS/cm (tomatoes, cucumbers, peppers) | (Dutta *et al.,* 2023) |
| Optimal EC for leafy vegetables | 1.2-2.0 mS/cm (lettuce, spinach) | (Dutta *et al.,* 2023) |
| Effect of high EC | Improves fruit sweetness and firmness in crops such as tomatoes but it generally reduces yield. | (Rosadi *et al.,* 2014) |
| EC requirement by growth stage | Lower EC needed during early vegetative stages; higher EC needed during reproductive stage (flowering & fruiting). | (Dutta *et al.,* 2023) |
| Chlorophyll Fluorescence & Green Index | Highest at EC levels of 2–3 mS/cm in Pepino (*Solanum muricatum*). | (Wongsorn *et al.,* 2024) |
| Plant Height & Stem Diameter | Improved at EC level of 4 mS/cm in Pepino. | (Wongsorn *et al.,* 2024) |
| Seasonal EC Optimization in “Friariello” Pepper | Optimal EC range of 3.8–4.1 mS/cm improved mineral uptake and fruit quality. | (Amalfitano *et al.,* 2017) |
| Alternative EC Management | Tofu wastewater used as nutrient source; microcontroller-based system effectively controlled EC levels. | (Telaumbanua *et al.,* 2019; Rai *et al.,* 2024) |

**REGULATION OF ELECTRICAL CONDUCTIVITY AND AUTOMATION IN HYDROPONICS**

Electrical conductivity (EC) is a dynamic variable in hydroponic crop production which can be influenced by a number of factors such as plant nutrient uptake, water loss through evaporation and transpiration. It is a key factor in determining plant health and growth as it tells about the concentration of dissolved ions in the nutrient solution. It is important to maintain optimal EC levels as variations in these levels can result in toxicities, osmotic stress or nutrient deficiencies, affecting overall crop quality and yield. Effective EC regulation relies on growers continuously adjusting water levels or nutrient content. Growers must dilute the solution with fresh water when the EC becomes too high to stop salt accumulation that leads to root damage. Growers need to add more nutrients when EC levels fall below the optimal range to ensure proper plant nutrition. Effective management of EC needs simultaneous attention to pH because these factors interact. The study by Kaewwiset & Yooyativong (2017) showed that changes in nitric acid concentration affected EC measurements which confirmed how these variables are related.

Modern hydroponic technology advancements created automated EC monitoring and adjustment systems which minimize human involvement and enhance both precision and efficiency. Hydroponic automation systems utilize real-time sensors to monitor EC and pH levels continuously to maintain the best conditions for plant growth. Control systems based on computers or microcontrollers work with these sensors to execute adjustments based on collected data. A major advancement observed in EC automation is the utilization of AI (Artificial Intelligence) and machine learning models. Besides, fuzzy logic controllers have been utilized in automated control systems for the regulation of EC dynamically. In all studies described, Fuzzy logic systems are capable to use a large number of input variables and manage the nutrient dosing in precision nutrient management (Khudoyberdiev*et al.,*2020). Such systems are more proportional to hydroponic management as they respond in real time with changes of environmental. Here is formula to calculate EC:

**OPTIMIZATION STRATEGIES FOR ELECTRICAL CONDUCTIVITY**

For best plant development, the management of specific electrical conductivity (EC) is one of the keys to success and optimal efficiency in any hydroponic system. EC levels can vary greatly by crop type and stage, as well as the growing environment. One major difficulty in EC optimization is to keep the nutrient balance due to plants different demand of selective nutrients. The changing ionic balance of the nutrient solution is a result of plants taking up elements, such as nitrogen and phosphorus and potassium (at different rates) creating potential deficiencies or toxicities. Different mitigation approaches like integrated nutrient solution replacement, partial replenishment and real-time monitoring of ion concentrations (Fathidarehnijeh*et al.,*2023) have been taken up by hydroponic growers to address these deficiencies.

$$EC = \frac{TDS (ppm)}{Conversion factor}$$

Sustainable approaches to EC optimization have gained attraction in modern hydroponics, focusing on resource efficiency and environmental impact reduction. Recirculating hydroponic systems, for instance, minimize nutrient wastage by continuously filtering and reusing nutrient solutions. These systems enhance water-use efficiency while reducing the discharge of excess nutrients into the environment (Fathidarehnijeh *et al.,* 2023). Additionally, artificial intelligence (AI) and machine learning-driven nutrient management systems provide real-time EC adjustments based on plant requirements. By analyzing plant growth parameters, environmental conditions, and nutrient uptake patterns, AI models optimize EC dynamically, improving overall crop yield and sustainability (Fathidarehnijeh *et al.,* 2023). Automated EC control systems, including fuzzy logic controllers and neural network-based models, have further revolutionized hydroponic nutrient management. These systems integrate sensors that continuously monitor EC and pH, making real-time corrections to maintain optimal growing conditions. For instance, predictive modelling approaches developed by Ferentinos & Albright (2002) accurately anticipate EC fluctuations, enabling precise nutrient dosing.

**CONCLUSION**

Hydroponic crop production is method of growing crops without soil. An important feature for maximizing hydroponic crop production is the efficient management of pH, electrical conductivity (EC) and nutrients balance. A pH range of 5.5-6.5 is ideal for crops like tomatoes, lettuce and strawberries allowing proper nutrient uptake and also minimizes the incidences of nutritional deficiencies or toxicities. Similarly, EC regulation also helps in nutrient availability. pH and EC ranges varies with plant to plant and according to the growth stages. Nutrient solutions play an important role for supplying nutrients to the growing plants in hydroponics. Nutrient recipes for leafy vegetables and fruit bearing crops are different because of the different needs of the plants. The use of advanced precision agriculture has served greatly in order to increase the hydroponic nutrient management efficiency due to automation and AI modelling etc., fuzzy logic controllers as well as sophisticated real-time sensors. Application of these technologies reduces human intervention to promote the yield and sustainability. Hydroponics systems are even more efficient in resource use (less waste of water and nutrients) because recirculating is used. In future, smart automation and sustainable management of nutrient will be quite essential for achieving the high productivity without causing any loss to the nature in hydroponics systems.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**Acknowledgements**

I would like to express my great appreciation and gratitude to all the authors for providing their assistance and their contribution for valuable and constructive suggestions.

**Declaration of interest statement**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**REFERENCES**

Abdel CG and Ali HO. 2016. Selenium enrichments of Cauliflower (Brassica oleracea L. var. Botrytis) and Broccoli (Brassica oleracea L. var. Italica) grown under drip-hydroponic system hybrid 704. *International Journal of Farming and Allied Sciences* 5:126-167.

Abd-Elmoniem EM, Abdrabbo MA, Farag AA and Medany MA. 2006. Hydroponics for food production: comparison of open and closed systems on yield and consumption of water and nutrient. In *2nd International Conference on Water Resources and Arid Environments. Riyadh, Saudi Arabia: King Saud University*  1-8.

Adams P. 1992. Crop nutrition in hydroponics. In *Symposium on Soil and Soilless Media under Protected Cultivation in Mild Winter Climates 323*: 289-306.

AliacCJ.G and Maravillas E. 2018. IoT hydroponics management system. In 2018 IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM) 1-5.

Amalfitano C, Del Vacchio L, Somma S, Cuciniello A and Caruso G. 2017. Effects of cultural cycle and nutrient solution electrical conductivity on plant growth, yield and fruit quality of'Friariello'pepper grown in hydroponics. *Horticultural Science* 44(2).

Caruso G, Villari G, Melchionna G and Conti S. 2011. Effects of cultural cycles and nutrient solutions on plant growth, yield and fruit quality of alpine strawberry (*Fragaria vesca* L.) grown in hydroponics. *Scientia Horticulturae* 129(3): 479-485.

Cho WJ, Kim HJ, Jung DH, Kang CI, Choi GL and Son JE. 2017. An embedded system for automated hydroponic nutrient solution management. *Transactions of the ASABE* 60(4): 1083-1096.

Dewir YH, Alsadon A, Ibrahim A and El-Mahrouk M. 2022. Effects of growing substrate, mode of nutrient supply, and saffron corm size on flowering, growth, photosynthetic competence, and cormlet formation in hydroponics. *Hort Technology* 32(2): 234-240.

Domingues DS, Takahashi HW, Camara CA and Nixdorf SL. 2012. Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. *Computers and electronics in agriculture* 84: 53-61.

Dorais M. 2019. Advances in organic greenhouse cultivation. In *Achieving sustainable greenhouse cultivation* Burleigh Dodds Science Publishing 121-176.

Dutta D, Sharma V, Guria S, Chakraborty S, Sarveswaran S, Harshavardhan D and Shah MN. 2023. Optimizing plant growth and crop productivity through hydroponics technique for sustainable agriculture: a review. *International Journal of Environment and Climate Change* 13(9): 933-940.

Fathidarehnijeh E, Nadeem M, Cheema M, Thomas R, Krishnapillai M and Galagedara L. 2023. Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems. *Canadian Journal of Plant Science*, *104*(2), 88-102.

Ferentinos KP and Albright LD. 2002. Predictive neural network modeling of pH and electrical conductivity in deep–trough hydroponics. *Transactions of the ASAE* 45(6): 2007.

Graves CJ. 1983. The nutrient film technique. *Horticultural reviews* 5: 1-44.

Hochmuth GJ and Sideman RG. 2022. Knott's Handbook for Vegetable Growers. John Wiley & Sons.

Hopkinson S and Harris M. 2019. Effect of pH on hydroponically grown bush beans (Phaseolus vulgaris). *International Journal of Environment Agriculture and Biotechnology* 4(1): 142-145.

Jones Jr, JB. 2016. *Hydroponics: a practical guide for the soilless grower*. CRC press.

Kaewwiset T and Yooyativong T. 2017. Electrical conductivity and pH adjusting system for hydroponics by using linear regression. *In 2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)* 761-764.

Kang YI, Park JM, Kim SH, Kang NJ, Park KS, Lee SY and Jeong BR. 2011. Effects of root zone pH and nutrient concentration on the growth and nutrient uptake of tomato seedlings. *Journal of plant nutrition* 34(5): 640-652.

Khudoyberdiev A, Ahmad S, Ullah I and Kim D. 2020. An optimization scheme based on fuzzy logic control for efficient energy consumption in hydroponics environment. *Energies* 13(2): 289.

Kour K, Gupta, D., Gupta, K., Dhiman, G., Juneja, S., Viriyasitavat W and Islam MA. 2022. Smart-hydroponic-based framework for saffron cultivation: a precision smart agriculture perspective. *Sustainability*14(3): 1120.

Lages Barbosa G, Almeida Gadelha FD, Kublik N, Proctor A, Reichelm L, Weissinger E and Halden RU. 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International journal of environmental research and public health* 12(6): 6879-6891.

Maneejantra N, Tsukagoshi S, Lu N, Supoaibulwatana K, Takagaki M and Yamori W. 2016. A quantitative analysis of nutrient requirements for hydroponic spinach (Spinacia oleracea L.) production under artificial light in a plant factory. *Journal of Fertilizers and Pestic*ides *7*: 2.

Mehboob A, Ali W, Rafaqat T and Talib A. 2019. Automation and control system of EC and PH for indoor hydroponics system. *In* *4th International Electrical Engineering Conference*.

Naseri E, Dalir N, Mokhtassi-Bidgoli A, Ebadi MT and Rahnemaie R. 2025. Optimizing saffron cormlet production through substrate composition nutrient concentration and irrigation management in soilless cultivation. *Scientific Reports* *15*(1): 36.

Olness, A., Gesch, R., Forcella, F., Archer, D., & Rinke, J. (2005). Importance of vanadium and nutrient ionic ratios on the development of hydroponically grown cuphea. *Industrial Crops and Products*, *21*(2), 165-171.

Pantanella E. 2012. Nutrition and quality of aquaponic systems.

Rai A, Smriti, Shubham and Kaushal S. 2024. Utilising crop residues as hydroponic media for sustainable food production system. *International Journal of Research in Agronomy* 7(4): 73-78.

Raviv M, Lieth JH and Bar-Tal A. (Eds.). 2019. Soilless culture: Theory and practice: Theory and practice. *Elsevier.*

Resh HM. 2022. *Hydroponic food production: a definitive guidebook for the advanced home gardener and the commercial hydroponic grower*. CRC press.

Rico ALJ. 2020. Automated pH monitoring and controlling system for hydroponics under greenhouse condition. *Journal of Engineering and Applied Sciences* 15(2): 523-528.

Ritambara, Shubham and Kaushal S. 2024.Expanding horizons: Exploring the potential of Dutch bucket hydroponics. *International Journal of Research in Agronomy* 7(11): 204-207.DOI: <https://doi.org/10.33545/2618060X.2024.v7.i11c.1962>

Rosadi RB, Senge M, Suhandy D and Tusi A. 2014. The effect of EC levels of nutrient solution on the growth, yield, and quality of tomatoes (Solanum lycopersicum) under the hydroponic system. *Journal of Agricultural Engineering and Biotechnology 2(1): 7.*

Saaid MF, Sanuddin A, Ali M and Yassin MSA. 2015. Automated pH controller system for hydroponic cultivation. In *2015 IEEE Symposium on Computer Applications & Industrial Electronics (ISCAIE)* 186-190. IEEE.

Salam SB, Shubham and Kaushal, S. (2024). Soil management assessment framework for optimizing soil quality. *International Journal of Research in Agronomy* 7(11): 01-06. <https://doi.org/10.33545/2618060X.2024.v7.i11a.1910>

Savvas D and Neocleous D. 2019. Developments in soilless/hydroponic cultivation of vegetables. In Achieving sustainable cultivation of vegetables. 211-244. Burleigh Dodds Science Publishing.

Saxena P and Bassi A. 2013. Removal of nutrients from hydroponic greenhouse effluent by alkali precipitation and algae cultivation method. *Journal of Chemical Technology & Biotechnology*88(5): 858-863.

Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, *17*(4), 364-371.

Shubham, Kaushal, S and Sharma, U. (2024 a). Influence of boron and molybdenum fertilization on brinjal cv. Punjab Bharpoor growth, nutrient uptake, and productivity in alluvial plains of Punjab. *Journal of Plant Nutrition* DOI: 10.1080/01904167.2025.2451925.

Shubham, Sharma U and Kaushal R. 2024(b). Effect of Conjoint Application of NPK Sources and Nitrification Inhibitors on Micronutrients Uptake in Late Sown Cauliflower under Sub-tropical to Sub-temperate Conditions. *Journal of the Indian Society of Soil Science* 72(1): 89-98.

Singh H and Dunn B. 2016. *Electrical conductivity and pH guide for hydroponics*. Oklahoma Cooperative Extension Service.

Son JE, Kim HJ and AhnTI. 2020. Hydroponic systems. In *Plant factory* (pp. 273-283). Academic Press.

Sonneveld C and Voogt W. 2009. *Plant nutrition of greenhouse crops*. Springer Science & Business Media.

Spinu VC, Langhans RW and Albright LD. 1997. Electrochemical pH control in hydroponic systems. *II Modelling Plant Growth, Environmental Control and Farm Management in Protected Cultivation* 456: 275-282.

Sublett WL, Barickman TC and Sams CE. 2018. The effect of environment and nutrients on hydroponic lettuce yield, quality, and phytonutrients. *Horticulturae* 4(4): 48.

Sulaiman H, Yusof AA and Mohamed Nor MK. 2025. Automated Hydroponic Nutrient Dosing System: A Scoping Review of pH and Electrical Conductivity Dosing Frameworks. *Agri Engineering* *7*(2): 43.

Telaumbanua M, Triyono S, Haryanto A and Wisnu FK. 2019. Controlled electrical conductivity (EC) of tofu wastewater as a hydroponic nutrition. *Procedia Environmental Science, Engineering and Management* 6(3): 453-462.

Trejo-Téllez LI and Gómez-Merino FC. 2012. Nutrient solutions for hydroponic systems. *Hydroponics-a standard methodology for plant biological researches* 1:1-22.

Wongsorn C, Nakdee M, Sritontip P, Boontem B and Sritontip C. 2024. Effects of electrical conductivity of the nutrient solution on the growth of pepino (*Solanum muricatum* Aiton) plants under hydroponic cultivation. *Journal of Agricultural Science and Technology* 5: 20-25.

Wortman SE. 2015. Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. *Scientia Horticulturae* *194*: 34-42.

Yafuso EJ and Boldt JK. 2024. Development of a hydroponic growing protocol for vegetative strawberry production. *Hort Science* *59*(3): 384-393.

Yan Q, Duan Z, Mao J, Li X and Dong F. 2012. Effects of root-zone temperature and N, P, and K supplies on nutrient uptake of cucumber (*Cucumis sativus* L.) seedlings in hydroponics. *Soil Science and Plant Nutrition* *58*(6): 707-717.

Yuvaraj M and Subramanian KS. 2020. Different types of hydroponics system. *Biotica Research Today* *2*(8): 835-837.

Zhang C, Xiao H, Du Q and Wang J. 2023. Hydroponics with split nutrient solution improves cucumber growth and productivity. *Journal of Soil Science and Plant Nutrition* 23(1): 446-455.