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Hydroponics agriculture as a modern agriculture technique

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ABSTRACT

Purpose: Hydroponics, also known as controlled environment agriculture, is a method of cultivating plants and herbs without soil using mineral-supplemented solutions. Agriculture biotechnology enhances its wings on developing genetically modified plants for expanding crop yield and introducing characteristic features such as growing seasonal crops throughout the year, weather-resistant, and pest resistance. Compared to traditional agriculture, hydroponic cultivation yields high-quality crops with 90% more efficient use of water. Therefore, hydroponic cultivation could be considered a succeeding future of agriculture. In this context, understanding agriculture through the hydroponic route is vital for the efficient cultivation of crops. This review elaborates on the different classes of hydroponic systems and the factors that enable the systematic elements of the frame-up.

Design/methodology/approach: The significant intent of this review is to provide information on distinct hydroponic systems.

Findings: The present review reports a comprehensive discussion about the significance of the hydroponics system, its mechanism, nutrient solution preparation, types of hydroponic setup, and the challenges faced and would light up the knowledge in the same.

Originality/value: This review focus on the current feasible hydroponic method of crop cultivation.

Keywords: Hydroponics, Agriculture, Hoagland solution, Macro and micronutrients, Types of hydroponic system

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CLEANER PRODUCTION AND BIOTECHNOLOGY

1. Introduction

Biotechnology is a vast kingdom that utilizes the biological system, as a whole or parts of it, to develop numerous technological products that would enhance the beneficence to humankind. Those end products find applications in various fields commencing from agricultural practice to the medical sector, where agriculture is the utmost focused area since it is the backbone of almost all developing countries [1]. More than half of the population in developing countries depend on agriculture for their livelihood [2]. As the world population is drastically escalating over the past decades, it is necessary to design modern biotechnology strategies to improve the productivity and yield of crops to cope with the increasing demand, which imparts various merits compared to conventional crops. These advantages help agriculture to expand and provide sufficient food for all humankind. However, due to massive industrialization and human occupation, the percentage of agricultural land has been deprived that reflected in declined crop production [3]. So, scientists have developed a hydroponics technique to facilitate improved crop productivity in a limited space [4]. In 1929, the word hydroponics was first coined by Dr. William Frederick Gericke, a Professor from California [5]. Long back, this hydroponic agriculture technique was utilized to grow fresh food for the U.S. army troops stationed at the infertile pacific island during world war II. In 1950, viable commercial forms of the hydroponic system had been established in America, Asia, Africa, and Europe [5]. As we know, Hydroponics is a technique where crops are grown in a liquid nutrient solution without the presence of soil; that liquid nutrient solution is supplemented with essential minerals such as calcium, magnesium, sulfur, and trace elements like boron, manganese, iron, and zinc which are necessary for plant growth. Through the hydroponics system, various crops, such as tomatoes, cucumber, spinach, lettuce, foliage, etc., have been cultivated, and they displayed promising results [6-10].

<u>Soil versus hydroponics</u>
The plants which are grown either hydroponically or in soil have no physiological difference. In general, the organic and inorganic components that are inbuilt into the soil are exchanged with the soil solution, which is absorbed by plant roots (Fig. 1). However, in hydroponic cultivation, the plant roots are in the vicinity of a nutrient solution containing these essential elements. The subsequent processes of mineral uptake by the plants are the same resulting in the same physiological outcome [11]. Usually, a hydroponic setup is constructed in an enclosed environment where the plants are protected and are restricted from the reach of external factors such as heat, pest infestation, and excess light.

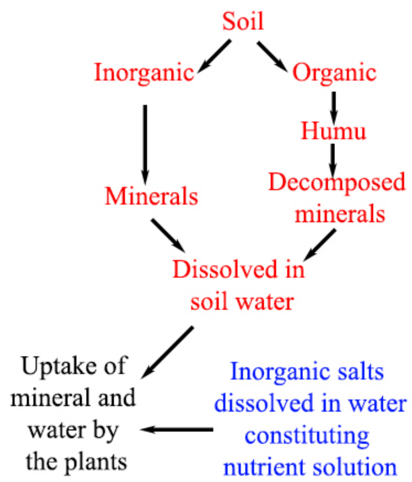

Fig. 1. Difference between the origin of nutrient source for soil and hydroponic cultivation

2. Hydroponic agriculture set up

In a typical hydroponics setup, different components are arranged to enable the effective uptake of nutrients by the crops, which are discussed in the following section.

2.1. Growth tray

The growth tray/growth chamber is the part where the roots of the plant will be in direct contact with the growth medium containing hydroponic solution (nutrient/mineral solution). Therefore, the plant roots have proper access to the dissolved nutrients/minerals in proximity. This arrangement declines the root's growth rate as they don't grow in length in search of nutrients/minerals and, thereby, enhances the growth rate of shoots resulting in higher productivity [8].

2.2. Growth medium

Growth medium act as a substitute for the soil here, where functionalities like mechanical support and anchoring of roots take place in the growth medium. The pH of the growth medium should be maintained close to neutral, or else the nutrient solution would become chemically unstable, which may affect the plant growth [12]. Coconut chips/coconut fiber, rock wool, and vermiculite are some of the growth media used in familiar [13].

2.3. Nutrient reservoir

Nutrient reservoir or simply termed as a reservoir where the nutrient solution is reserved with easy accessibility to the plant. The reservoir is usually engineered using plastic or glass to impart inert nature [14] since the metal-based reservoir can easily corrode and could give rise to harmful elements in the nutrient solution that would, in turn, affect the growth kinetics of the plant [15].

2.4. Air pump

Dissolved oxygen plays a crucial role in plant growth. It avoids wilting process, where the plants lose their turgidity [16]. It has been reported that circulating air bubbles can help to keep the nutrient solution oxygenated for a long time [17]. Therefore, to improve the level of dissolved oxygen in the nutrient solution, an air pump is used, which is connected to the air stone through which the air reaches the nutrient solution.

2.5. Nutrient solution

The nutrient solution is a very important requirement for plant growth, where essential minerals such as calcium, potassium, magnesium, phosphates, nitrates, etc., are present. These nutrients are added at the apt levels suitable for hydroponic cultivation. Dennis Robert Hoagland and Snyder formulated this in 1933. Again, the formulation was refined by Hoagland and Arnon in 1938. This solution is widely called Hoagland solution and is composed of various nutrient salts dissolved in distilled water at the appropriate level, which is summarized in Table 1.

The mineral salts are added appropriately to ensure that the required macro- and micro- nutrients reach the plant for proper growth and development.

Macronutrient and micronutrients

Macronutrients play a chief role in increasing crop yield, growth, and quality. These nutrients are termed as 'macronutrients since they are required by the plants in a larger quantity. Each macronutrient has its functionality involved in various beneficial activities and metabolic processes of the plant during its lifecycle [19]. Further, they contribute aid to the plants to protect themselves from various biotic stress such as attacks by different pathogens, pests, etc., and are also helpful to recover from abiotic stress

Table 1.
Constituents present in the basic Hoagland solution [18]

COMPONENT	STOCK SOLUTION (SS)	(SS) in 1000 ml water
	Source for Macronutrients	
Potassium nitrate (KNO_3)	202 g/L	2.5 ml
Calcium nitrate ($Ca(NO_3)_2$)	236 g/0.5L	2.5 ml
Fe (II) ethylenediaminetetraacetate (Fe-EDTA)	15 g/L	1.5 ml
Magnesium sulphate ($MgSO_4$)	493 g/L	1 ml
	Source for Micronutrients	
Boric acid (H_3BO_3)	2.86 g/L	1 ml
Manganese II chloride ($MnCl_2$)	1.81 g/L	1 ml
Zinc sulphate ($ZnSO_4$)	0.22 g/L	1 ml
Copper II sulphate ($CuSO_4$)	0.051 g/L	1 ml
Molybdic acid (H_2MoO_4)	0.09 g/L	1 ml
Sodium molybdic acid (Na_2MoO_4)	0.12 g/L	1 ml
	Source for Phosphate	
Potassium phosphate (KH_2PO_4)	136 g/L	1 ml

Table 2.
Macronutrients in Hoagland solution and their functions

Sl. No.	Macronutrients	Function	Deficiency	Ref.
1	Potassium	-Stimulates plant growth and involves in plant reproduction -Maintains osmotic regulation -Metabolism and chlorophyll synthesis	-Causes chlorosis -Hinders plant growth	[20-22]
2	Nitrogen	-Essential element in amino acid formation which is responsible for plant survival -Prevent diseases particularly among fruiting plants	-Stunted growth -Pale leaves due to lack of chlorophyll	[23,24]
3	Phosphorus	-Catalysis the conversion of numerous key biochemical reactions that include energy transfer, transformation of sugar and starch, photosynthesis, and transfer of genetic information -Help in photosynthesis -Vital elements in DNA and RNA	-Stem and leaf become dark -Stunted growth may occur	[25-27]
4	Magnesium	-Promotes healthy growth -Central atom in the chlorophyll molecule. -Activation of many enzymes such as catalase, peroxidase, cytochromes, and cytochrome oxidase needed for plant growth -Contributes to protein synthesis	-Cause chlorosis -Leaf vein colour become green to yellow leading to fall of leaves	[28,29]
5	Calcium	-Role in controlling membrane structure and function -Essential for cell elongation and cell division	-Affects the growth of young leaves	[30,31]
6	Sulphur	-Involve in the formation of plant proteins, amino acids, some vitamins and enzymes -It interacts with nitrogen to structurally form amino acids essential for protein synthesis -Influences the taste and pungency smell of some vegetables like onion, garlic and mustard	-Cause premature tissue death (necrotic or necrosis)	[32,33]
7	Carbon	-Promotes healthier growth of plants -Facilitates productive growth	-Slow growth of the plants -Stunted growth	[34,35]

like heavy metal intake, drought, UV radiation, excessive heat, salinity, etc. [36]. Macronutrients are classified into two groups: primary macronutrient and secondary macronutrient. The primary macronutrients are the ones that are required in larger quantities like nitrogen (N), phosphorus (P), and potassium (K), whereas the secondary macronutrients are usually required in moderate measure compared to the primary macronutrients, some of these are calcium (Ca), magnesium (Mg), sulphur (S), and carbon (C) [37]. The macronutrients supplemented in the Hoagland solution, and their physiological functions are summarized in Table 2.

Micronutrients have their role in all the metabolic and cellular activities of the plant. They are essential for plant growth but are needed in minimal quantity than the macronutrient. Required micronutrients include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), sodium (Na), cobalt (Co), silicon (Si), and vanadium (V). However, the last four elements rarely influence plant growth. The physiological functions of the micronutrients are summarized along with its deficiency syndrome in Table 3.

Obviously, there is a tolerance concentration limit for each nutrient in the hydroponics medium. This tolerance limit depends on the plant species and their origin. Therefore, understanding the tolerance limit of each nutrient against the plants that are grown hydroponically is much required. Also, the hydroponic medium has to be replenished periodically to improve the yield of the cultivation. So, the hydroponic medium is monitored using total dissolved solid content and pH in regular intervals.

2.6. Other parameters

Water

Water quality is an important parameter in the hydroponic system. The salts are usually dissolved in soft water as they are devoid of other undesired dissolved salts,

Table 3.
Micronutrients in Hoagland solution and their functions

Sl. No.	Micronutrients	Function	Deficiency	Ref.
1	Iron	-Respiration and photosynthesis -Production of chlorophyll	-Leaves become yellowish with dark green veins	[38,39]
2	Manganese	-Photosynthesis and enzyme antioxidant-cofactor -It involves in developing resistance against root pathogens -Growth of pollen tube and pollen germination	-Declines the growth rate -Causes chlorosis	[27,40]
3	Zinc	-Prevent low yield, spotted leaves and stunted growth -Constituent of many proteins and enzymes -Produce growth hormone and involves in internode elongation	-Declined growth rate	[41,42]
4	Boron	-Plays an important role in the physiological processes of plants such as cell elongation, protein synthesis, cell maturation, meristematic tissue development, etc. -Regulates internal water balance by opening and closing of stomata	-Affects the reproduction of the plants -Display very poor meristematic development	[43,44]
5	Molybdenum	-Plays a major role in rate of transpiration and water relation -It helps in nitrogen fixation to the root nodes in the plants like legume, broccoli, etc.	-Pale leaves with interveinal, marginal chlorosis (yellowing) and necrosis (scald)	[45,46]
6	Copper	-Activates catalytic reaction and enzymes for plant growth -Ensures successful photosynthesis	-Cupping or puckering between the veins of leaves	[47,48]

unlike hard water. Therefore, the desired alkalinity of the water is not altered, which is a necessary parameter for the healthy growth of plants [49].

Light

Sunlight is an essential component in the process of photosynthesis that provides energy to plants. If plants are grown in indoor conditions, they must imitate the natural environment facilitated through an artificial light source like a light-emitting diode. Two types of light sources are High-Intensity Discharge [HID] and Metal Halide [MH]. The HID source is the finest choice for the flowering and fruiting stage of the plant as it emits light in the yellow and green spectrum but plays a lesser role in the production of photosynthesis. MH source is mostly used during the vegetative state of plants which emits blue and violet light [50].

Temperature

It is reported that the optimum temperature of the nutrient solution should be 23°C. However, plant growth occurs at a different temperatures [51] and depends on the plant type. For example, plants like lettuce and violet carnation grow at 4°C while cucumber, tomatoes, orchids, etc. grow at 21°C [52].

The pH of nutrient solution

pH is an important factor for plant growth because when the pH level is too low, the nutrient solution becomes acidic, and plants lose their tendency to absorb the nutrients through the root zone, which leads to lethality [53]. If the pH is high, the nutrient medium will turn out to be alkaline, which would prevent the nutrient uptake and thereby leads to deficiencies. For instance, iron deficiency occurs when the pH exceeds 6-6.5. And hence, productivity and yield will be drastically affected [54]. For quick absorption of nutrients, the plants must be grown in a perfect environment with vital nutrients. If the pH concentration of the media is not in control, there will be retention in the plant growth. A pH value of about 5.5-6.5 is advisable for plants grown using a hydroponic system [55].

3. Types of hydroponics

3.1. Wick system or passive system

The wick system uses a wick that has a high capillary solution where the nutrient solution will be supplied to the plant roots via this wick (Fig. 2a). Here, the wick is made up of fibrous material like nylon that would absorb the nutrient solution and re-direct it to the plant roots [56]. This technique possesses the advantage over other techniques as it is simple and doesn't require electrical accessories like electricity, pumps, or aerators. However, the wick system is not a wise choice for long-term plants that require a large quantity of water than could provide by the wick supply [57].

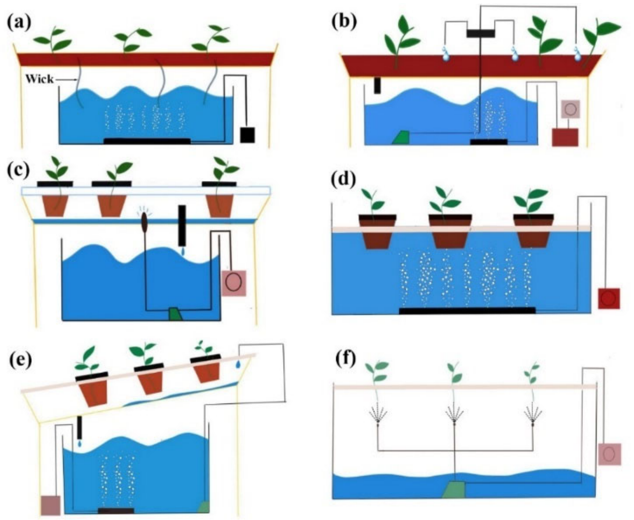

Fig. 2. Types of hydroponic systems. (a) wick system, (b) drip system, (c) Ebb-Flow system, (d) water culture system, (e) nutrient film technique, and (f) aeroponic system

3.2. Drip system

The drip system is used globally for soil-based agriculture and also, can be incorporated into the hydroponic system. The nutrient solution is provided in measured drops, and therefore, the plant roots are always kept moist without overwatering (Fig. 2b). As the solution is supplied in a dripping manner, the evaporation of water can be avoided, which declines wastage of water through leaching or runoff as in the case of conventional agriculture [58]. Usually, the home plants are grown in slightly permeable media, and the requirement of nutrient suspension is moderate for the growth and development of the plants. Distinct plants can be grown systematically with prolonged water supply [59].

3.3. Ebb and flow system

In the ebb and flow system, crops are grown in large grow beds filled with growth medium. In this type of flow system, the grow tray is made to flood with the nutrient solution temporarily and to counteract the overflow of the solution; it is made to drain back into the reservoir (Fig. 2c). This action is performed several times a day by the submerge pump, making use of a timer. The timer would shut off the water pump allowing the nutrient solution to runoff through the pump to the reservoir which completely drains the grow bed. The timer ON/OFF is determined as per the plant variety and environmental factors such as humidity and temperature [60]. This method is one of the most preferred for beginners; even experts also opt for this method. The advantage of this system is that it does not require any machinery and the production of crops is also quite higher. The major fallback of this system is the requirement for an increased water supply [61].

3.4. Deep water culture

Using simple hydroponic systems, the need for large land space for the cultivation of crops can be reduced by 75%, also the requirement of water for irrigation can be lowered by 90% with the negligible environmental resource [62]. It is the simplest of hydroponics setup of all types where a platform made up of polystyrene foam holds the plants and are suspended on the nutrient solution which means that the roots remain immersed in the nutrient-rich oxygenated solution (Fig. 2d). Thus, plants can easily absorb nutrients. The air pump is involved to supply oxygen to roots. Plants such as cucumber and radish, grow well in this system. However, the cultivation of long-term crops may not be possible using this system. And, one of the cons of this system includes the repetitive check of pH level, water level, and concentration as it may fluctuate widely.

3.5. Nutrient film technique (NFT)

In NFT, plants are inserted into the slit cuts in the polyethylene tube where nutrient solution is pumped through (Fig. 2e). Here, a constant flow of nutrient solution is achieved. This system is best suited for plants with small root structures like berries, celery, and lettuce. Even though the roots are small, this architecture would help them to stay constantly submerged in the nutrient solution [63].

3.6. Aeroponics system

It is the most high-tech type of hydroponic system for plant cultivation. In an aeroponics system, roots of the plant remain suspended in an enclosed growing chamber where the nutrient solution is sprayed over it at short intervals, usually every few minutes with the help of a high-pressure sprayer (Fig. 2f). This system is rarely utilized for commercial use because of its high cost involved in installation and maintenance. Also, a frequent cleaning process is required to avoid the spread of plant diseases and blockage in the sprayer. Even partial failure of this system may easily affect the growth conditions and damage the entire crops, and hence ending up with less commercial use compared to others [64].

4. Recent advancements in hydroponics

For the cultivation of various crops, hydroponics is one of the most preferred methods in the future. It is expected that tomatoes, lettuce, and other leafy vegetables are produced more using hydroponic systems. In developing countries like Europe and Asia pacific, people opt for the use of hydroponic method for green-house crop cultivation for its excellent quality of crop yield. In addition to tomatoes and peppers, crops like cucumber, cucurbits, and cantaloupe are successfully grown using this system [59]. With quick urbanization, increased population, and also the increase of community-sponsor programme has paved the way for the cultivation of crops using hydroponics as the incidence of recollection of crops has played a significant role in the development of hydroponic industries globally [65]. Aeroponics and hydroponics are developing technologies for agriculture, as in the case of expanding population and also by the decreased land resources [66]. Lei et al. in 2021 confirmed no morphological difference in lettuce when grown in hydroponics media. The features of hydroponically cultivated lettuce were the same as that of the plant that is grown normally [67]. Another investigation was made in 2018 by Talukder wherein he stated that the production of strawberries was decreased in a hydroponics media when it is reused for a prolonged period.

In this case, the author treated the reused media by applying DC-ED and AC-ED; after this treatment, the growth of the strawberries increased [68]. The most common pest infection in hydroponically grown cucumbers is *Tetranychus urticae*. According to a study in 2019, the authors recommended the reduction and management of pest infection by the IPM program for greenhouse plants [69]. In 2020 a study conducted by Gao et.al; suggested that the ratios of R: B in LED's plays a significant role in the growth and accumulation of nutrients in hydroponically grown spinach [70]. As per Hopkinson et al.; plants that are hydroponically grown in 5, 8, and 9 pH have a drastic difference in their growth pattern later resulted in the expiry of the plant. And plants that are grown in a neutral pH nutrient media have shown to be much healthier [71]. Using hydroponics systems, the demand for the growth of crops has been enlarged. This advancement has shown to be more environmental friendly wherein the need for human performance is limited.

5. Advantages and issues

The forthcoming evolution of hydroponics will be notably dependent on the acclimatization of medium as well as low technical point expanding methods capable of emulating with the expensive structures utilized in large advanced countries. This will undoubtedly be feasible by utilising regionally accessible substratum and also cultivating inherent or endemic crops with cost-effective prospective for food as well as for therapeutic targets. It can prevent crops from soil-borne pathogens and diseases resulting in better yield. Using this system, cultivation of crops is made possible even in the place where soil quality is poor. Using the nutrient solution, nutrition can be supplied to the crops with precision and can be controlled as per the requirement. Further, the environmental parameters can be controlled so that the seasonal crops can be cultivated throughout the year without any genetic modifications. Hydroponic crop cultivation also provides quality crops because its devoid of the usage of herbicides and pesticides. Another major advantage is that the water used here is not wasted as in the case of soil-based cultivation where water is wasted through runoff and evaporation. Even though, the hydroponic system poses many advantages, it is a complex technical procedure. The de-merits of the system could be addressed by:

- This requires frequent monitoring of the system;
- This method seems quite expensive;
- They require a constant power supply and would collapse if the power supply is interrupted;
- Lack of detection of bad microbial activity at one plant can result in infection of all other plants in the system, as they all are interconnected;
- Water contaminated infections would easily fuse through the system, making the system waterborne;
- Growing a hydroponic garden demands technical expertise;
- Production is limited in comparison to the field agriculture;
- If the system fails, plant death will occur spontaneously.

If all the above-mentioned cons could be rectified in the upcoming days, the hydroponic system can be preferred and utilized as one of the major modern agriculture techniques.

Additional information

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References

[1] A. Sulemana, S.A. Adjei, Microfinance impact on agricultural production in developing countries: a study of the Pru District in Ghana, International Journal of Academic Research and Reflection 3/3 (2015) 26-44.

[2] A. du Toit, D. Neves, The government of poverty and the arts of survival: mobile and recombinant strategies at the margins of the South African economy, The Journal of Peasant Studies 41/5/1 (2014) 833-853. DOI: https://doi.org/10.1080/03066150.2014.894910

[3] N. Van Suu, Industrialization and Urbanization in Vietnam: How Appropriation of Agricultural Land Use Rights Transformed Farmers’ Livelihoods in a Peri-Urban Hanoi Village?, Final Report of an EADN Individual Research Grant Project, EADN Working Paper 38, 2009.

[4] C. Treftz, ST. Omaye, Hydroponics: Potential for augmenting sustainable food production in non-arable regions, Nutrition and Food Science 46/5 (2016) 672-684. DOI: https://doi.org/10.1108/NFS-10-2015-0118

[5] A. Sarkar, M. Majumder, Economic of cubical and semi-spherical shape stacked protected farms for marginal farmers, Agricultural Engineering International: CIGR Journal 21/2 (2019) 1-6.

[6] W. Radzki, F.G. Mañero, E. Algar, J.L. García, A. García-Villaraco, B.R. Solano, Bacterial siderophores efficiently provide iron to iron-starved tomato plants in hydroponics culture, Antonie Van Leeuwenhoek 104/3 (2013) 321-330. DOI: https://doi.org/10.1007/s10482-013-9954-9

[7] R. Azarmi, S.J. Tabatabaei, N. Chaparzadeh, Interactive effects of Mg and shading on the yield, physiology and antioxidant activity in cucumber grown in hydroponics, Journal of Plant Process and Function 6/22 (2018) 63-72.

[8] Q. Li, X. Li, B. Tang, M. Gu, Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture, Horticulturae 4/4 (2018) 35. DOI: https://doi.org/10.3390/horticulturae4040035

[9] D. Dhanasekaran, M. Jasmine, Rooting behavior of certain foliage ornamentals grown under hydroponic nutrient solutions, Annals of Plant and Soil Research 21/4 (2019) 346-350.

[10] K. Jeyasubramanian, U.U.G. Thoppey, G.S. Hikku, N. Selvakumar, A. Subramania, K. Krishnamoorthy, Enhancement in growth rate and productivity of spinach grown in hydroponics with iron oxide nanoparticles, RSC Advances 6/19 (2016) 15451-15459. DOI: https://doi.org/10.1039/C5RA23425E

[11] N.C. Uren, Types, amounts, and possible functions of compounds released into the rhizosphere by soil-grown plants, in: S. Willig, Z. Varanini, P. Nannipieri (eds), The rhizosphere, CRC Press, Boca Raton, 2000, 35-56.

[12] M.H. Jensen, Hydroponic culture for the tropics: opportunities and alternatives, Asian and Pacific Council, Food Technology Center, 1991.

[13] G. Schmilewski, The role of peat in assuring the quality of growing media, Mires and Peat 3 (2008) 02.

[14] J.E. Rakocy, Aquaponics—Integrating fish and plant culture, aquaculture production systems, in: J.H. Tidwell (ed), Aquaculture Production Systems, Wiley-Blackwell, Oxford, 2012, 344-386. DOI: https://doi.org/10.1002/9781118250105.ch14

[15] K. Al Akeel, Empirical investigation of water pollution control through use of Phragmites australis, PhD Thesis, Brunel University School of Engineering and Design, London, 2013.

[16] P. Morard, J. Silvestre, Plant injury due to oxygen deficiency in the root environment of soilless culture: a review, Plant and Soil 184/2 (1996) 243-254. DOI: https://doi.org/10.1007/BF00010453

[17] R.A. Pastorok, M.W. Lorenzen, T.C. Ginn, Environmental Aspects of Artificial Aeration and Oxygenation of Reservoirs: A Review of Theory, Techniques, and Experiences, Final Report, U.S. Army Engineer Waterways Experiment Station, 1982.

[18] D.R. Hoagland, D.I. Arnon, The water-culture method for growing plants without soil, Circular 347, California Agricultural Experiment Station, 1950.

[19] D.K. Tripathi, V.P. Singh, D.K. Chauhan, S.M. Prasad, N.K. Dubey, Role of macronutrients in plant growth and acclimation: recent advances and future prospective, in: P. Ahmad, M. Wani, M. Azooz, L.S. Phan Tran (eds), Improvement of Crops in the Era of Climatic Changes, Springer, New York, 2014, 197-216. DOI: https://doi.org/10.1007/978-1-4614-8824-8_8

[20] M.F. Mondal, M. Asaduzzaman, M. Ueno, M. Kawaguchi, S. Yano, T. Ban, H. Tanaka, T. Asao, Reduction of potassium (K) content in strawberry fruits through KNO_3 management of hydroponics, The

Horticulture Journal 86/1 (2017) 26-36. DOI: https://doi.org/10.2503/hortj.MI-113
[21] V. Römheld, E.A. Kirkby, Research on potassium in agriculture: needs and prospects, Plant and Soil 335/1 (2010) 155-180. DOI: https://doi.org/10.1007/s11104-010-0520-1
[22] R.A. Sharma, A.R. Azad A Research Note on Chlorosis (Yellowing) in Plants: A Serious Problem and its Remedy, Agriculture and Food: e-Newsletter 2/10 (2020).
[23] W.H. Allaway, The effect of soils and fertilizers on human and animal nutrition, Agriculture Information Bulletin No. 378 (1975) 1-52.
[24] Z.-A. Huang, D.-A. Jiang, Y. Yang, J.-W. Sun, S.-H. Jin, Effects of nitrogen deficiency on gas exchange, chlorophyll fluorescence, and antioxidant enzymes in leaves of rice plants, Photosynthetica 42/3 (2004) 357-364. DOI: https://doi.org/10.1023/B:PHOT.0000046153.08935.4c
[25] A.M. Rychter, I.M. Rao, Role of phosphorus in photosynthetic carbon metabolism, in: M. Pessarakli (ed), Handbook of Photosynthesis, Taylor and Francis Group, 2005, 123-48.
[26] R. Huang, C. Fang, X. Lu, R. Jiang, Y. Tang, Transformation of phosphorus during (hydro) thermal treatments of solid biowastes: reaction mechanisms and implications for P reclamation and recycling, Environmental Science and Technology 51/18 (2017) 10284-10298. DOI: https://doi.org/10.1021/acs.est.7b02011
[27] A. McCauley, C. Jones, J. Jacobsen, Plant nutrient functions and deficiency and toxicity symptoms, Nutrient Management Module 9 (2009) 1-16.
[28] K. Mengel, E.A. Kirkby, H. Kosegarten, T. Appel, Nutrient uptake and assimilation, in: K. Mengel, E.A. Kirkby, H. Kosegarten, T. Appel (eds), Principles of Plant Nutrition, Springer, Dordrecht, 2001, 111-179. DOI: https://doi.org/10.1007/978-94-010-1009-2_3
[29] R. Uchida, Essential nutrients for plant growth: nutrient functions and deficiency symptoms, Plant Nutrient Management in Hawaii's Soils 4 (2000) 31-55.
[30] P.J. White, M.R. Broadley, Calcium in plants, Annals of Botany 92/4 (2003) 487-511. DOI: https://doi.org/10.1093/aob/mcg164
[31] E.W. Simon, The symptoms of calcium deficiency in plants, New Phytologist 80 (1978) 1-15.
[32] Y.P. Abrol, A. Ahmad (eds), Sulphur in plants, Springer, Dordrecht, 2003. DOI: https://doi.org/10.1007/978-94-017-0289-8
[33] J.I. Alvarez-Leite, Nutrient deficiencies secondary to bariatric surgery, Current Opinion in Clinical Nutrition and Metabolic Care 7/5 (2004) 569-575.
[34] E. Keleş, P. Kefeli, Determination of student misconceptions in "photosynthesis and respiration" unit and correcting them with the help of cai material, Procedia - Social and Behavioral Sciences 2/2 (2010) 3111-3118. DOI: https://doi.org/10.1016/j.sbspro.2010.03.474
[35] C. Shand, (2007). Plant Nutrition for Food Security. A Guide for Integrated Nutrient Management. By R. N. Roy, A. Finck, G. J. Blair and H. L. S. Tandon. Rome: Food and Agriculture Organization of the United Nations (2006), pp. 348, US $70.00. ISBN 92-5-105490-8. Experimental Agriculture, 43(1), 132-132. DOI: https://doi.org/10.1017/S0014479706394537
[36] J.F. Ma, Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses, Soil Science and Plant Nutrition 50/1 (2004) 11-18. DOI: https://doi.org/10.1080/00380768.2004.10408447
[37] F.J.M. Maathuis, Physiological functions of mineral macronutrients, Current Opinion in Plant Biology 12/3 (2009) 250-258. DOI: https://doi.org/10.1016/j.pbi.2009.04.003
[38] S.S. Merchant, The elements of plant micronutrients, Plant Physiology 154/2 (2010) 512-515. DOI: https://doi.org/10.1104/pp.110.161810
[39] M. Zekri, T.A. Obreza, Micronutrient deficiencies in citrus: iron, zinc, and manganese, EDIS 2003 (2003) SL 204. DOI: https://doi.org/10.32473/edis-ss423-2003
[40] C.A. Hebbern, K.H. Laursen, A.H. Ladegaard, S.B. Schmidt, P. Pedas, D. Bruhn, J.K. Schjoerring, D. Wulfsohn, S. Husted, Latent manganese deficiency increases transpiration in barley (Hordeum vulgare), Physiologia Plantarum 135/3 (2009) 307-316. DOI: https://doi.org/10.1111/j.1399-3054.2008.01188.x
[41] N. Kawagashira, Y. Ohtomo, K. Murakami, K. Matsubara, J. Kawai, P. Carninci, Y. Hayashizaki, S. Kikuchi, K. Higo, Multiple zinc finger motifs with comparison of plant and insect, Genome Informatics 12 (2001) 368-369. DOI: https://doi.org/10.11234/gi1990.12.368
[42] D.P. Schachtman, R.J. Reid, S.M. Ayling, Phosphorus uptake by plants: from soil to cell, Plant Physiology 116/2 (1998) 447-453. DOI: https://doi.org/10.1104/pp.116.2.447
[43] N. Pradhan, R. Rani, J. David, A Review on Utility of An Astonishing Fruit: Psidium Guajava (Guava), Journal of Science and Technology 06/01 (2021) 60-72.
[44] B. Dell, L. Huang, Physiological response of plants to low boron, Plant and Soil 193/1 (1997) 103-120. DOI: https://doi.org/10.1023/A:1004264009230
[45] G. Schwarz, R.R. Mendel, Molybdenum cofactor biosynthesis and molybdenum enzymes, Annual

Review of Plant Biology 57 (2006) 623-647. DOI: https://doi.org/10.1146/annurev.arplant.57.032905.105437

[46] E.A. Waraich, R. Ahmad, M.Y. Ashraf, Saifullah, M. Ahmad, Improving agricultural water use efficiency by nutrient management in crop plants, Acta Agriculturae Scandinavica, Section B – Soil and Plant Science 61/4 (2011) 291-304. DOI: https://doi.org/10.1080/09064710.2010.491954

[47] W. Claussen, Growth, water use efficiency, and proline content of hydroponically grown tomato plants as affected by nitrogen source and nutrient concentration, Plant and Soil 247/2 (2002) 199-209. DOI: https://doi.org/10.1023/A:1021453432329

[48] S. Carruthers, Copper: Deficiency and toxicity, Practical Hydroponics and Greenhouses 173 (2016) 50-53.

[49] F.G. Schröder, J.H. Lieth, Irrigation control in hydroponics, in: D. Savvas, H. Passam (eds), Hydroponic Production of Vegetables And Ornamentals, 2002, 263-298.

[50] R.W. Langhans, T.W. Tibbitts (eds), Plant growth chamber handbook, North Central Regional Research Publication No. 340, Iowa Agriculture and Home Economics Experiment Station Special Report No. 99, 1997.

[51] J.S. Amthor, The role of maintenance respiration in plant growth. Plant, Cell and Environment 7/8 (1984) 561-569. DOI: https://doi.org/10.1111/1365-3040.ep11591833

[52] O.K. Atkin, D. Bruhn, V.M. Hurry, M.G. Tjoelker, Evans Review No. 2: The hot and the cold: unravelling the variable response of plant respiration to temperature, Functional Plant Biology 32/2 (2005) 87-105. DOI: https://doi.org/10.1071/FP03176

[53] S.M. Alam, Nutrient uptake by plants under stress conditions, in: M. Pessarakli (ed), Handbook of Plant and Crop Stress, Second Edition, Marcel Dekker, New York – Basel, 1999, 285-313.

[54] A.K. Islam, D.G. Edwards, C.J. Asher, pH optima for crop growth, Plant and Soil 54/3 (1980) 339-357. DOI: https://doi.org/10.1007/BF02181830

[55] M.R. Rahim, R.M. Akir, Automated pH Monitoring and Controlling for Hydroponics Cultivation, Evolution in Electrical and Electronic Engineering 2/2 (2021) 775-782.

[56] R.M. Mugundhan, M. Soundaria, V. Maheswari, P. Santhakumari, V. Gopal, “Hydroponics" - a novel alternative for geoponic cultivation of medicinal plants and food crops, International Journal of Pharma and Bio Sciences 2/2 (2011) P-296.

[57] I.A. Lakhiar, G. Jianmin, T.N. Syed, F.A. Chandio, N.A. Buttar, W.A. Qureshi, Monitoring and control systems in agriculture using intelligent sensor techniques: A review of the aeroponic system, Journal of Sensors 2018 (2018) 8672769. DOI: https://doi.org/10.1155/2018/8672769

[58] A. Hussain, K. Iqbal, S. Aziem, P. Mahato, A.K. Negi, A review on the science of growing crops without soil (soilless culture)-a novel alternative for growing crops, International Journal of Agriculture and Crop Sciences 7/11 (2014) 833-842.

[59] N. Sharma, S. Acharya, K. Kumar, N. Singh, O.P. Chaurasia, Hydroponics as an advanced technique for vegetable production: An overview, Journal of Soil and Water Conservation 17/4 (2018) 364-371. DOI: http://dx.doi.org/10.5958/2455-7145.2018.00056.5

[60] S. Lee, J. Lee, Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods, Scientia Horticulturae 195 (2015) 206-215. DOI: https://doi.org/10.1016/j.scienta.2015.09.011

[61] D.A. Kluko, Home hydroponics, Popular Mechanics 2 (2017) 85-87.

[62] A. Hamza, R.E. Abdelraouf, Y.I. Helmy, S.M. El-Sawy, Using deep water culture as one of the important hydroponic systems for saving water, mineral fertilizers, and improving the productivity of lettuce crop, International Journal of Health Sciences 6/S9 (2022) 2311-2331. DOI: https://doi.org/10.53730/ijhs.v6nS9.12932

[63] M. Schwarz, Soilless Culture Management, Springer Berlin, Heidelberg, 1995. DOI: https://doi.org/10.1007/978-3-642-79093-5

[64] K.A. El-Kazzaz, A.A. El-Kazzaz, Soilless agriculture a new and advanced method for agriculture development: an introduction, Agricultural Research and Technology: Open Access Journal 3/2 (2017) 63-72.

[65] D.N. Gilmour, C. Bazzani, R.M. Nayga Jr, H.A. Snell, Do consumers value hydroponics? Implications for organic certification, Agricultural Economics 50/6 (2019) 707-721. DOI: https://doi.org/10.1111/agec.12519

[66] M.D. Sardare, S.V. Admane, A review on plant without soil-hydroponics, International Journal of Research in Engineering and Technology 2/3 (2013) 299-304.

[67] C. Lei, N.J. Engeseth, Comparison of growth characteristics, functional qualities, and texture of hydroponically grown and soil-grown lettuce, LWT 150 (2021) 111931. DOI: https://doi.org/10.1016/j.lwt.2021.111931

[68] M.R. Talukder, M. Asaduzzaman, H. Tanaka, T. Asao, Electro-degradation of culture solution improves growth, yield and quality of strawberry plants grown in closed hydroponics, Scientia Horticulturae 243 (2019) 243-251.
DOI: https://doi.org/10.1016/j.scienta.2018.08.024

[69] M.S. Saleem, T.S. Batool, M.F. Akbar, S. Raza, S. Shahzad, Efficiency of botanical pesticides against some pests infesting hydroponic cucumber, cultivated under greenhouse conditions, Egyptian Journal of Biological Pest Control 29/1 (2019) 37. DOI: https://doi.org/10.1186/s41938-019-0138-4

[70] W. Gao, D. He, F. Ji, S. Zhang, J. Zheng, Effects of daily light integral and LED spectrum on growth and nutritional quality of hydroponic spinach, Agronomy 10/8 (2020) 1082.
DOI: https://doi.org/10.3390/agronomy10081082

[71] S. Hopkinson, M. Harris, Effect of pH on Hydroponically Grown Bush Beans (phaseolus vulgaris), International Journal of Environment Agriculture and Biotechnology 4/1 (2019) 142-145. DOI: https://dx.doi.org/10.22161/ijeab/4.1.23