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Hydroponics as an Advanced Agricultural Production System for Cultivation of Vegetables and Short Duration High Value Crops

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Abstract: Currently hydroponic cultivation methods are gaining popularity all over the world because of efficient resources management and quality food production. Soil based agriculture is now facing various challenges such as urbanization, natural disasters, climate change, indiscriminate use of agriculture chemicals and pesticides which are depleting the land fertility and quality. At global level leading countries in hydroponic technology are Netherland, Australia, France, England, Israel, Canada and USA. For successful implementation of commercial hydroponic technology, it is important to develop low cost techniques which are easy to operate and maintain; requires less labour and lower overall installation and operational cost. In this article various hydroponic systems *viz*. wick, ebb and flow, drip, deep water culture and Nutrient Film Technique (NFT) system; their operations; pros and cons; performance of different vegetable crops like tomato, cucumber, pepper, leafy greens, and other high value crops and water conservation by these techniques, global market and economic analysis of different crops grown under this system are presented.

Keywords: Hydroponic system, nutrient management, nutrient film technique, water conservation, yield

INTRODUCTION

Hydroponics is a technique of growing plants in nutrient solutions with or without the use of an inert medium such as gravel, soil, vermiculite, rock wool, peat moss, saw dust, coir dust, coconut fibre to provide mechanical support. The term Hydroponics was derived from the Greek words ‘hydro’ means water and ‘ponos’ means labour and means water work. The word hydroponics was coined by Professor William Gericke in the early 1930s; describe the growing of plants with their roots suspended in water containing mineral nutrients. Researchers at Purdue University developed the nutriculture system in 1940. During 1960s and 70s, commercial hydroponics farms were developed in Arizona, Abu Dhabi, Belgium, California, Denmark, German, Holland, Iran, Italy, Japan, Russian Federation and other countries. Most hydroponic systems operate automatically to control the amount of water, nutrients and photoperiod based on the requirements of different plants [1].

Due to rapid urbanization and industrialization not only, the cultivable land is decreasing but also conventional agricultural practices causing a wide range of negative impacts on the environment. To sustainably feed the world’s growing population, methods for growing sufficient food have to evolve. Modification in growth medium is an alternative for sustainable production and to conserve fast depleting land and available water resources. In

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the present scenario, soil less cultivation might be commenced successfully and considered as an alternative option for growing healthy food plants, crops or vegetables [2]. Agriculture without soil includes hydro agriculture (Hydroponics), aqua agriculture (Aquaponics) and aerobic agriculture (Aeroponics) as well as substrate culture. Among these hydroponics techniques is gaining popularity because of its efficient management of resources and food production. Various commercial and specialty crops can be grown using hydroponics including leafy vegetables, fruit vegetables like tomatoes, cucumbers, peppers, and other high value fruit crops, cut flowers and medicinal plants. This article covers different types of hydroponics, its benefits and limitations, various components and aspects of hydroponics, different environmental factors to be considered, performance of different crops under hydroponic system, global hydroponic market and economic analysis of crops under hydroponics.

Hydroponic systems andits operation:

Hydroponic system is customized and modified according to recycling, reuse of nutrient solution and supporting media. Commonly used systems are wick, drip, ebb-flow, deep water culture, nutrient film technique (NFT) and aeroponics systems which are described below.

Wick System

This is simplest hydroponic system requiring no electricity, pump and aerators [3]. Plants are placed in an absorbent medium like coco coir, vermiculite, perlite with a nylon/cotton wick running from plant roots into a reservoir of nutrient solution. Water or nutrient solution supplied to plants through capillary action. This system works well for small plants, herbs and spice and doesn't work effectively that needs a lot of water.

Fig 1a. Wick system in hanging bucket style (Photo courtesy: J Suresh Kumar)

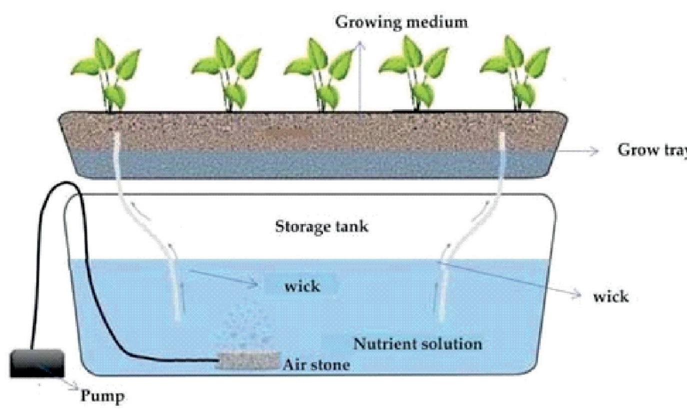

Fig 1b. Wick system with aerator for more number of plants (line diagram)

Deep water culture system

In deep water cultures, roots of plants are suspended in nutrient rich water and air is provided directly to the roots by an air stone. Hydroponics buckets system is classical example of this system. Plants are placed in net pots and roots are suspended in nutrient solution where they grow quickly in a large mass. It is mandatory to monitor the oxygen and nutrient concentrations, salinity and pH [4] as algae and moulds can grow rapidly in the reservoir.

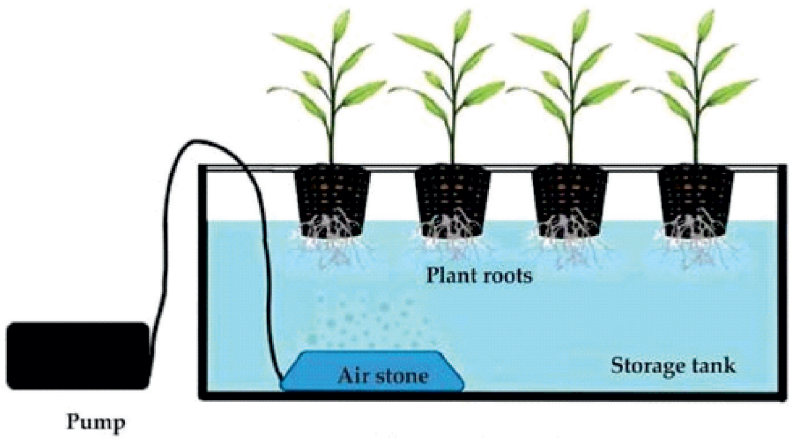

Figure 2a: Deep water culture line diagram

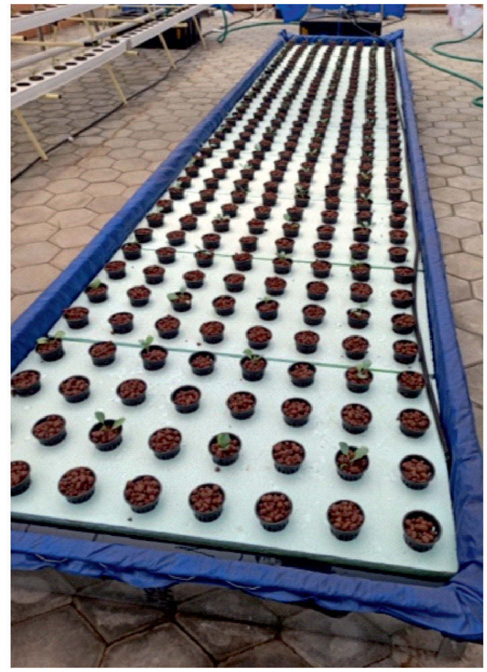

Figure 2b: Deep water culture of lettuce in net pots fixed in thermocol sheet floating on nutrient solution (*Photo courtesy:* J Suresh Kumar)

Ebb and Flow system

This is first commercial hydroponic system which works on the principle of flood and drain. Nutrient solution and water from reservoir flooded through a water pump to grow bed until it reaches a certain level and stay there for certain period of time so that it provides nutrients and moisture to plants. Besides, it is possible to grow different kinds of crops but the problem of root rot, algae and mould is very common [5] therefore, some modified system with filtration unit is required.

Drip system

The drip hydroponic system is widely used method among both home and commercial growers. Water or nutrient solution from the reservoir is provided to individual plant roots in appropriate proportion with the help of pump [6]. Plants are usually placed in moderately absorbent growing medium so that the nutrient solution drips slowly. Various crops can be grown systematically with more conservation of water.

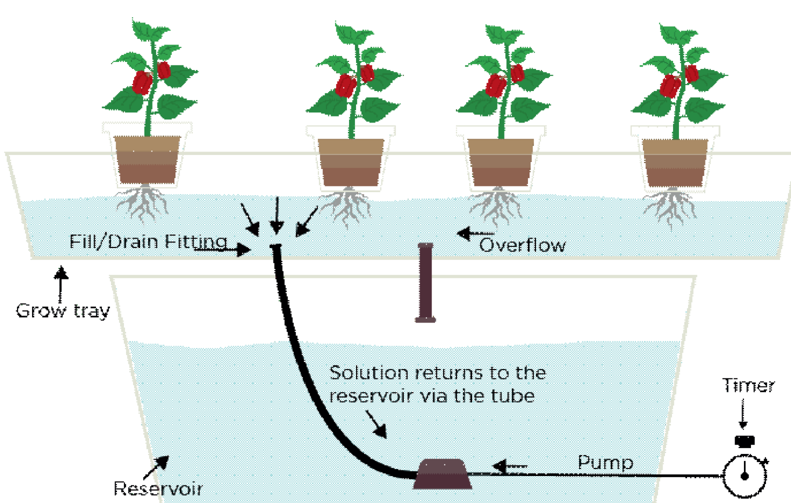

Figure 3a: Ebb and flow system line diagram

Figure 3b: Ebb and flow model available in market

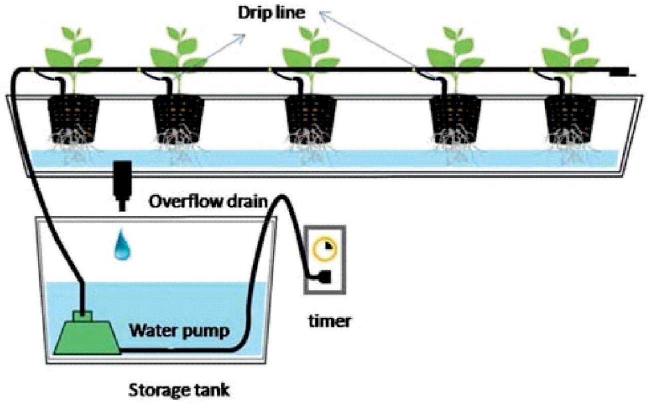

Figure 4a: Drip system of hydroponics line diagram

Figure 4b: Drip system of tomato cultivation in hydroponics (*Photo courtesy:* J Suresh Kumar)

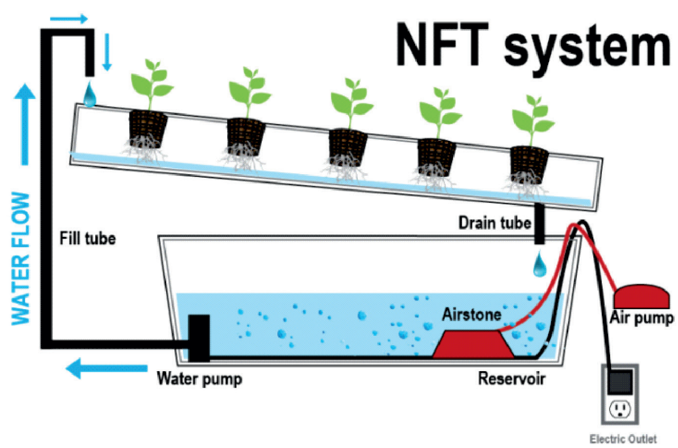

Figure 5a: Nutrient film technique line diagram

Figure 5b: Nutrient film technique - cultivation of leafy veggies (*Photo courtesy:* J Suresh Kumar)

Nutrient Film Technique (NFT) system

NFT was developed in the mid-1960s in England by Dr. Alen Cooper to overcome the shortcomings of ebb and flow system. In this system, water or a nutrient solution circulates throughout the entire system; and enters the growth t ray via a water pump without a time control [4]. The system is slightly slanted so that nutrient solution runs through roots and down back into a reservoir. Plants are placed in channel or tube with roots dangling in a hydroponic solution. Although, roots are susceptible to fungal infection because they are constantly immersed in water or nutrient. In this system, many leafy greens can easily be grown. This is the most widely and commercially used for production of lettuce.

Aeroponics

The basic principle of aeroponic growing is to grow plants suspended in a closed or semi-closed environment by spraying the plant's dangling roots and lower stem with an atomized or sprayed, nutrient-rich water solution. The leaves and canopy extend above. The roots of the plant are separated by the plant support structure like cell foam is compressed around the lower stem and inserted into an opening in the aeroponic chamber.

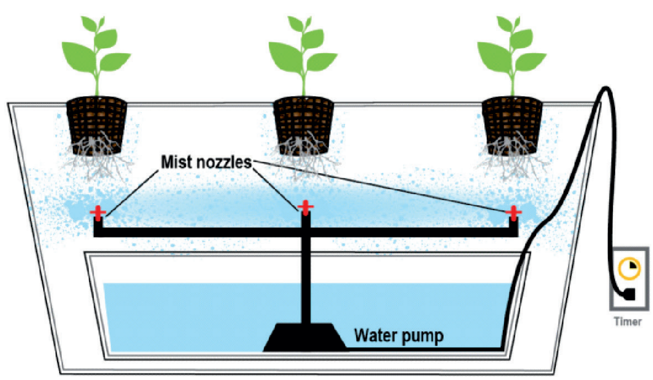

Figure 6a: Aeroponics line diagram

Fig 6b. Aeroponics seed potato tuber production
(*Source*: https://www.patrika.com**)**

Benefits and limitationsof hydroponics

Hydroponic technique is becoming popular because this is clean, relatively easy method and there is no chance of soil-borne disease,insect pest infection to the crops thereby reducing or eliminating use of pesticides and their resulting toxicity. Besides, plants require less growing time as compared to crop grown in field and growth of plant is faster as there is no mechanical hindrance to the roots and the entire nutrient are readilyavailable for plants. This technique is very useful for the area where environmental stress (cold, heat,dessert) is a major problem [7]. Crops in hydroponic system are not influenced by climate change therefore, can be cultivated year-round. Further, commercial hydroponic systems are automatically operated and expected to eliminate the traditional agricultural practices like weeding, spraying, watering and tilling [8]. Hydroponics saves large amount of water. The problem of pest and disease can be controlled easily. Higher yields can be obtained since the number of plants per unit is higher compared to conventional agriculture.

Although soil-less cultivation is an advantageous technique but some limitations are significant. Technical knowledge and higher initial cost are fundamental requirement for commercial scale cultivation [1]. Plant in a hydroponics system is sharing the exact same nutrient, sometimes contamination of nutrient solution may easily spread from one plant to another [9]. Hot weather and limited oxygenation in the nutrient solution may limit production and can result in loss of crops. Maintenance of pH, EC and proper concentration of the nutrient

Table 1. Different hydroponics systems and their pros and cons:

S. No	Hydroponic system	Pros	Cons
1.	Wick System (Basic system)	• Affordable • No maintenance • Low nutrient pump	• Limited oxygen access • Slow growth rate • No nutrient recirculation • Prone to algae growth
2.	Deep water culture system	□ Cheapest of the active systems □ Simple set up □ No nutrient pump □ Reliable	□ Risk of root rot if not cleaned □ Slower growth rate □ Must top water until roots are long enough to fall into the nutrition solution □ Must frequently refill reservoir
3.	Ebb and Flow system	• Affordable • Low maintenance • Excess nutrient solution recirlculates	• Fall to algae growth • Technical malfunction could results in crop loss
4.	Drip system	□ Excess nutrient solution recirculates □ Sufficient oxygen flow	□ Prone to clogging □ Prone to algae growth □ Requires regular cleaning
5.	Nutrient Film Technique (NFT)	• Excess nutrient solution recirculates • Plentiful oxygen flow • Space efficiency	• Prone to clogging • Technical malfunctions could results in crop loss
6.	Aeroponics (Most advanced system)	□ Maximum nutrient absorption □ Excess nutrient solution recirculates □ Plentiful oxygen flow □ Space efficient	□ Prone to clogging □ Technical malfunctions could results in crop loss very quickly □ High-tech and costly □ Time intensive □ Poorly suited to thick organic based nutrients and additives

solutions are of prime importance. Finally, light and energy supply are required to run the system under protected structures.

Different components of hydroponics

Medium or substrate required

One of the most important factors for hydroponics system is to choose the right substrate or medium. Different media or substrate can be used for different growing techniques. The substrate which can be used for hydroponics farming is an inert material and it doesn't provide any nutrients to the plant, it only acts as base to grow the better plant roots and holds moisture [10], it shouldn't hold any poisonous materials [11]. The most common materials used as growing media are coarse sand, gravel, perlite, vermiculite, shredded coconut fibers, expanded clay pellets and Rockwool [12] either alone or mixing of these substrate [13, 14, 15].

Plant nutrients used in hydroponics

Nutrient solution is one of the most vital factors which influence crop growth, quality and yield. A hydroponics system contains mainly aqueous solution of essential elements of inorganic compounds, some organic compounds such as iron chelates [16]. All 17 essential elements namely carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn) are required for plant growth [17] are supplied using different chemical combinations. *Hoagland's* solution is used as most common nutrient solutions for hydroponic systems. *Cooper's* 1988 and *Imai's* 1987 nutrient solutions were also used for growing different leafy vegetables and fruit vegetables (tomatoes and cucumber).

Proper pH and EC of the nutrient solution is very essential and should be maintained properly for optimum plant growth and yield [24]. Optimum range of EC and pH values for different hydroponic crops mentioned in Table 3.

Total amount of ions of dissolved salts in nutrient solutions determine the plant growth,

Table 2: Concentration ranges of essential mineral elements according to various authors [18, 19, 20, 21]

Nutrient (mg L^{-1})	*Hoagland & Arnon [22]*	*Hewitt [23]*	*Cooper [18]*	*Steiner [20]*
N	210	168	200-236	168
P	31	41	60	31
K	234	156	300	273
Ca	160	160	170-185	180
Mg	34	36	50	48
S	64	48	68	336
Fe	2.5	2.8	12	2-4
Cu	0.02	0.064	0.1	0.02
Zn	0.05	0.065	0.1	0.11
Mn	0.5	0.54	2.0	0.62
B	0.5	0.54	0.3	0.44
Mo	0.01	0.04	0.2	Not considered

PH and electrical conductivity (EC)

development and production of plants which exert a force called osmotic pressure. It is fully dependent on the measure of dissolved solutes [25]. The ions associated with EC are Ca^{2+}, Mg^{2+}, K^+, Na^+, H^+, NO^{3-}, SO_4^{2-}, Cl^-, HCO_3^-, OH^- [26]. The supply of micro nutriments, namely Fe, Cu, Zn, Mn, B, Mo, and Ni, are very small in ratio to the others elements (macro nutrients), so it has no a significant effect on EC [27]. Ideal EC range for hydroponics for most of the crops is between 1.5 and 2.5 dS m^{-1}. Higher EC will prevent nutrient absorption due to osmotic pressure and lower level severely affects plant health and yield. So, appropriate management of EC in hydroponics technique can give effective tool for improving yield and quality [28, 29]. A97I Ns an example, yield of tomato under hydroponic system increased as EC of nutrient solution from 0 to 3 dSm^{-1} and decreased as the EC increased from 3 to 5 dS m^{-1} due to increase of water stress [30]. Level of EC @ 1.5, 2 and 3 dS m^{-1} at vegetative, middle vegetative and generative phase, respectively had increased crop height, fruit number and pepper fresh weight [30].

Table 3. Optimum range of EC and pH values for hydro-ponic crops [29]

Crops	*EC (dSm^{-1})*	*pH*
Asparagus	1.4 to 1.8	6.0 to 6.8
African Violet	1.2 to 1.5	6.0 to 7.0
Basil	1.0 to 1.6	5.5 to 6.0
Bean	2.0 to 4.0	6.0
Banana	1.8 to 2.2	5.5 to 6.5
Broccoli	2.8 to 3.5	6.0 to 6.8
Cabbage	2.5 to 3.0	6.5 to 7.0
Celery	1.8 to 2.4	6.5
Carnation	2.0 to 3.5	6.0
Courgettes	1.8 to 2.4	6.0
Cucumber	1.7 to 2.0	5.0 to 5.5
Egg plant	2.5 to 3.5	6.0
Ficus	1.6 to 2.4	5.5 to 6.0
Leek	1.4 to 1.8	6.5 to 7.0
Lettuce	1.2 to 1.8	6.0 to 7.0
Pak Choi	1.5 to 2.0	7.0
Peppers	0.8 to 1.8	5.5 to 6.0
Parsley	1.8 to 2.2	6.0 to 6.5
Rhubarb	1.6 to 2.0	5.5 to 6.0
Rose	1.5 to 2.5	5.5 to 6.0
Spinach	1.8 to 2.3	6.0 to 7.0
Strawberry	1.8 to 2.2	6.0
Sage	1.0 to 1.6	5.5 to 6.5
Tomato	2.0 to 4.0	6.0 to 6.5

The pH is a parameter that measures the acidity or alkalinity of a solution. This value indicates the relationship between the concentration of free ions H^+ and OH^- present in a solution and ranges between 0 and 14. In a nutrient solution, pH determines the availability of essential plant elements (Figure 7) [32]. Optimum pH range of nutrient solution for development of plants is 5.5 to 6.5 [33] for most species but some can differ from this range. pH values below 6.0 causing the solubility of phosphoric acid, calcium and magnesium to drop and above 7.5 causes iron, manganese, copper, zinc and boron ions to be less available to plants. Once the plants grow, it will change the composition of nutrient solution by depleting specific nutrients more rapidly than others, removing water from the solution and altering the pH by excretion of either acidity or alkalinity. Wang [34] found that mixture of three [nitric acid (HNO_3), phosphoric acid (H_3PO_4) and sulfuric acid (H_2SO_4)] acids were much more effective than only single acid for maintaining an optimal solution pH of 5.5 to 6.5. Change in pH may cause nutrient imbalance and plant will show some deficiency or toxicity symptoms [35]. Hence, care is required for maintaining optimum pH, EC and nutrient level in hydroponic solution. Crops such as vegetables, spices, flower and ornamentals, medicinal plants, fruits like straw berry, fodders, and up to some extent cereals like maize can be raised through soil less hydroponic technique (Table 3).

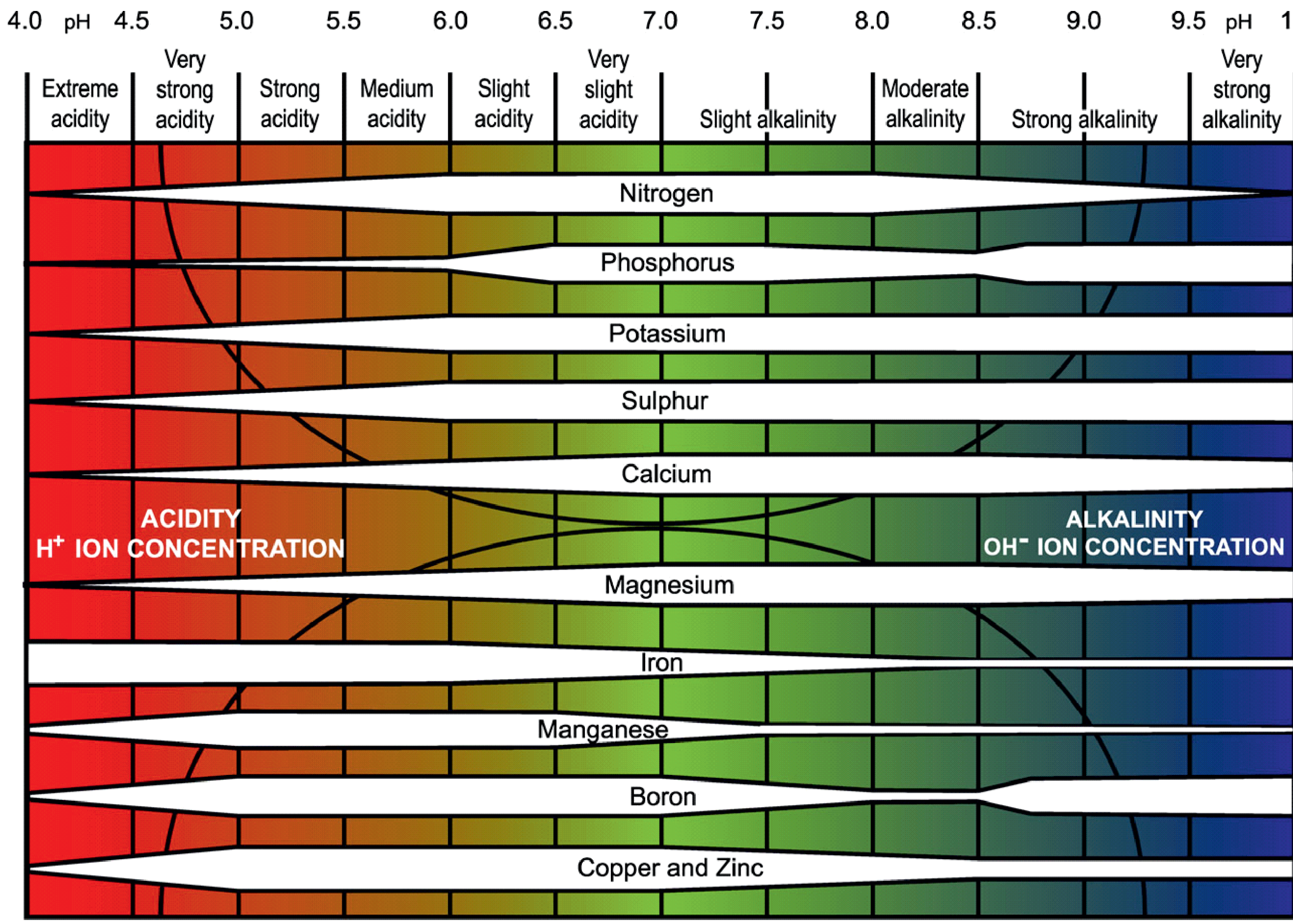

Figure 7: Troug diagram of nutrient availability. Each nutrient is represented with a band; the thickness is proportional to the availability

The following steps should be performed for EC and pH management:

- Set the desired EC and pH value of the solution.
- Calibrate the meters probe with buffer solution. Make sure the nutrient solution is stirred properly and allow the reading to stabilize, which may take a couple of minutes.
- If the pH reading is high, add phosphoric acid, citric acid, vinegar or pH down products into the solution and stir it well. Repeat the process until the pH reaches the optimum range.
- If the pH value is low, add potassium hydroxide, potassium carbonate or a pH up product slowly. Repeat until the pH reaches the optimum range.
- If the EC reading is higher than the required level, then dilute the nutrient solution by adding more water, repeat the process until it reaches the required level.

- If the reading is below the optimum level, add stock nutrient solution until the required level is attained.
- Clean the probe using distilled water.

Water Quality

Water quantity is a key factor in hydroponic system used in recirculating nutrient solution. In general, water quality is a complex concept. However, water quality of hydroponics can be limited to the quantity of specific ions and growth promoting elements relevant for plant nutrition and also with the presence of organisms and substance that clog the irrigation systems [36].

First step for hydroponics is to have the water analyzed, pH, electrical conductivity (EC) and alkalinity of the water has to be tested. Nutrient toxicity or deficiency problems may occur in the initial or later stages of production if poor quality water is used. Normally water contains salts like chlorides and sulfates of sodium, calcium, magnesium, carbonates and bicarbonates. These salts should not be above an acceptable level (Table 4) because it has an effect on EC and pH of the nutrient solution.

Table 4: Acceptable values for common salts found in water [37]

Salt	*Acceptable value (ppm)*
Sodium	<50
Calcium	<150
Magnesium bicarbonate	<50
Chloride	<140
Sulfate	<100

Dissolved Oxygen

Dissolved oxygen indicates the amount of oxygen available in solution. Concentration of oxygen required in nutrient solution varies with crop demand, it changes with the photosynthetic rate [38]. The consumption of O_2 increases with increase in temperature of nutrient solution. If the root aeration is not enough, concentration of carbon dioxide in the root vicinity surge due to root respiration. First symptom of oxygen deficiency is inhibited root growth, followed by brown colored roots [39].

Oxygen-enriched method is often used for research purposes to supply pure, pressurized oxygen gas to the nutrient solution and it is called oxyfertigation [40]. Usually the oxygen level is 8 ppm, but it can be maintained within the range of 7 to 10. In case of small units, it is better to aerate the system using an air pump and aquarium air stone. The supply of potassium peroxide as an oxygen generator at a concentration of 1 g L^{-1} is the best fraction to use in soilless culture. The yield of sweet pepper and melon in 20 and 15% treatment using potassium peroxide increases respectively, in comparison to the control, whereas there was no significant difference in cucumber yield [41].

Various aspects of nutrient management in hydroponics

Nutrient management programs should begin with an understanding of the nutrient solution concentrations in parts per million (ppm) for the various nutrients required by different crops. By managing the concentrations of individual nutrients, growers can control the growth and yield of the crop.

Composition of nutrients in the hydroponics solution

Steiner created the concept of ionic mutual ratio which is based on the anions (NO_3^- , $H_2PO_4^-$ and SO_4^{2-}) and the mutual ratio of cations (K^+, $Ca^{2+,}$ Mg^{2+}). Such a relationship is not just about the total amount of each ion in the solution, but in the quantitative relationship that keep the ions together; if improper relationship between them take place, plant performance can be negatively affected [24].

When a nutrient solution is applied continuously, plants can uptake ions at very low concentrations. So, it has been reported than a high proportion of the nutrients are not used by plants or their uptake does not impact the production. However, there are evidences of positive effects of high concentrations of nutrient solution. In salvia, the increase of Hoagland concentration at 200% caused that plants flowered 8 days previous to the plants at low concentrations, increasing total dry weight and leaf area [42]. High K also can be a problem since it can interfere with the plant's capability to absorb Ca and Mg. Plants exposed to excess K often develop Mg deficiency on the lower leaves and the fruits often develop blossom-end rot (BER), especially early in the season.

Nutrient interaction in hydroponics solution

Nutrients in the solution may interact in various ways that may gain either positive or negative effects on crop production, depends on crop growth stages, amounts, combinations, and balance [43]. Inadequate or excessive concentrations of elements or an imbalanced ion composition in the nutrient solution may inhibit plant development, resulting in toxicity or nutrient-induced deficiencies [44]. Nutrient interactions can be either synergistic or antagonistic and also possible to have no interactions. Interaction between nutrients occurs when the supply of one nutrient affects the absorption and utilization of other. Upon the addition of two nutrients, an increase in crop yield that is more than adding only one, the interaction is positive or synergistic. Similarly, if addition of nutrients produced less yield as compared to individual ones, the interaction is said to be negative or antagonistic [45].

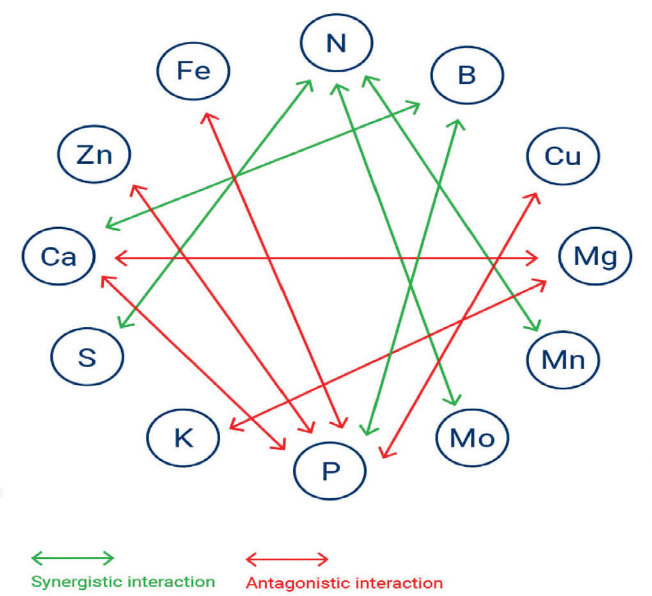

Figure 8: Synergistic and antagonistic interaction

(Source: https://images.app.goo.gl/sioAUj19UvAkqcWV7)

Monitoring the ratio between Ca^{2+} Mg^{2+} and K^+ in the solutions is very important to avoid K^+ /Ca^{2+} induced Mg^{2+} deficiency. Similarly, very high rates of Mg^{2+} fertilizers will depress K+ absorption by plants, but this antagonism is not nearly as strong as the inverse relation of K^+ on Mg^{2+}. Calcium, magnesium, and potassium compete with each other and the addition of any one of them will reduce the uptake rate of the other two. The uptake of nitrogen, sulfur, and iron is not entirely depending on its availability in the hydroponic solution but also on presence of other elements [46].

Several physical-chemical phenomena also alter the nutrient availability for plants, the most important of which are precipitation, co-precipitation, and complexation. Precipitation reactions may occur when cations and anions in an aqueous solution combine to form a precipitate. It is known that phosphate availability will be reduced at pH above 7 mostly due to precipitation with calcium and different calcium-phosphate minerals [47], and precipitation of phosphates must be avoided in hydroponic solutions because it is not only depleting phosphorus from the nutrient solution, but it may also reduce the solubility of other nutrients, such as calcium, magnesium, iron, and manganese. Also, sulfur availability may be affected by precipitation with calcium, as calcium-sulfate mineral [48]. Co-precipitation also may strongly reduce the solubility of nutrients added at trace amount, such as copper, zinc, manganese, and nickel [49].

In hydroponic solutions, a complex chemical compound is formed when a metal nutrient is bound by one or more neutral molecules or anions, either of organic or inorganic nature. The resulting complex can be a neutral compound, a cation, or an anion. The addition of organic ligands, such as: ethylene diamine tetra acetic acid (EDTA), Diethylene triamine Penta acetic Acid (DTPA), Ethylenediamine (O-Hydroxyphenyl acetic) Acid (EDDHA), and citrate, can increase the stability of certain elements in solution, especially iron, copper, and zinc. In hydroponic solutions, interactions among solutes cannot be neglected and therefore ion activity should also be considered along with the calculation of nutrient concentration [50].

Nutrient solution management

An optimized and well-balanced supply of nutrients is a prerequisite for efficient use of the resources by hydroponically grown vegetables and short duration high value crops, not only to ensure a high yield but also to guarantee the quality of the edible plant parts. In hydroponics, frequency and volume of the nutrient solution applied depends on the type of substrate, the crop and growth stage, the size of the container, the irrigation systems used, and the prevailing climatic conditions. Depending on the stage of plant development, some elements in the nutrient solution will be depleted more quickly than others and as water evaporates from the nutrient solution, the fertilizer becomes more concentrated and can burn plant roots. In hydroponics, nutrient management is very important and must be done as highly efficient as possible to improve productivity without harming the environment.

Nutrient management included application of the right fertilizers source (e.g., ammonium or nitrate as nitrogen source), balanced nutrient solution according to plants needs and according to plant growth stages and climatic conditions. Strong difference between the ion ratios presented in the nutrient solution and those absorbed by plants led to the accumulation of certain ions in the nutrient solution, which caused an imbalance of mineral elements in the nutrient solution and created more energy to absorb the suitable ions. Recycling exhausted solutions may also represent an efficient strategy to prevent groundwater and environmental pollution.

Fertilizer formulation

There are basically two methods to supply the fertilizer nutrients to the crop, premixed products and grower formulated solutions. The two methods differ in the approach to formulating the fertilizer and the resulting nutrient use efficiency

Pre-mix method

There are several commercial pre-mixed fertilizer formulations in the market. The pre-mixed materials contain nutrients at a fixed proportion and quantity making it difficult to achieve the desired level.

Grower formulated solution

The grower formulated solution contains individual ingredients formulated based on grower's preference. Additional acidification might be required for some water and this can be accomplished with phosphoric acid. This formulation also uses potassium chloride to provide K. There is no problem with using potassium chloride as a partial source of K. It provides K in the same form as potassium nitrate and potassium chloride is less expensive.

Environmental factors to be considered

There are many environmental factors affecting the growth and development of plants under protected condition, especially temperature, light intensity and humidity have a strong effect on the growth, yield and nutritional quality of crops grown under hydroponic condition.

Temperature

Optimum temperature is one of the important factors for nutrient uptake, proper growth, and yield. Chilling and high temperatures affect growth and crop performance. Temperature can influence the amount of oxygen consumption of plants and uptake capacity of roots. Different plant species have different optimum temperature range for better growth, yield. Graves [51] observed that at temperatures below 22 °C the dissolved oxygen in the nutrient solution is sufficient to cover the demand nutrients in tomato. In spinach optimum growth recorded at 28 °C [52]. Solution with lower temperature increased NO^{3-} uptake and lead to thin-white roots production, but water uptake got reduced. Nutrient solution temperature also had an effect on the photosynthetic efficiency. In general terms, the effective quantum yield and the fraction of PSII reaction centers were higher in plants grown at cold solution [53]. The higher the temperature of the solution the lesser the oxygen solubility in water (table 5)

Table 5: Solubility of oxygen in water pure at various temperatures [33]

Temperature (^{o}C)	*Oxygen solubility, mg L^{-1} of pure water*
10	11.29
15	10.08
20	9.09
25	8.26
30	7.56
35	6.95
40	6.41
45	5.93

Light

One of the most basic pre-requisites of plant growth and survival is light. It helps the leaves to produce energy required for growth and development. Three principal characteristics of light affect plant growth: quantity, quality and duration. Light quantity refers to the intensity, or concentration, of sunlight. Up to a point, the more sunlight a plant receives, the greater its capacity for producing food via photosynthesis, and the plant growth is promoted under a certain range of light intensity. Increased light intensity promoted the growth of lettuce [54, 55]

Light quality refers to the wavelength of light. Blue and red light, which plants absorb, have the greatest effect on plant growth [56]. Duration, or photoperiod, refers to the amount of time a plant is exposed to light. Photoperiod controls flowering in plants. In order to attain maximum yield with a high quality from crops grown in a closed production system, optimum light intensity is very important. Higher light intensity contributed significantly for above-ground biomass, and also increased activity of anti-oxidative enzymes and mild stress in lettuce [57].

Humidity

Growing plants contain about 90 percent water. Water vapor present in the surrounding has a major role in plant growth. The amount of moisture in the air is generally expressed as relative humidity (RH). Humidity inside a polyhouse depends on the temperature; Warm air has a higher moisture holding capacity than cool air, therefore, as the temperature of air increases relative humidity decreases.

Proper watering and adequate plant spacing, having well-drained floors, warming plants, moving air and venting moisture are ways to reduce humidity in greenhouses. Watering early in the day time allow plant surfaces to dry before evening. The highest relative humidity in a greenhouse is generally found inside plant canopies, where moisture is generated from transpiration and trapped due to insufficient air movement. Adequate plant spacing and mesh benches will help to improve air circulation at the plant level. High humidity level in the greenhouse reduced the leaf area and fruit quality of tomatoes [58].

Performance of different crops under hydroponic system

A large number of plants and crops can grow by hydroponics system. Quality, taste and nutritive value of end products are generally higher than the natural soil-based cultivation. Various experimental findings outline that leafy greens (lettuce, spinach, parsley, celery and atriplex, etc) can be successfully grown in hydroponic systems. Lettuce and spinach are most promising species to grow in hydroponics because of its higher growth and nutrient uptake capacity. However, there are some other high value crops which can be grown under hydroponics.

Table 6: Various species of plants grown under soil less hydroponic system [59, 60, 61].

Type of crops	*Name of the crops*
Cereals	Rice, Maize
Fruits	Strawberry
Vegetables	Tomato, Chilli, Brinjal, Green bean, Beet, Winged bean, Bell pepper, Cucumbers,Melons, green Onion
Leafy vegetables	Lettuce, Spinach, Celery, Swiss chard, Atriplex, Mint
Condiments	Coriander leaves, Methi, Parsley, Mint, Sweet basil, Oregano
Flower/Ornamental crops	Marigold, Roses, Carnations, Chrysanthemum
Medicinal crops	Indian Aloe, Coleus, Indian Ginseng (Ashwagndha), Basil

Hydroponic research on leafyvegetables

Lettuce

Life cycle of hydroponic lettuce is very short compared to traditionally grown lettuce. Hydroponic lettuce can be harvested after 35 to 40days of production. Lettuce can be successfully grown in NFT system and more than 8 crops per year can be grown efficiently in this system. Horizontal and vertical hydroponic systems were also evaluated with different nutrient solutions for yield optimization of lettuce [62]. Growing of lettuce in recirculation hydroponic system at spacing of 50 plants m^{-2} significantly increased yield and yield components [63]. Frezza [64] found that there issignificant difference in productivity and nitrate content of lettuce in both soil less (floating system and substrate culture) and soil culture however, other traits like leaf area, dry weight and ascorbic acid content were remain unaffected. In non-circulated and non-aerated system, air space between nutrient solution and tank cover also determines optimum lettuce yield. Marketable yield, shoot biomass and leaf area index of lettuce grown in floating system was not affected by nutrient solution composition [65]. Hydroponically grown lettuce statistical superior to conventionally grown lettuces for the quality and yield [66].

Spinach

Besides lettuce, recently various hydroponic experiments were conducted using spinach as model crop. Ranawade [67] have compared spinach yield in hydroponic, aquaponics and in traditional system in which perlite (aquaponics) and sphagnum moss (hydroponics) were used to support the plants. The yield of the aquaponically cultivated spinach was slightly more than hydroponically cultivated spinach. The results of Mwazi [68] showed that salinity has negative impact on vegetative growth, but spinach has some tolerance to saline water with 5 ppm. When spinach grown in floating system, lack of aeration and hypoxia was not severe enough to influence yield and yield component as spinach is short duration crop but quality somehow was affected [69].

Other leafy vegetables

Hydroponic Swiss chard when grown in gravel film technique, plant density of 40 plant m^{-2} and 14 days of harvesting interval improved crop yield, leaf area, biomass and leaf fresh weight [63]. Contrary to this, hydroponically grown Swiss chard, lettuce and sweet basil contain high mineral content, high root/shoot ratio, low level of nitrates, then grown in soil culture, however, their nutrient uptake and yield was lower [70]. Effectiveness of rice husk bio-char alone and in combination with perlite as substrates was also evaluated in NFT system for growing crops like cabbage, red lettuce, dill and mallow [71].

Fruit vegetables grown under hydroponics system

Many hydroponic systems can be used for growing tomatoes but NFT and deep flow technique (DFT) are commonly used system for successful tomato production. Tomatoes grown in NFT system with regular recycling of nutrient solutions improved growth, productivity and mineral composition whereas, in NFT with prolonged recycling of nutrient solution yield was reduced [72]. Open and closed hydroponic systems were evaluated for performance of various cultivars of tomato and in closed system higher marketable yield was obtained as because of fruit cracking, yield was reduced in open system [63]. Schmautz [73] compared yield, quality and overall tomato plant vitality in three different systems of hydroponics (NFT, drip system and floating raft) system, Drip system was better in terms of yield and was statistically on par with other two systems. Better taste and high quality for vitamins and carotenoids in tomatoes were recorded in soil less culture to conventional production [28]. Researchers also investigate effects of plant population, pruning and plant growth regulators on yield and quality of hydroponically grown pepper in various systems. Effectiveness of different substrate (vermiculite + sand, Peat + perlite, rockwool) were evaluated on growth and yield of hydroponically grown green pepper and reported that peat + perlite had most significant effect on growing traits and yield of green pepper [74].

Besides tomato and pepper other fruit vegetables such as brinjal, okra, peas, cucurbits and cantaloupes are successfully grown in various hydroponic systems. An experiment conducted to evaluate the yield attributes of brinjal in relation to different growing media and various levels of nitrogen and potassium showed that coco peat media with 125% of N and K in modified Hoagland solution was found to be optimum for soilless substrate culture of brinjal [75]. Similarly, Okra yielded significantly under root dipping hydroponic method of farming with respect to plant height; stem girth, number of leaves, biomass and yield of the plants compared to conventional farming [76]. Peas grown in ammoniacal hydroponics solution had significantly greater nodulation than the one without ammonium ion [77]. Experiments were conducted on cucumber for optimization of salinity level, EC and nutrients in various hydroponic. NFTsystem was found to be most suitable for growth and productivity of cantaloupe.

Hydroponic research on other high value crops

Fruits

Apart from vegetables, nowadays some high value fruits such as strawberry, blueberry, watermelon, grapes and cranberry are commercially grown under various hydroponic systems. The positive influence of perlite and its mixtures on better root development may result in improved aeration thus forming greater root system in strawberries which may have promoted shoot nutrient uptake leading to increased berry yield. Similar reports indicating increased yield under perlite and its mixtures have been reported in Sweet Charlie strawberry [78] Hydroponic culture increased number of shoots per bush and total shoot length in blueberries compared with non-hydroponic culture and higher concentrations of inorganic elements and organic compounds were found in the hydroponic, indicating active nutrient absorption of the bush [79]. The demand for K by blueberry was very low compared to other crops [80] shoot growth, leaf number and root/shoot ratio of grapevine were significantly decreased with increased level of salinity in hydroponics solution. Nitrate-N, as the sole form of N, in solution appears to stunt cranberry root and shoot growth compared to NH_4 -N and roots of cranberry plants grown at pH 6.5, regardless of N treatment, were more branched than those grown at pH 4.5. [81, 82].

Cutflowers

Carnations and orchids are the most commonly cultivated flowers in hydroponic system because of the increased demand and high price. Suitability of different medium for the carnation (*Dianthus caryophyllus* L.) were studied by choosing six different substrates for growing medium and found that mineral soil in combination with perlite was the best to support better carnation growth, when compared to other mediums [83]. Orchid cultivation has been increasing steadily over the last few years. A study conducted to evaluate the yield of orchid in two soilless systems showed that pot cultivation system yielded more flowers and improved vegetative parameters than the NFT hydroponic system. Similarly, soilless systems can be adopted to eliminate soil related diseases in chrysanthemum production. In case of gypsophila highest vegetative growth, flower yield and better quality were observed when plant was grown using bag culture hydroponics compared to that of tray and ground laid bed systems [84].

Medicinal plants

Some medicinal plants like basil, aloe, and coleus can be also cultivated under hydroponics. Basil (*Ocimum* sp.) is the most popular culinary herb. The effect of hydroponic systems on growth and yield characteristics of basil was evaluated, the fresh weight of plants grown in DFT systems was 2.6 g greater compared with plants grown in NFT systems [85]. Major limiting factors for growing coleus (*Plectranthus barbatus* Andr.) is the incidence of soil-borne diseases, wilt complex and nematodes, it was found that coco peat media with 80% of recommended dose of fertilizer was effective for optimum yield and there was no yield loss due to wilt or nematode [86]. Nutrient solution with the highest level of nitrogen increased Aloe vegetative growth without any negative effect on qualitative indices including Aloin, total phenol, total antioxidative activity and element contents; it was possible to produce the highest level of vegetative growth in Aloe vera [87].

Economic analysis of crops under hydroponics

Globally hydroponics market has crossed USD 2.1 billion in 2020. It is expected to expand at a compound annual growth rate (CAGR) of 20.7% from 2021 to 2028 [88]. Global hydroponics market includes tomato, cucumber, pepper, lettuce, herbs, and other leafy vegetables. Tomato forms the largest market segment and it accounts for 30.4% share of the global market, during 2018. Leading countries in hydroponic technology are Netherland, Australia, France, England, Israel, Canada and USA. Income generated through hydroponics crop production is expected to be more in tomatoes, spinach and other leafy vegetables. However there are some other short duration high value crops suitable for hydroponics. Production and gross returns of gerbera in perlite soilless culture (PSS) system and traditional soil culture systems (TS) were evaluated and compared and it was estimated that, even though operating cost between the two systems ($42,132 and $40,930 for PSS and TS, respectively), gross returns of the PSS were greater than that of TS by 6.6% and B:C ratio was 3.3 for PSS. Use of PSS in gerbera production can substantially improve producer's income. Producers that adopted PSS earned an estimated net income of $18,414 over 9 years [89]. Similarly, a study conducted to know the economic returns from lettuce cultivation under soil and soilless systems found that, income from crop produced through nutrient film technique (NFT) adopted in green house (187.8 baht/m^2) and the same in outdoor (175 baht/m^2) was higher than soil culture (31.6 baht/m^2) system [90].

CONCLUSION

It is possible to grow short duration crops like vegetables year-round in limited spaces with less labour requirement, by making it more affordable and user friendly many local farmers with limited resources will be benefited and crop suitability for hydroponics can be widened with the advancement of technology. The hydroponic industry is expected to grow exponentially in near future. To encourage commercial hydroponic farm, it is important to develop low cost hydroponic technologies and thereby overall startup and operational cost could be reduced. Hydroponic technology is an efficient mean for food production under extreme environmental ecosystems and in highly populated areas, it can provide locally grown high-value crops with better quality. Proper hygiene throughout the production cycle is very important in soil less production systems under closed structures else which lead to complete collapse of the production due to its quick spread of pest and diseases.

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