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(REVIEW ARTICLE)

Hydroponics: Factors influencing the growth of the plants: Vertical farming-Carbon footprint- Marketing updates

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Abstract

This review paper of literature highlights the factors governing hydroponics and carbon foot print of vertical farming. Hydroponics is the art of growing plants without a soil but with using nutrient solution under hi-tech greenhouse controlled conditions in urban area. Because of the precise regulation of watering and feeding the plant, this method is superior to the traditional method. Hydroponics is influenced by many factors such as, light, oxygen level, carbon di-oxide (CO_2), nutrients supply, pH, electrical conductivity (EC), water, humidity, temperature, human labor, maintenance of the machinery, electricity, and water supply. Vertical farms generate an opportunity to grow crops in locations and altitudes that are not optimal for the plants growth. However, carbon foot print of hydroponic vertical farming is very high. In many cases, vertical farm production methods contribute more to greenhouse gas (GHG) emissions than products grown in the field and shipped long distances to market. Transportation of food materials results in carbon emissions from trucks burning fossil fuels. Initial investment to start hydroponic farming is very high. These greenhouses are energy intensive. Growing with green versions of conventional methods was more climate change advantageous than hydroponic systems. Therefore, hydroponic vertical farming are not going to reverse climate change. Hence degrading land and it is becoming un-farmable, then hydroponics is a good back up plan. Therefore, vertical farms, as they exist today, are not able to provide a sustainable solution to the global issues of decreasing availability of arable land and increasing food demands, even though they offer great benefits when compared to conventional farming methods. Vertical farms in urban cities will not solve food shortages or provide the calories that stave off hunger. This makes it difficult to justify the high environmental cost of lighting a hydroponic vertical farm and therefore, not a successful story.

Keywords: Carbon foot print; Climate change; Greenhouse gas (GHG) emissions; Hydroponic; Vertical farming

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1. Introduction

Hydroponic is defined as the science of growing or the production of plants in nutrient-rich solutions or moist inert material, instead of soil [1-150, 214-223-232-245]. Hydroponics, a soilless cultivation technique using nutrient solutions under controlled conditions, is used for growing vegetables, high-value crops, and flowers [1- 160, 210-223, 245]. It produces significantly higher yields compared to conventional agriculture despite its higher energy consumption [1- 180-232-245]. The success story of a hydroponic system relies on the composition of the nutrient solution, which contains all the essential mineral elements necessary for optimal plant growth and high yield [1- 175-223-232-245]. This method empowers growers to optimize various spaces for cultivating crops, whether it be indoors using layered systems, in multi-story buildings, on stacked racks, or within warehouses. Hydroponics means growing plants without soil, with the sources of nutrient elements as either a nutrient solution or nutrient-enriched water[1-174-223-244]. An inert mechanical root support (sand or gravel) may or may not be used [1- 90-245]. The hydroponic system is the technique of growing vegetable crops in a nutrient-rich solution or soilless environments such as rock-wool, coir, perlite, peat moss, coconut husk, gravel, coarse sand, mineral wool, vermiculite, or sawdust [1- 184-223-232, 245]. Hydroponics has multiple advantages compared to open field soil-based agricultural farming [1 -100-223, 245]. Hydroponic growth systems are a convenient platform for studying whole plant physiology[1- 180-223, 245]. The hydroponic method is successfully used for fast-growing leafy vegetables and commercial crops, such as lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), potato (*Solanum tuberosum* L.), tomato (*Solanum lycopersicum* L.), Kale (*Brassica alboglabra* L.), pepper (*Capsicum annuum* L.), cucumber (*Cucumis sativus* L.), and strawberry (*Fragaria ananassa)* [1-184-223-232-238-245]. Some of the more common techniques used in greenhouse production include drip irrigation, hydroponics and aeroponics.

The term "hydroponics" was first introduced by American scientist Dr. William Gericke in 1937 to describe all methods of growing plants in liquid media for commercial purposes [214-224]. Dr. William F. Gericke is attributed with being the father of modern hydroponics [214-224]. Born on a Nebraska farm August 30th, 1882 [214-224]. Educated at Ohio State, Johns Hopkins, California [8, 214-224]. He was a professor and plant physiologist at UC Berkeley, USA [214-224]. Before 1937, scientist were using soilless cultivation as a tool for plant nutrition studies [214-225]. In 1860, two scientists, Knop and Sachs, prepared the first standardized nutrient solution by adding various inorganic salts to water, then using them for plant growth [214-224, 245]. Later, scientists started using an aggregate medium to provide support and aeration to the root system[214-225]. Quartz sand and gravel were the most popular aggregate mediums used in soilless cultivation at that time [214-225]. In the late 1960s, Scandinavian and Dutch greenhouse growers tested rockwool plates as a soil substitute, which resulted in revolutionary expansion of rockwool-grown crops in many countries[214-225]. Today, many alternative porous materials are used as growing media in hydroponics, including organic medias like coconut coir, peat, pine bark and inorganic mediums such as mineral wool, growstone, perlite and sand [214-225, 245].

Greenhouse hydroponic farming is now a well adopted technology and influenced by many factors such as climate change, building construction, industrialization, mining, forest fires, commercial logging, rapid growth of the world population, agricultural land and forest area is decreasing worldwide [6, 8-61-90, 245]. Population growth and migration to urban areas are two interrelated aspects while referring to the hazardous impact of urbanization on the environment [6, 8-61-100, 245]. According to United Nations Food and Agriculture Organization (FAO) research, 9.73 billion people will populate the earth by 2050 [6, 8-61, 222, 223, 245]. Moreover, additional challenges like lack of labor, sudden weather changes, and water scarcity put more pressure on farmers [6, 8-61, 245]. Global challenges linked to population growth, urbanization, and climate change have led to bringing innovative features to conventional greenhouse cultivation techniques [6, 8-61, 245].

Additionally, hydroponics makes it possible to harvest several crops throughout the year, without chaotic discharges of either pesticides or fertilizers to the environment [1-184, 245]. Hydroponics uses less land and water than traditional open-field agriculture [1-184-223-243, 245]. Indeed, by using smart greenhouses equipped with several technologies to control critical parameters for healthy plant physiology [1-90, 245]. Furthermore hydroponics optimizes the use of water and chemicals to eliminate potentially hazardous waste and residuals [1-180, 245]. Large-scale hydroponics facilities operate under controlled conditions of climate, lighting, and irrigation, rendered by numerous sensors, web platforms, software (IOT applications), and mobile applications available now a days [15, 43, 55-59, 62, 66 ,73, 92, 118, 125, 134, 176-183, 245]. Due to such technological advancements, the hydroponics' market is expected to grow significantly from 2021 to 2028, at a compound annual growth rate (CAGR) of 20.7% from 2021 to 2028 [1-180, 245].

Hydroponics allows for precise control over the growing environment, which is a significant advantage in producing higher yields [224-226-230-243, 245]. In traditional farming, crops are exposed to varying weather conditions, pests, and soil quality issues, all of which can adversely affect growth and yield[224-226-230, 245]. In contrast, hydroponic systems create a stable and controlled environment where variables can be adjusted to meet the specific needs of the plants[224-226-240, 245]. For instance, hydroponic growers can maintain consistent temperature and humidity levels, which are critical for optimal plant development. By avoiding extreme weather conditions and seasonal changes, plants can grow continuously and more predictably [224-226, 245]. This consistency leads to multiple cropping cycles within a year, further boosting overall productivity[224-226-230, 245]. Companies in the hydroponics sector are continuously working on improving and innovating new technologies for more efficient and sustainable plant growth. These advancements include the development of smarter climate control systems, energy-efficient lighting solutions, and automation technologies. [224-226, 245].

Providing quality nutritive food to more than 1.5 billion people in India by the Year 2025 would be a major challenge for the country [20, 22-27, 72, 140, 141, 146, 149-151, 245]. Increasing population, decreasing land and water holding, urbanization, industrialization, global warming are some of the major impediments for the country. Vertical farming is in infancy in India and not a successful story [20, 22-27, 72, 140, 141, 146, 149-151, 245]. Although vertical farming units for production of crops like strawberry, lettuce and other leafy vegetables, foliage and flowers are functioning in major metros of India [20, 22-27, 72, 140, 141, 146, 149-151, 245]. However, the organized vertical farms for production of food crops are not available in India [20, 22-27, 72, 140, 141, 146, 149-151, 245]. Therefore, only a few successful vertical farms have been built in India mainly due to the initial high price tag on construction and the cost of maintenance [20, 22-27, 72, 140, 141, 146, 149-151, 245]. Further, vertical farming is very expensive, energy intensive and food is also very expensive too. Only rich and corporate people can afford this food in metros in India. Public in India are also confused hydroponic food as organic or non-organic [20, 22-27, 72, 140, 141, 146, 149-151, 245].

Internet of Things (IoT) technologies has been used through AI and machine learning-based energy- and water-saving measures, automated farm operations, and mechanization to resolve crop monitoring challenges in a controlled urban hydroponics [15, 43, 55-59, 62, 63, 66 ,73, 92, 118, 125, 134, 176-183, 245]. Hydroponics, a cultivation technique without soil, facilitates the growth of organic vegetation while concurrently minimizing water use and eliminating the necessity for pesticides. In order to achieve effective cultivation of hydroponic plants, it is essential to maintain a controlled environment that encompasses essential factors such as temperature, carbon dioxide (CO_2) levels, oxygen availability, and appropriate lighting conditions [1- 176-183, 245]. Additionally, it is crucial to ensure the provision of vital nutrients to maximize output and productivity[1- 176-183, 245]. Due to the demanding nature of a hydroponic farmer’s schedule, it is necessary to minimize the amount of time dedicated to nutrient management, as well as pH and EC adjustments[1- 176-183, 245].

Hydroponics makes people more comfortable growing their vegetables and pesticide-free food quickly at home [1- 176-183, 245]. Sangeetha and Periyathambi (2024) [176] are of the opinion that the main issue with hydroponics is the constant monitoring of the pH and EC levels of the nutrient solution, as well as the surrounding temperature and humidity range [176]. Hydroponics culture highly depends on human attention to supply the suitable parameters for the quality growth of plants [176]. In this process, it was observed that plants nutrients consumption changed based on the plant stages such as germination, vegetative, reproduction, and harvesting [176]. In one of the study reported by Sangeetha and Periyathambi (2024) [176] concluded that Growth Stage Identification Algorithm is a sophisticated mechanism that determines the developmental phases of plants in a hydroponic environment, ensuring exact nutrient administration adapted to each growth stage [176]. This program uses multiple data sources to make informed conclusions about the plants age [176].

Progress in climate control, nutrient farming techniques, sensing technologies, and related areas is anticipated to impact market expansion positively throughout the forecast period [176-240-245]. Providers of hydroponics farming solutions present consumers with diverse tools for monitoring and overseeing their crops, including an array of sensors, web platforms, software, and mobile applications. One notable example is SmartBee Technology, Inc., which offers farmers real-time control through offerings such as irrigation controls, water, nutrient sensors, environmental sensors, and dedicated software[176-240-245].

Hydroponic systems allow growing plants in nutrients and water without using soil as a base[1-176-240-245]. Hydroponic systems are a combination of several technologies including a specific set of system models[1-176-240]. These systems enable growers to obtain higher yields with each harvest and eliminate the need for pesticides and herbicides as compared to traditional cultivation methods. Exotic vegetables, cabbage, peas, and salad vegetables grow well using hydroponics[1-176-245]. Crops such as tomatoes, exotic vegetables, cabbage, peas, and salad vegetables required proper care and continuous maintenance[1-176-245].

Hydroponic systems are classified into different types, vary in the pattern of their water/nutrition supply, among which Deep Water Culture, Dutch Bucket method, Wick System, Ebb and Flow (or Flood and Drain), Nutrient Film Technique

(NFT), Vertical farming, Aeroponics, Aquaponics, Fogoponics, Kratky, and Drip irrigation system are the most popular hydroponics systems[1-176-184-223-245]. Following are the factors controlling the hydroponic system of plant cultivation.

2. Hydroponic: Factors influencing Growth of Plant

Hydroponic or liquid culture is one of the hi-tech urban agriculture methods for growing plants, which provides conditions for plant growth without soil [1-176-184-223-245]. The diet in hydroponic production is very optimal and based on the needs of the plant, which allows these products to have a better and healthier quality than their counterparts in soil cultivation[1-176-184, 245]. Because of the precise regulation of watering and feeding the plant, this method is superior to the traditional method[1-176-184, 245]. Greenhouses with a glass roof or plastic cover are among the most widely used materials[1-184, 245]. Glass greenhouses are very expensive, but they have high resistance compared to other types of greenhouses[1-184, 245]. In addition, the high ability to pass light and heat in cold seasons or cold regions increases production efficiency [1-184, 245]. Greenhouses with plastic covers are usually cheaper and more economic, but they are not durable[1-176-184, 245].

Hydroponic systems are designed to provide plants with the right amount of water, nutrients, and oxygen for optimal growth [224-245]. They are used in both commercial and private settings to cultivate various plants, including vegetables, fruits, herbs, and flowers [224-226, 245]. The origins of hydroponics can be traced back to ancient civilizations, although it has progressed greatly with developments in technology and agricultural methods[224-226, 245]. Modern hydroponic systems were developed in the mid-20th century [234-237, 245]. Today, hydroponics is applied in numerous ways, ranging from small-scale home gardens to huge commercial operations[224-226, 245]. This evolution has been driven by the desire to increase agricultural efficiency, improve resource utilization, and reduce the environmental impact of farming operations [224-226, 245].

Another area of focus is the development of alternative products for hydroponic cultivation. These include new types of substrates, nutrient solutions, and growth mediums that provide optimal conditions for plant growth[237]. Scientists are exploring the use of algae in hydroponics[237, 245]. Algae can provide additional nutrients and can also be used as a sustainable source of biofuel [237]. Hydroponic cultivation is also being integrated into educational programs to teach students about sustainable agriculture and the importance of food security [230-237, 245].

Following are some of the factors controlling the hydroponic system of cultivation of plants.

2.1. Light

One of the important sources of energy for plant growth is sunlight [1-176, 185, 245]. Plants convert sunlight into biochemical energy through photosynthesis, which is biologically transmitted in the food chain [185]. However, excessive heat will increase the internal temperature of the greenhouse, which is not good for optimizing plant growth[185]. Furthermore, plants photosynthesis usually occurs in wavelengths between 400 and 700 nanometers [185]. Weather conditions and seasonal changes can affect the amount of sunlight entering the greenhouse [185]. Therefore, the use of artificial light LED is very crucial to control the amount of light required by plants for photosynthesis [185, 245]. Lighting control has become a critical issue for high energy efficiency and plant productivity in greenhouse cultivation, particularly with the enhanced use of supplementary lighting [1-176, 185]. Plant growth in controlled greenhouse conditions is influenced by three parameters of light, including light spectrum, light intensity, and duration of light exposure [185]. Lower light intensity can reduce the level of chlorophyll and prevent the growth of leaves [185]. On the other hand, too much light intensity causes heat stress in the plant and overall yield loss [185]. Various light sources are used as supplementary light in the controlled greenhouse system [185]. One of the light control methods in the greenhouse is measuring the photosynthetic photon flux density (PPFD) from solar light, which is called the dynamic control of light-complementary growth [185]. In recent studies, the parallel particle swarm optimization algorithm has been used to solve the problem of light intensity optimization in greenhouses[1-880, 185]. The purpose of this is to discover the most suitable locale and number of LED lamps based on the plant's need for light and to reduce energy consumption[185]. The use of LED systems consumes 82.6% and 54.2% less energy compared to fluorescent and incandescent lamps, respectively [1-185, 245].

The significance of light in photosynthesis cannot be overstated, as it is the primary source of energy for plants to synthesize organic compounds [1-185, 245]. Through this process, plants convert light energy into chemical energy, which is then utilized to support their metabolic processes and promote growth [1-185, 245]. Artificial lighting systems such as LED lights can be utilized in smart hydroponics to regulate light's intensity, spectrum, and duration meticulously [1-179, 185]. The optimization of light settings is a crucial factor in plant growth, as it enables growers to provide the appropriate amount and quality of light that is required for each growth stage [1-179-185, 245]. The light requirements of plants vary depending on the species, with some requiring specific amounts of red and blue light [1-179, 185]. Light regulation in smart hydroponics is crucial for providing plants with adequate energy for photosynthesis, which leads to healthy growth, strong development, and enhanced yield [1-179, 185, 245].

2.2. Essential Nutrients

Plant growth primarily depends on the availability of 17 essential nutrients and can be broadly classified into macronutrients and micronutrients [1-185-223, 245]. The importance of both for the nourishment and growth of plants cannot be overstated [1-185-189-193]. This includes macro-nutrients like carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulphur, calcium, and magnesium and micro-nutrients like iron, manganese, zinc, boron, molybdenum, chlorine, copper, and nickel [1-179-185, 245]. Plants acquire carbon, hydrogen, and oxygen through natural means, specifically from the air and water they consume, with the remainder obtained from the soil[1-185]. The roots obtain nutrients from nutrient solutions or aggregate media in hydroponic systems[1-179-185-193]. Research has shown that hydroponic systems are comparatively less tolerant than soil-based systems, and any issues related to nutrients can rapidly manifest plant symptoms[1-179, 185, 245]. One way to measure these levels is by using a nutrient tester or meter specifically designed for hydroponics [186-189-193]. These meters work by measuring the electrical conductivity of the nutrient solution, which is directly related to the concentration of nutrients[186-189-193, 245]. For hydroponics the pH of the nutrients should be within 5.8 to 6.5[185-189-193-223, 245].

The criticality of the nutrient solution composition, regular monitoring of the nutrient solution and plant nutrient status is a significant aspect to consider [1-179-186-189-193, 245]. The major salt deficiencies that a hydroponic system may encounter include nitrogen, calcium, iron, magnesium, and boron deficiencies[1-179-186-193, 245]. The detrimental effects of soluble salts have been attributed to various factors, including but not limited to over-fertilization, suboptimal water quality, gradual accumulation of salts in the aggregate media, and inadequate drainage[1-179-186]. Insufficient leaching during the process of fertigation in hydroponics can lead to the accumulation of soluble salts in the medium due to water evaporation [1-179-186-189, 245]. Nutrient antagonism and interaction is a crucial parameter that warrants serious consideration in the context of hydroponic systems[1-179-186]. Research suggests that plants tend to absorb nutrients proportionally to their presence in the nutrient solution[1-179-186-193, 245]. The phenomenon of nutrient uptake in excess leading to a higher uptake of one nutrient at the cost of yet another has been observed and is classified as nutrient antagonism [1-179-186-189]. The nutrient levels in the nutrient solution may not necessarily guarantee optimal plant growth and development[1-179-186-189-193, 245]. Despite sufficient nutrient supply, plant nutrient deficiency may still occur. For instances of nitrogen deficiency, the color of leaves may change to a lighter shade of green or, in severe cases, a yellow hue[1-179-186]. Observations can be made from stunted development and discoloration, specifically a slight purple tint, on the stems and undersides of leaves [1-179-186-193]. Whereas if the feeding solution includes excessive nitrogen, roots become stunted, causing blossoming to be delayed [1-179-186-189]. Boron deficits are rare and often accompany calcium shortages, mainly in the case of plant's deficit with water[1-179-186-189]. Boron generally improves root uptake of potassium and phosphorus and keeps plant cell walls intact and functioning [1-179-186-189]. Hydroponic production requires a full hydroponic nutrient solution, which includes Mg as one of the key ingredients [1-179-189, 245]. Mg insufficiency can be made worse by nutritional inconsistencies. Low Fe levels influence pigment and micronutrient contents of Chile pepper (*Capsicum annuum* L.) were studied through a hydroponic system [1-179-186]. It was found that the total extractable pigments of red fruits and their surface color remained unaffected by iron treatment[1-179-186]. However, leaf Fe and Fe ++ were directly proportional to iron supplement, on the other hand, indirectly proportional to copper, phosphorus, and zinc concentrations in the leaf [1-179-186-193, 245].

2.3. Carbon di-oxide (CO_2)

Carbon dioxide (CO_2) concentration plays an important and critical role in plant photosynthesis [1-179-186-193, 222, 223, 245]. Usually, CO_2 concentration fluctuates in the greenhouse environment during the day and night based on photosynthesis and plant respiration[1-179-186-193]. In fact, during the day, the concentration of CO_2 in the greenhouse environment is at a high level due to plant respiration and the release of CO_2 at night [1-179-186-193, 222, 223, 245]. The low concentration of CO_2 limits the amount of photosynthesis of the plant, even if there is enough light at the disposal of the plant[1-179-186-193]. In addition, air conditioning in the greenhouse environment plays a vital role in the concentration of CO_2, temperature, and humidity [1-179-186-193]. CO_2 concentration is one of the important factors for plant growth and photosynthesis[1-179-186-193, 245]. The method of CO_2 enrichment is found to increase the productivity of plants gown in greenhouses [1-179-186-193, 245]. By increasing the amount of CO_2 from 340 to 1000 ppm (parts per million), most plants perform pure photosynthesis[185-186-193-223, 245]. The concentration of CO_2 in the outside air is usually 400 ppm, which is higher than the level of CO_2 inside the greenhouse [185-186-193-

223]. Hence, CO_2 enrichment is essential. The optimal time to inject CO_2 is when the intensity of sunlight and the temperature inside the greenhouse are low, such as early morning [185-186-193, 245].

Carbon dioxide is the precursor to the carbohydrates that are fixed through photosynthesis [1-185-189]. When CO_2 concentrations in the growing environment decrease, the growth and productivity of hydroponic crops diminish[220-245]. The less carbon that is available from CO_2, the less that can be converted to carbohydrates, which ultimately are used for plant growth or stored [1-185-186-193, 245]. This highlights one of the reason that CO_2 management can be critical for food crops. Unlike ornamental plants, which are sold by units, food crops are frequently sold by weight. The outdoor, ambient atmosphere contains about 400 ppm CO_2 [1-185-186-193]. When greenhouses are being ventilated and outdoor air is frequently being introduced into the greenhouse, the CO_2 concentration in the greenhouse can be similar to outside [1-185-186-193, 245]. However, CO_2 concentrations can decrease to concentrations below 400 ppm when the greenhouse is not being ventilated [1-185-186-193]. This occurs mostly in the winter when cooling is not required to maintain the desired air temperatures in the greenhouse [1-185-186-193]. When light levels are strong, CO_2 concentrations can decline quickly if plants are actively growing in the greenhouse, since uptake is increased [1-185-186-193, 245].

To measure the levels of CO_2 in hydroponics, the more intermediate to advanced grower can use a CO_2 monitoring system[1-185-186-193]. These units measure the amount of CO_2 in ppm (parts per million) which is the unit of measurement for carbon dioxide [1-185-186-193, 245]. Co_2 controllers and monitors can be purchased at local hydroponics or indoor gardening supply store[1-185-186]. They can also order them online from www. ehydroponics.com [1-185-186]. The average or recommended levels of CO_2 in hydroponics systems should be between 1,000 and 2,000 ppm [1-185-186-193]. There are CO_2 monitoring systems available which will automatically boost CO_2 levels if they fall below a certain ppm level [1-185-186, 245]. These units can also be put on a timer so that they only dispense CO_2 during the day/lighting cycle, at the time when photosynthesis occurs[1-185-186].

Results of the study conducted by Singh et al., (2020) [223] suggest that supplemented CO_2 has significant potential to increase growth and development of leafy greens grown in NFT systems [223]. Increased growth rate could result in early harvest and more crop cycles each year and thereby help in feeding the increasing world population[223]. The growth response of different species varied, but this study showed increased growth of all three species[223]. Supplementing CO_2 in greenhouse environments during growth of hydroponically grown leafy greens may also result in lighter green (due to low chlorophyll content) produce which may impact the marketability of the produce[223]. Physiological disorders such as **tipburn** in '*Auvona'* may also reduce produce quality when grown under supplemented CO_2 conditions [223, 245]. For mineral concentrations, the study conducted by Singh et al., (2020) [223], suggests that CO_2 supplementation may have both a positive and negative effect as lower leaf N concentration might affect available protein, while greater Fe concentration in food when grown with a nutrient solution containing 2.30 ppm of Fe is a desired quality [223].

2.4. pH and Electrical conductivity (EC)

The success story of hydroponic agriculture depends on two important parameters such as electrical conductivity (EC) and pH [1-185-193, 213-223, 245]. The electrical conductivity (EC) values of specific crop are from 1.5 to 2.5 ds/m for hydroponics depending on environment [1-185-193]. Higher electrical conductivity(EC) increases osmotic pressure and hinders nutrient uptake while lower electrical conductivity (EC) severely affects the plant growth and yield [1-185-193-223, 245]. Another important fact is that reduction in water uptake is strongly correlated to electrical conductivity (EC) [1-185-193]. The pH value determines the nutrient availability for the plants [1-185-193]. Therefore, it needs daily adjustment due to the lower buffering capacity of soilless systems [1-185-193]. Regulation of pH can also be carried out by using nitric, sulphuric or phosphoric acid, either individually or in combination by using pH meter [1-185-193, 245]. Furthermore, oxygen is essential for cell growth and activity, the roots require oxygen to absorb water and nutrients [1-185-193]. Therefore, aeration, is an important factor that influences root and plant growth in hydroponic system [1-185-193]. Maintenance of proper balance of water and oxygen in plant roots is very important in vertical farming and requires standardization [1-185-193, 245]. Prevention and management of bio-stress in vertical farming is as important as in any other farming system [1-185-193]. The major biotic stresses include spider mites, thrips, aphids, whiteflies, fungal gnats (*Bradysia* spp.), powdery mildew, downy mildew, grey mould, root rot, etc. The high humidity and excessive fertilizers aggravate the stress [1-185-193, 245].

Optimal nutrient solution management can lead to a high water and nutrient efficient system [1-185-193, 245]. A better management of nutrient solution in hydroponic systems requires optimum pH, EC, or ions concentration [1-185-193, 245]. The pH of a nutrient solution is one of the most important factors affecting nutrient availability, uptake, and solubility[1-185-193, 245]. The optimum pH range for plants is between 5.5 and 6.5 in which the plants have readily available nutrients [1-185-193]. For example, high pH increases the precipitation of calcium and magnesium and reduces the solubility of iron and phosphate in the nutrient solution, which forms the ions as the unavailable nutrients for roots [1-185-193]. This also inhibits the absorption of micronutrients such as iron, copper, zinc, and manganese [1-185-193, 245]. On the other hand, low pH decreases the absorption of macronutrients, including nitrogen, phosphorus, potassium, calcium, and magnesium [1-185-193]. Although pH stabilization is important in the nutrient solution, the pH fluctuation frequently occurs in hydroponics due to low buffering capacity of the substrates in hydroponics compared to soil [1-185-193]. Moreover, roots release anion and cation, such as HCO_3 − and H+, to absorb nutrients, which leads to unbalanced anion and cation exchange and pH fluctuation in the substrate [1-179-193]. Therefore, an optimum pH range should be maintained for proper plant growth [1-179-193]. Adopting the optimal nutrient solution management strategy to reduce water and nutrient consumption and the cost of production to increase crop growth is essential [1-179- 193, 245].

The Electrical conductivity(EC) -based strategy is the simplest method. However, it cannot follow the nutrient variations in the solution over time [1-179-193]. Hence, ion-based strategies have been studied to improve the quality of the nutrient solution, thus increasing the yield[1-179-193]. Monitoring the concentration of nutrients could be the most effective contribution to reducing water and fertilizer consumption and achieving the ambition of having an eco-friendly hydroponic system[1-179-193, 245]. The nutrient-based strategy can reduce water and nutrient consumption by up to 60% more than the electrical conductivity (EC)-based technique[1-179-193].

Since the electrical conductivity (EC) value represents the nutrient concentration of the solution. Hence the monitoring of the nutrient solution is based on the measurement of EC few times daily [1-179-193, 245]. Nutrient concentration alteration occurs over time due to plant nutrient uptake, crop growth, and evaporation[1-179-193]. When the EC value drops from a specific threshold or exceeds the optimum range of 1.5–2.5 dS m^{-1}, the nutrient solution with a corrected concentration should be recalculated [1-179-193]. Plant nutrient uptake decreases the EC depending on the crop growth stage, while evaporation may increase the electrical conductivity and salt concentration in the coco coir bags or any other substrates [1-185-193]. However, plants uptake more water than mineral nutrients in general. This is because an increase in the nutrient concentration and, subsequently, increase the electrical conductivity or salt concentration in the nutrient solution over time [1-185-193]. Electrical conductivity (EC) monitoring is the most commonly used approach as the nutrient solution management strategy because its measurement is fast, simple, low-cost, and can be used directly in situ [1-185-193, 245]. However, the electrical conductivity value indicates only the total amount of dissolved ions in the nutrient solution without indicating the individual ions' concentrations (macronutrients or micronutrients) in the solution [1-185-193, 245].

2.5. Temperature

Temperature plays a significant role in plant growth and metabolic processes[1-179-193]. In smart hydroponics, the temperature can be precisely regulated to create an ideal plant environment [1-179-193]. Each plant species has an optimal temperature range for growth and development, including germination, root growth, and flowering [1-179-193]. Maintaining the appropriate temperature range can enhance enzymatic activity, nutrient uptake, and overall plant performance[1-179-193]. Smart hydroponics systems often use sensors and automated controls to monitor and adjust temperature levels, ensuring that plants are kept within their preferred temperature range [1-179-193, 245].

2.6. Water and Humidity

The hydroponic cultivation method can optimize water consumption[185]. In this method, irrigation and water circulation in the greenhouse are conducted with an electric pump[185]. The nutrients in the water are provided to the roots of the plants. This process helps the optimal growth of plants by controlling water and nutrients[185]. Humidity inside the greenhouse can affect the respiration and infectious diseases of plants[185]. If the surrounding air is dry, the stomata in the plant are closed and reduce the rate of respiration. As a result, the exchange of CO_2 between the leaves and the air is limited and the photosynthesis rate of the plant decreases[1-185, 245]. Therefore, controlling the humidity inside the greenhouse is necessary[10, 44, 185, 245]. The hydroponic cultivation system was least affected by water salinity, and the highest water consumption was related to uncovered soil, which reached over 58% [1-185]. The results indicated that the hydroponic cultivation system is the most suitable system for cultivation, especially for irrigation with saline water [10, 44, 185, 245]. The advancement of replacing conventional water sources with desalinated seawater linearly increased the amount of energy consumption and GHG emissions in both cultivations[10, 44, 185, 245]. The results of one of the study showed that considering the limited water resources, desalinated seawater along with the hydroponic cultivation system can be a valuable method for sustainable agriculture with high production, although it is highly dependent on energy[10, 44, 185]. The amount of water vapor is measured as relative humidity or vapor pressure deficit [185]. Water vapor or humidity can impact the growth and development of plants as well as pathogens[185]. When humidity is high, plants diminish their transpiration [1-185]. The greenhouse farming experts are of the opinion that one of the biggest problems associated with low transpiration is tip burn on lettuce[1-185, 245]. Since calcium is taken up passively when plants take up water, less water uptake also causes less calcium uptake [1-185]. This is why air movement, which reduces humidity around shoot tips, is used to reduce tip burn of lettuce[1-185]. In addition to water use and nutrient uptake, humid environments can favor the development of pathogens[1-185]. On the basis of literature survey it is confirmed that powdery mildew and botrytis are two pathogens that can thrive in humid environments [1-185]. One of the best methods to reduce humidity in greenhouse is to vent at night when heating. This practice will help to expel humidity from inside the greenhouse[1-185, 245].

The term humidity pertains to the quantity of water vapor in the atmosphere[1-179-185]. The careful management of humidity in hydroponics can lead to the creation of an optimal growing environment[1-185]. The impact of high humidity levels on transpiration rates in plants has been studied, with findings suggesting potential benefits for certain plant species during the vegetative growth stage[1-185, 245]. Research has shown that high humidity levels can lead to the development of fungal diseases[1-179-185]. Low humidity has been found to cause rapid moisture loss in plants, potentially resulting in water stress. Incorporating humidifiers, dehumidifiers, or ventilation systems in smart hydroponics systems enables the maintenance of accurate humidity levels[1-179-185, 245]. The manipulation of humidity levels by growers can facilitate an optimal environment for plants, fostering robust growth and mitigating the likelihood of pathogenic infections [1-179-185]. In hydroponics, the ability to control and optimize physical factors gives growers greater precision and flexibility in creating an ideal growing environment for plants [1-179-185, 245]. By fine-tuning light, temperature, and humidity, growers can mimic optimal conditions for specific plant species, growth stages, and environmental preferences[1-179-185, 245]. Hydroponic systems are highly space-efficient and required less land [1-179-289]. Vertical growing techniques maximize production in limited areas. Suitable for urban farming, rooftops, or areas with limited agricultural space[1-179-185, 245].

2.7. Electricity

The electricity in the greenhouse is used to extract water from the well to irrigate crops[185]. The irrigation system in greenhouse cultivation is a drip that spreads water throughout the greenhouse system by using electric pumps[185]. Additionally, electricity is also used to drive air conditioning systems to regulate the temperature and humidity of the greenhouse environment[185]. By controlling the environmental conditions of the greenhouse with the use of electricity, it is possible to boost the yield and quality of the crops[1-185]. Hence, reducing electricity consumption to achieve optimal environmental conditions is an important issue in green house cultivation[1-185]. Electricity was used to illuminate LED artificial lights in greenhouses for the photosynthesis of plants [1-185, 245]. In hydroponic culture, lighting systems are usually inefficient and have high electricity consumption, as a result of using light-emitting diodes (LED) in hydroponic culture[1-185, 245]. They can significantly reduce electricity consumption. Further, using a transparent cover for the greenhouse such as glass can provide the light needed for plants' photosynthesis and is very useful in reducing electricity consumption [185, 245].

2.8. Human labor

Human labor energy includes the amount of work completed by the manpower, from planting to harvesting, as well as packaging crops[185]. The equipment used in greenhouses is very effective in the amount of manpower used for planting and harvesting[185]. Human labor in product packaging was a major part of energy input. This energy input was used for packing, sorting, and transporting the products to the market[185]. Labor cost is generally the first overhead expenditure in the greenhouse production and after that, the second overhead expenditure is energy[185].

2.9. Pesticides

One of the features of the greenhouse cultivation system is its closed structure and covering materials that prevent insects from invading crops[1-185]. Thus, it reduces the consumption of pesticides and saves energy[1-185]. Aquaponic culture, which is a combination of hydroponic cultivation and aquaculture, reduces the infectious diseases of insects and pests, and by removing most of the pesticides, they reduce the level of toxicity[1-185]. This study showed that aquaponic culture, which includes hydroponic cultivation, as a global method in the future, has more advantages, including organic plant cultivation and optimal fish breeding[1-185]. This also provides the possibility of plant cultivation in any harsh environmental conditions, which saves money and energy consumption[185].

2.10. Oxygen

Oxygen is critical in the development and growth of edible crops grown in hydroponic systems such as nutrient film technique (NFT) and deep water raft culture[207-212, 245]. Oxygen at the root zone helps to convert nutrients into forms that are more easily absorbed by plants, facilitating efficient nutrient uptake, promoting healthier, and more robust growth [207-212, 245]. Adequate oxygenation ensures that plants absorb nutrients efficiently, fosters beneficial aerobic bacteria, and prevents root diseases[207-212]. Dissolved Oxygen is the life force for plants and failure to provide enough oxygenation will lead to crop stress, root disease and in some cases total crop loss [207-212]. Dissolved oxygen (DO) in water is a critical parameter in greenhouse and hydroponic operations [207-212, 245]. Dissolved oxygen (DO) is required for plant respiration, which influences nutrient uptake [207-212]. Dissolved oxygen (DO) is also important for root health, as low oxygen levels favor harmful anaerobic organisms that cause root rot (e.g. *Pythium* and *Fusarium*) [207-212, 245]. Sufficient dissolved oxygen (DO) levels promote an aerobic environment favoring beneficial microorganisms [207-212, 245].

Unlike traditional soil cultivation, hydroponics requires a more hands-on approach to ensure that plants receive the right amount of oxygen[207-212]. This is crucial because in hydroponic systems, the roots are submerged in water, and without proper oxygenation, they can suffocate, leading to poor nutrient absorption, stunted growth, and even the demise of plants [207-212, 245]. Therefore, understanding the art and science of oxygenating hydroponic system is very important [207-212]. The use of an air pump and air stone is among the most popular oxygenation techniques in hydroponics [207-212, 245]. An air pump pushes air through an air stone submerged in the nutrient solution, creating a stream of fine air bubbles [207-212]. This process not only delivers oxygen directly to the roots but also promotes nutrient circulation within the reservoir [207-212]. The effectiveness of this method can be adjusted by varying the pumps power and the size or number of air stones, making it suitable for systems of all sizes [207-212].

Current methods for increasing dissolved oxygen (DO) include hydrogen peroxide, air pump/stones to bubble through atmospheric gases (21% oxygen), and mixers/stirrers to promote air/water surface contact[207-212]. While these methods are inexpensive, they also have drawbacks [207-212]. Air stones are the most highly adopted, but dissolved oxygen (DO) is limited by its air composition intake (if greenhouse air is the supply, it also pulls in detrimental CO_2 levels) [207-212]. Other techniques include air diffusers and electrolysis (largely out of favor in recent years, due to high cost of power for low quantity of oxygen) [207-212]. It is increasingly common to see pure oxygen in use in greenhouses [207-212].

An air gap method is simplicity at its best, creating a space between the plant roots and the nutrient solution[207-212, 245]. This gap allows roots to access oxygen directly from the air [207-212]. The air gap technique is commonly employed in systems such as the Kratky method or certain types of deep water culture (DWC), where the root tips are submerged, and the upper portion remains exposed to air [207-212]. This method is particularly advantageous for its simplicity and low maintenance, requiring no electricity or moving parts[207-212]. However, its effectiveness can be limited by the systems design and the environmental conditions [207-212]. It is important to note that most hydroponic systems/designs utilize an air gap to some degree [207-212].

Falling water, or the act of allowing water to splash, naturally incorporates oxygen into the nutrient solution[207-212]. This can be achieved through techniques such as using a waterfall, a fountain, or simply positioning the return lines above the water level to create a splashing effect [207-212]. The agitation and surface disturbance increase gas exchange, which enriches the water with oxygen[207-212]. This method is especially beneficial in systems with re-circulating nutrient solutions, such as the NFT (Nutrient Film Technique), and some tower systems[207-212].

Misting systems, aka aeroponic setups, deliver oxygen and nutrients by spraying a fine mist directly onto the roots[207-212]. This method ensures that the roots are exposed to air and nutrient solution simultaneously, maximizing oxygen absorption[207-212]. Misting can lead to rapid growth and high oxygen efficiency but requires precise control over the misting cycle and droplet size to prevent root suffocation or drying out [207-212].

The Venturi effect utilizes a change in fluid pressure to draw air into the water as it flows through a constructed section of pipe [207-212]. By installing a Venturi injector in the system's water line, air is naturally sucked into the water stream, enriching it with oxygen without the need for additional equipment like air pumps [207-212]. While more common in aquaponic systems, this method is highly efficient and can be integrated into many hydroponic systems with minimal adjustments [207-212].

Dissolved Oxygen Meter (DO Meter) is used for the measurement of oxygen, with recommended levels at about 8 mg/L, which represents environmental water oxygen levels at atmospheric saturation [207-212]. Further dissolved oxygen (DO) saturation decreases with increasing temperature and presence of salts in the nutrient solution [207-212]. Effective dissolved oxygen (DO) levels usually range from 6-8 ppm. Chillers are sometimes used to increase dissolved oxygen (DO) levels [207-212]. Generally, a dissolved oxygen level between 5 to 8 mg/L (parts per million or ppm) is considered ideal for most hydroponic setups[207-212]. However, higher levels, up to 20 ppm, can further enhance plant growth and resilience against root diseases[207-212]. It is essential to monitor oxygen levels regularly using a dissolved oxygen meter to ensure optimal conditions for plants [207-212]. Regularly cleaning hydroponic system, maintaining the right water temperature (oxygen dissolves better in cooler water), and ensuring proper circulation are critical steps [207-212]. A temperature range of 18°C to 22°C (64°F to 72°F) is typically recommended for most hydroponic systems to maintain high dissolved oxygen levels [207-212].

While introducing oxygen into hydroponic system might seem straightforward, but there are many challenges [207-212]. For example, high temperatures can decrease oxygen solubility in water, and overcrowded plants can lead to uneven oxygen distribution [207-212]. These challenges are addressed by employing cooling mechanisms during hot periods, spacing plants appropriately, regularly checking and adjusting oxygenation methods as necessary [207-212]. Beyond the traditional methods, innovative techniques such as electrochemical oxygenation are being explored [207-212]. These advanced methods promise even higher levels of dissolved oxygen, offering exciting possibilities for enhancing plant growth and system efficiency [207-212].

3. Hydroponic Vertical Farming: Carbon Footprint

Agriculture is one of the major contributors to climate change, emitting ~11% of total anthropogenic greenhouse gas (GHG) emissions and between 26%, and 37% of greenhouse gas (GHG) emissions when considering the full value chain [162, 184, 194, 195, 196, 245]. Greenhouse gas (GHG) emissions have natural and anthropogenic origin [162, 184, 194, 195, 196]. Climate change is a multidimensional and simultaneous variation in duration, frequency and intensity of parameters like temperature, precipitation, altering the seasons and life on the Earth. Climate change in the form of temperature increase, frequent periods of drought, unpredictable weather patterns, and poor management of water resources has created a serious threat [162, 184, 194, 195,196, 245]. Greenhouse gas (GHG) emissions are one of the forces driving climate change [162, 184, 194, 195,196, 245]. Life on Earth, as it relies on the natural atmospheric greenhouse effect [162, 184, 194, 195, 196]. Greenhouse gas (GHG) emissions have natural and anthropogenic origin [162, 184, 194, 195, 196]. This is the result of a process in which a planets atmosphere traps the sun radiation and warms the planets surface [162, 184, 194, 195, 196]. Greenhouse gas effect occurs in the troposphere (the lower atmosphere layer), where life and weather occur. Greenhouse effect is produced by greenhouse gasses (GHG) [162, 184, 194-196]. Greenhouse gas (GHG) emissions are those gaseous constituents of the atmosphere that absorb and emit radiation in the thermal infrared range [162, 184, 194-196]. Traces of greenhouse gas (GHG) emissions, both natural and anthropogenic, are present in the troposphere [162, 184, 194-196]. Life on Earth is possible due to greenhouse effect [162, 184, 194-196]. Without it, temperature on Earth's surface would be around -19^{o}C, instead of the current average of 14^{o}C [162, 184, 194-196]. Greenhouse gasses (GHG) effect is produced by greenhouse gasses (GHG) like water vapor, carbon dioxide (CO_2), methane (CH4), nitrous oxides (NxO) and ozone (O_3) [162, 184, 194-196]. However, increasing greenhouse gas (GHG) emissions provokes extreme climate changes such as floods, droughts and heat, which induce reactive oxygen species (ROS) and oxidative stress in plants [162, 184, 194-196]. The main sources of ROS in stress conditions are, augmented photorespiration, NADPH oxidase (NOX) activity, β-oxidation of fatty acids, disorders in the electron transport chains of mitochondria and chloroplasts [162, 184, 194-196].

Urban hi-tech hydroponic agriculture is generally equipped with greenhouses and environmental control systems to create the best environment for food growth and increase food production[1-162, 184, 194-197, 245]. Across the world, vertical farming has seen tremendous growth [197]. As an example, Japan is the leading country when it comes to the development of vertical farming [197]. The number of vertical farms producing mainly lettuce has increased exponentially over the last few years [197-242, 245]. In 2009, there were 35 vertical farming factories in the country and in 2017 this number exceeded 150 and now more than 300 in 2024 [197]. No other country has as many vertical farms as Japan; subsequently, the cost of leafy greens has been reduced extensively by mass production in Japan [197, 242]. Hydroponic experts are of the opinion that many benefits as well as drawbacks for vertical-hydroponic farming [197]. A drawback could be that the initial costs for starting a vertical farm, with hydroponic water systems, artificial lighting, are higher than that for conventional farms[197]. It was found that vertical farms required more energy than greenhouses mainly due to lighting[197, 245]. However, despite the many benefits, a number of disadvantages have also been outlined with hydroponic systems[197]. Hydroponic experts are of the opinion that the production costs, in terms of energy used for vertical farming ends up too high when natural sunlight is removed from the equation[197].

However, carbon foot print of hydroponic vertical farming is very high [197]. Life cycle assessment (LCA) is an internationally recognized method for structured and comprehensive assessment of the use of resources and the subsequent emissions associated with a product or service [1-197]. However, more resilient to climate change, the high energy use of vertical farming still produce GHGs that contribute to warming the climate [197, 198]. The extremely high costs of implementation aside, vertical farming have high carbon footprints [197, 198, 245]. In many cases, vertical farming production methods contribute more to greenhouse gas (GHG) emissions than products grown in the field and shipped long distances to market [197, 198]. Transportation of food materials results in carbon emissions from trucks burning fossil fuels. Initial investment to start hydroponic farming is very high [197-199]. These greenhouses are energy intensive[199]. Large hydroponic farms with more than 10,000 square feet of crops spend an estimated 25% of total spending on energy to simply power climate control systems[199]. If the energy demand to supply vertical farms is greater than the reductions in greenhouse gas emissions they bring, large-scale adoption of the technology would do more harm than good [199]. Growing with green versions of conventional methods was more climate change advantageous than hydroponic systems [199]. Therefore, hydroponics are not going to reverse climate change[199]. Hence degrading land and it is becoming un-farmable, then hydroponics is a good back up plan [199].

One of the study by Blom et al., [194] (2022) performed a quantitative carbon footprint assessment of lettuce cultivation within a typical open-field farm, soil-based greenhouse, hydroponic greenhouse, and an operational vertical farm (VF) in the Netherlands to evaluate the current carbon footprint of vertical farming systems [194]. The assessment included the emissions related to both the life cycle of the farm and the crop, from cradle-to-grave[194]. The baseline empirical data showed that the carbon footprint of the VF (8.177 kg CO_2- eq kg^{-1}) was 16.7 times greater than OF (0.490 kg CO_2-eq kg^{-1}), 6.8 times greater than GH(s) (1.211 kg CO_2-eq kg^{-1}) and 5.6 times greater than GH (h) (1.451 kg CO_2-eq kg^{-1}) per kg FW[194]. Three alternative scenarios were considered to improve the comparability of the baseline data as well as present potential carbon savings in all case studies by using renewable energy[194]. These scenarios included: the lost carbon sequestration potential as a result of land-use change (1), identical packaging for all farming systems (2), and the transition to renewable energy (3) [194]. When these scenarios were considered collectively, the carbon footprint of the VF (1.797 kg CO_2-eq kg^{-1}) reduced to only 3.3 times greater than OF (0.544 kg CO_2-eq $kg^{-1}1$), 2.3 times greater than GH(s) (0.788 kg CO_2-eq kg^{-1}) and 2.4 times greater than GH(h) (0.751 kg CO_2-eq kg^{-1}) [194]. Even with the use of PV panels, the largest contributor to the vertical farm carbon footprint was electricity, representing 66% of the overall alternative carbon footprint. Artificial light accounted for 65% of this electricity[194]. This illustrates that vertical farms, as they exist today, are not able to provide a sustainable solution to the global issues of decreasing availability of arable land and increasing food demands, even though they offer great benefits when compared to conventional farming methods[194]. This study by Blom et al., (2022) confirmed that the carbon footprint of the vertical farm was 5.6–16.7 times greater than that of the conventional farming methods in the baseline scenario and 2.3 to 3.3 times in the alternative scenario[194] The electricity demands of the vertical farm represented 85% of the carbon footprint in the baseline scenario and 66% in the alternative scenario, suggesting that a significant reduction in electricity use is required to compete with conventional farming methods from a carbon footprint perspective[194]. The advantages of Closed-box vertical farms (CBVFs), however, result in higher electricity demands for artificial lighting and air conditioning. This electricity demand exceeds the energy consumption of greenhouse systems to such an extent that, in terms of carbon footprint, it could outweigh the aforementioned benefits altogether[194]. Closed-box vertical farms (CBVFs) are indoor growth systems that use artificial light and air treatment systems exclusively alongside multi-layer hydroponic systems; creating uniform growing conditions independent of the outdoor climate[194].

According to the study conducted by Casey et al., 2022 [200], hydroponic closed-environment agriculture systems use a large amount of electricity for lighting, cooling, ventilation and pumping, equating to 15 kWh per kg of lettuce cultivated [200]. However, hydroponic closed-environment agriculture (CEA) systems are energy intensive, and the environmental footprint of food produced in such systems requires careful evaluation to transformation[200]. Life Cycle Assessment (LCA) is a holistic approach that can be used to assess the environmental efficiency of food value chains [200]. Hydroponic CEA systems have been environmentally assessed in Sweden, Arizona, USA and France [200]. One of the study found that hydroponic CEA systems to be more efficient than open-field and heated greenhouse systems[200]. All these studies found that energy use is the main environmental hotspot that could be mitigated through use of renewable energy[200]. Closed-environment agriculture could be one of the least sustainable forms of food production if poorly implemented, and has many environmental hotspots[200]. But with careful design, scaling and business models, deployment of hydroponic closed-environment agriculture could play a role in positive food system transformation, reducing environmental footprints, sparing land to deliver other ecosystem services, and potentially helping to reconnect consumers with (urban) producers[200].

Vertical farms are artificial, indoor environments where layers of electrically lighted crops that are stacked on top of each other [2, 33, 34, 58, 68, 103, 136-143, 145, 201]. They have been built in old warehouses, factories, shipping containers, and abandoned mines [2, 33, 34, 58, 68, 103, 136-143, 145, 201]. The benefits of vertical farming are real, but found very cost effective [2, 33, 34, 58, 68, 103, 136-143, 145, 201]. Artificial light LED technology now enables entire crops to be cultivated completely indoors with no natural light [201, 245]. This means that multiple crops can be raised in the same space at the same time by stacking them on top of one another in addition to growing year-round, regardless of outdoor weather [201]. Vertical farming may reduce land use, but it leaves a huge carbon footprint [201]. Every layer of plants in a vertical farm needs energy for light, which has to be generated using (mostly) fossil fuels rather than the free sunlight available outdoors [201]. Further, each pound of field-grown lettuce trucked for 1,000 miles produces a quarter pound of carbon dioxide [201]. Fossil fuels burned to grow a pound of lettuce in a vertical farm produce 8 pounds of CO_2[201]. Even with renewable energy sources, the cost is still high [201]. Solar conversion to electricity is not very efficient, so it takes more than nine acres of solar panels to light one acre of crops in a vertical farm[201]. Because of the high cost to build, light, and manage vertical farms, they only make sense for high-value crops that do not need much light[201]. Leafy greens, herbs, and microgreens have proven to be cost-effective, but the rest of salad ingredients (cucumbers, tomatoes, peppers) need so much light to flower and fruit that it is not feasible to grow without the sun [201]. Vertical farms in inner cities will not solve food shortages or provide the calories that stave off hunger[201]. This makes it difficult to justify the high environmental cost of lighting a vertical farm[201].

Vertical farming can only suit a selection of crops, mainly herbs, that will not grow taller than the average height of the shelves, which is around 40 cm[201]. The plants in the vertical farms must also be fast-growing, meaning they will be harvested within roughly one month after planting and require low intensity of light and high density of plants[201]. Furthermore, they must also be valuable plants, fresh and high in nutrition, where more than 85 % of the actual crop can be sold[201]. Good examples of crops, besides salad, that could be cultivated indoors with artificial lighting are fruit-vegetables like tomatoes, peppers, berries and high-end flowers[201]. Crops that are not well suited for this kind of cultivation are staple crops including, e.g. rice, corn and potatoes[201].

Heating a greenhouse is still cheaper and produces less CO_2 than lighting an equivalent vertical farm [201]. Vertical farms generate an opportunity to grow crops in locations and altitudes that are not optimal for the plants growth [201]. Vertical farms make sense in areas where land and water are scarce, where lands are deserts, hilly mountainous regions, islands, limited transportation facility to reach the place, countries with harsh environments with coldest weather conditions, especially if renewable energy is available [201]. They can also create jobs and give new purpose to old vacant buildings [201]. So, despite their drawbacks, vertical farms are still worthy of consideration in certain scenarios [201].

However, existing research suggests that hydroponic farming may have a large carbon footprint for three main reasons [197, 202, 204, 205]. First, infrastructure production in facility agriculture requires a large consumption of resources and energy, potentially producing a large carbon footprint [197, 202, 245]. Second, the operation facility of agriculture consumes considerable energy and produces a high carbon footprint[197, 202]. Third, in the disposal of infrastructure after it is discarded, resources and energy may be consumed, potentially generating a carbon footprint [197, 202]. On the basis of literature survey, many studies have revealed that energy and resource consumption during the operation of facility agriculture, especially electricity, is the most important reason for the high carbon footprint of urban facility agriculture [197, 202, 204, 205]. To become a sustainable solution, vertical farms need to decrease their energy use drastically to significantly reduce their carbon footprint and compete with conventional farming techniques from an environmental perspective [194, 197, 202, 204, 205].

Hydroponic experts are of the opinion that in near future vertical farming will replace conventional farming, with staple crops that are efficiently grown outdoors [197]. Vertical farming is not a replacement, but a compliment to food production, with high-value crops grown in facilities using LED lights and green electricity [197]. One of the primary disadvantages with vertical farming is the initial costs [197]. The efficiency of vertical farms have been compared to that of conventional greenhouses and greenhouses have been determined to be more energy efficient as they use direct solar energy for light and heating [197]. Electricity for lighting has been found to be the greatest energy consumer in vertical farms[197].

LEDs are low in radiant heat and can therefore, be placed near the growing plant[197, 245]. This makes LEDs a more suitable lamp for vertical farms with narrow height shelves[197]. LEDs also allow for optimization of light for greenhouses as it is easily scaled up and down[197]. Electricity costs in a vertical farm could be reduced by using advanced LED systems[197]. The lighting could be further improved by installing reflectors to increase the ratio of the light and improvements of light quality[197]. In the first case, the energy consumption is reduced by 40 %, and in the second it is reduced by 86%[197]. One of the main obstacles in the development of vertical farms is the costs of building a lighting system, and the energy consumption[197]. The lighting of a vertical farm, lit by artificial light, accounts for 70-80 % of the total electricity costs which makes it one of the most important aspects[197]

The results of the study conducted by Newell et al., (2021) [203] indicated that incorporating hydroponic systems into barley production has the potential to reduce GHG emissions, given seed-to-fodder output and energy consumption are maintained at certain levels and the systems are powered by renewable energy[203]. Results also showed that hydroponic farming can provide greater carbon sequestration opportunities than simply shifting to no-tillage farming [203]. The research indicates that hydroponic fodder farming could contribute to climate mitigation objectives if complemented with effective energy and land use policies [203]. Education and research play a crucial role in advancing the field of hydroponics. Universities and research institutions are conducting studies to further understand the benefits and limitations of hydroponic systems [237, 245]. Hydroponic cultivation is also being integrated into educational programs to teach students about sustainable agriculture and the importance of food security [237, 245].

4. Hydroponics: Global Marketing

Hydroponics is a soil-less farming technique that involves growing plants in nutrient-rich water solutions, often in controlled environments such as greenhouses or vertical farms [233-245]. By providing optimal conditions for plant growth and nutrient uptake, hydroponic systems offer several advantages over traditional soil-based agriculture, including higher yields, water conservation, and space efficiency[233-237, 245]. The market's expansion is further driven by technological advancements, government initiatives promoting greenhouse farming, and the growing popularity of locally grown, pesticide-free produce[233-237].

In the year 2024, the hydroponics industry is experiencing significant advancements and growth [234-237, 245]. New technologies, research, market information, and events are shaping the future of hydroponic cultivation[234-237, 245]. With the increasing demand for sustainable and locally grown produce, hydroponics is playing a vital role in the agricultural sector[234, 245]. The hydroponics market continues to grow rapidly, driven by increasing consumer demand for fresh and locally grown produce[237, 245]. Investors are recognizing the potential of hydroponics and are making significant investments in the sector [237, 245]. Market information, such as pricing trends, consumer preferences, and market forecasts, is essential for businesses operating in the hydroponics industry[234-237, 245]. Companies are using market data to make informed decisions and develop effective marketing strategies [234-237].

Global hydroponics market size reached USD 2.56 billion in 2021 and is expected to register a revenue CAGR of 19.2% during the forecast period, according to latest analysis by Emergen Research, Vancouver, BC, Canada [233]. Independent of external climatic conditions and rise in desertification are expected to support market revenue growth between 2022 and 2030 [233]. In addition, rapid change in climate due to global warming had adversely impacted weather patterns giving rise to erratic rainfall, drought, and desertification, thereby declining agricultural productivity [233]. This has led to an increase in global demand for food. Therefore, rising demand for alternative farming practices such as hydroponics, which is expected to propel revenue growth of the market [233]. The hydroponics market is witnessing rapid growth, propelled by the increasing demand for sustainable and high-yield farming practices, rising urbanization, and the need for efficient food production systems[233].

According to Grand View Research Report, the global hydroponics market size was valued at USD 5.00 billion in 2023 and is expected to grow at a compound annual growth rate (CAGR) of 12.4% from 2024 to 2030(www.grandviewresearch.com) [240]. The rapid growth in this sector is linked to the expanding utilization of hydroponic systems in the indoor cultivation of vegetables [240]. Additionally, the increasing acceptance of alternative farming approaches for growing cannabis is experiencing a swift surge[240]. This trend is propelled by the legalization of marijuana in various countries, including Canada, USA, the Czech Republic, South Africa, and others [240]. A growing awareness among consumers about the adverse effects of pesticides and artificial ripening agents on health is anticipated to fuel the demand for hydroponics[240]. This is because hydroponic cultivation eliminates the necessity for such products, resulting in the production of nutritionally superior vegetables[240]. Moreover, the low installation costs and operational simplicity of these systems are poised to further stimulate their adoption throughout the forecast period[240].

The market growth stage in the hydroponics market is high, and the pace of the market growth is accelerating [240]. The hydroponics market is marked by a robust culture of innovation, driven by the pursuit of cultivating superior-quality agricultural products in a cost-effective manner [240]. The adoption of vertical farming and closely stacked plant configurations enables the simultaneous growth of diverse crop types, optimizing space and resources with minimal operational intricacies. This innovative approach not only enhances crop yields but also contributes to sustainability goals by maximizing output in a controlled environment [240]. The industry's commitment to continuous improvement and resource efficiency positions hydroponics as a dynamic and forward-thinking segment within the broader agricultural landscape[240, 245].

5. Conclusion

Hydroponics, a soilless cultivation technique using nutrient solutions under controlled conditions, is used for growing vegetables, high-value crops, and flowers. However, existing research suggests that hydroponic vertical farming may have a large carbon footprint. When comparing vertical farms to conventional farming, at greenhouses and open fields, the result showed a larger yield per square meter from vertical farms. However, comparisons of energy use and environmental impacts are more difficult. One of the primary disadvantages with hydroponic vertical farming is the initial costs. One of the greatest arguments for urban farming is the reduced need for transportation. Another advantage of hydroponics is the ability to grow more food in a localized area without the need to transport as many materials. With the cultivation taking place in close connection to the consumption, the distance for transportation is greatly reduced. The energy use is higher for vertical farms than conventionally grown vegetables and herbs. Vertical farming is an opportunity to grow crops in urban environments and thereby, support the local community with jobs and strengthen food supply. The environmental impacts may not be in favor for vertical arming when comparing to results found in literature for conventional farming. Electricity for lighting has been found to be the greatest energy consumer in vertical farms. Many studies have revealed that energy and resource consumption during the operation facility of hydroponic agriculture, especially electricity, is the most important reason for the high carbon footprint of urban facility agriculture. Electricity costs in a vertical farm could be reduced by using advanced LED systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Singh H, Dunn BL, Payton M, Brandenberger L. Selection of fertilizer and cultivar of sweet pepper and eggplant for hydroponic production. Agronomy. 2019; 9(8): 433. doi:10.3390/agronomy9080433.

[2] Zhao Z, Xu T, Pan X, White JC, Hu X, Miao Y, Demokritou P, Woei Ng K. Sustainable Nutrient Substrates for Enhanced Seedling Development in Hydroponics. ACS Sustainable Chemistry and Engineering. 2022 ;10 (26): 8506-8516. DOI: 10.1021/acssuschemeng.2c01668.

[3] Solis-Toapanta E, Fisher PR, Gomez C. Effects of nutrient solution management and environment on tomato in small scale hydroponics. HortTechnology. 2020; 30(6): 697–705. doi:10.21273/ horttech04685-20.

[4] Son JE, Kim HJ, Ahn TI. Hydroponic systems. In Plant factory. Academic Press. 2020; 273–283. doi:10.1016/b978-0-12-816691-8. 00020-0.

[5] Yafuso EJ, Boldt JK. Development of a hydroponic growing protocol for vegetative strawberry production. HORTSCIENCE. 2024; 59(3):384–393. https://doi.org/10.21273/HORTSCI17523-23.

[6] Eigenbrod C, Gruda N. Urban vegetable for food security in cities. A review. Agron. Sustain. Dev. 2015; 35: 483–498. doi:10.1007/ s13593-014-0273-y.

[7] Sharma N, Acharya S, Kumar K, Singh N, Chaurasia OP. Hydroponics as an advanced technique for vegetable production: An overview. J. Soil Water Conserv. 2018; 17(4): 364–371. doi:10.5958/ 2455-7145.2018.00056.5.

[8] Silva G. Feeding the world in 2050 and beyond–Part 1: Productivity challenges. Michigan State University Extension. 2018.

[9] Silva MG, Alves LS, Soares TM, Gheyi HR, Bione MAA. Growth, production and water use efficiency of chicory (Cichorium endivia L.) in hydroponic systems using brackish waters. Adv. Hortic. Sci. 2020; 34(3): 243–253.

[10] Nicola S, Pignata G , Ferrante A, Bulgari R , Cocetta G, Ertaini A. Water use efficiency in greenhouse systems and its application in horticulture. AgroLife Scientific Journal. 2020; 9(1): 248–262. doi:2434/ 740785

[11] Castillo SD, Moreno-Perez EDC, Pineda-Pineda J, Osuna JM, Rodriguez-Perez JE, Osuna-Encino T. Hydroponic tomato (Solatium lycopersicum L.) production with and without recirculation of nutrient solution. Agrociencia. 2014;48(2): 185–197.

[12] Sahdev RK, Kumar M, Dhingra AK. A comprehensive review of greenhouse shapes and its applications. Front. Energy. 2019; 13: 427–438.

[13] Montero JI, Stanghellini C, Castilla N. Greenhouse technology for sustainable production in mild winter climate areas: Trends and needs. Acta Hortic. 2009; 807: 33–44.

[14] Petropoulos SA, Fernandes Â, Katsoulas N, Barros L, Ferreira ICFR. The effect of covering material on the yield, quality and chemical composition of greenhouse-grown tomato fruit. J. Sci. Food Agric. 2019; 99: 3057–3068.

[15] Shekarchi N, Shahnia F. A comprehensive review of solar-driven desalination technologies for IOT grid greenhouses. Int. J. Energy Res. 2019; 43: 1357–1386

[16] Kuddus Md A, Tynan E, McBryde E. Urbanization: A problem for the rich and the poor? Public Health Reviews. 2020; 41:1. https://doi.org/10.1186/s40985-019-0116-0.

[17] Pandya M, Didwania K. Existential Repercussions of Development: Deforestation caused by Haphazard Urbanisation and Rapid industrialisation. International Journal of Policy Sciences and Law. 2021; 1(3):1372-1397.

[18] Ortiz DI, Piche-Ovares M, Romero-Vega LM, Wagman J, Troyo A. The Impact of Deforestation, Urbanization, and Changing Land Use Patterns on the Ecology of Mosquito and Tick-Borne Diseases in Central America. Insects. 2021; 23;13(1):20. doi: 10.3390/insects13010020.

[19] Breukers A, Hietbrink, O, Ruijs M. The power of Dutch greenhouse vegetable horticulture. An analysis of the private sector and its institutional framework. Report 2008$049. Project number 40637, LEI Wageningen UR, The Hague. ISBN/EAN 978$90$8615$248$3; Price ;20 (including 6% VAT). tps://www.researchgate.net/publication/40096170.

[20] Imam AU, Banerjee UK. Urbanisation and greening of Indian cities: Problems, practices, and policies. Ambio. 2016;45(4):442-57. doi: 10.1007/s13280-015-0763-4. Epub 2016 Jan 14.

[21] Greenhouses cover more and more of Earth’s surface – University of Copenhagen (ku.dk)

[22] Greenhouse Farming in India (beginner guide 2024) (agricultureguruji.com).

[23] Tiwari GN. Greenhouse technology for controlled environment. Harrow, U.K. Alpha Sci. Int. Ltd; 2003.

[24] Agriplast Tech India Private Limited
Survey No. 426/3B-1B, Nallur Village Opp Nallur Government High School, Hosur Panchayat Union & Taluk, Krishnagiri Dist - 635 103, Tamil Nadu.

[25] Agrawal RK, Tripathi MP, Verma A, Sharma GL, Khalkho D. Hydroponic systems for cultivation of horticultural crops: a review. J. Pharmacogn. Phytochem. 2020; 9(6): 2083–2086.

[26] Hasan M, Sabir N, Singh AK, Singh MC, Patel N, Khanna M, Rai T, Pragnya, P. Hydroponics Technology for Horticultural Crops. Tech. Bull. 2018;TB-ICN 188/2018. Publ. by I.A.R.I., New Delhi-110012 INDIA Pp. 30.

[27] Bawa AK. Vertical Farming. Policy paper-89. Published by Dr Anil K. Bawa, Executive Director on behalf of NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NASC, Dev Prakash Shastry Marg, New Delhi - 110 012. India. Pp 1-19. May 2019.

[28] Gustafson DJ. Rising food costs and global food security: Key issues and relevance for India. Indian. J. Med. Res. 2013; 138: 398–410.

[29] Ashton L. The Greenhouse Boom: How indoor farming can transform food production and exports - RBC Thought Leadership. RBC Climate Action Institute. June 12, 2024.

[30] LaPlante G, Andrekovic S, Young RG, Kelly JM, Bennett N, Currie EJ, Hanner RH. Canadian Greenhouse Operations and Their Potential to Enhance Domestic Food Security. Agronomy. 2021; 11, 1229. https://doi.org/ 10.3390/agronomy110612.

[31] Germany: New 'supermarket of the future' has a greenhouse on top (hortidaily.com). August 19, 2024.

[32] Pant T, Agarwal A, Bhoj AS, Joshi RP, Om Prakash K, Dwivedi SK. Vegetable cultivation under hydroponics in Himalayas- challenges and opportunities. Defence Life Science J. 2018; 3 (2):111-115.

[33] Rameshkumar DN, Jagathjothi S, Easwari R, Rajesh R, Naveen Kumar MP, Minithra R, Suresh R, Baladhandapani KK. Vertical Farming- Agriculture of the Future, Indian Farmer. 2020; 7(11) :1013-1017.

[34] Bhattacharya S. et al. VERTICAL FARMING A HOPE FOR INDIA TO ERADICATE THE CRISIS OF FOOD SHORTAGE. Galaxy International Interdisciplinary Research Journal. 2021;9(10): 529-535.

[35] Atherton HR, Li P. Hydroponic Cultivation of Medicinal Plants—Plant Organs and Hydroponic Systems: Techniques and Trends. Horticulturae. 2023; 9: 349. https://doi.org/10.3390/ horticulturae9030349.

[36] Oztekin GB, Tuzel Y, Tuzel IH, Meric KM. Effects of EC levels of nutrient solution on tomato crop in open and closed systems. Acta Hortic. 2007; 801: 1243–1250. doi:10.17660/actahortic.2008.801.152.

[37] Velazquez-Gonzalez RS, Garcia-Garcia AL, Ventura-Zapata E, Barceinas-Sanchez JDO, Sosa-Savedra JC. A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. Agriculture. 2022; 12: 646. https://doi.org/10. 3390/agriculture12050646.

[38] Conn et al.: Protocol: optimising hydroponic growth systems for nutritional and physiological analysis of Arabidopsis thaliana and other plants. Plant Methods. 2013; 9:4.

[39] Sela Saldinger S, Rodov V, Kenigsbuch D, Bar-Tal A. Hydroponic Agriculture and Microbial Safety of Vegetables: Promises, Challenges, and Solutions. Horticulturae. 2023; 9: 51. https://doi.org/10.3390/ horticulturae9010051.

[40] Suhl J, Oppedijk B, Baganz D, Kloas W, Schmidt U, van Duijn B. Oxygen consumption in recirculating nutrient film technique in aquaponics. Sci. Hortic. 2019; 255: 281–291. doi:10.1016/j.scienta.2019. 05.033.

[41] Asao T. (Ed.). Hydroponics: a standard methodology for plant biological researches. BoD–Books on Demand. doi:10.5772/2215. 2012.

[42] Talukder MR, Asaduzzaman M, Tanaka H, Asao T. Electrodegradation of culture solution improves growth, yield and quality of strawberry plants grown in closed hydroponics. Sci. Hortic. 2019; 243: 243–251. doi:10.1016/j.scienta.2018.08.024.

[43] Tatas K, Al-Zoubi A, Christofides N, Zannettis C, Chrysostomou M, Panteli S, Antoniou A. Reliable IoT-based monitoring and control of hydroponic systems. Technologies. 2022; 10(1): 26. doi:10.3390/ technologies10010026.

[44] Tavallali V, Esmaili S, Karimi S. Nitrogen and potassium requirements of tomato plants for the optimization of fruit quality and antioxidative capacity during storage. J. Food Meas. Charact. 2018; 12: 755–762. doi:10.1007/s11694-017-9689-9.

[45] Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R. et al. 2014. Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC. 2014.

[46] Pardossi A, Malorgio F, Incrocci L, Tognoni F. Hydroponic technologies for greenhouse crops. 2006. https://api.semanticscholar.org/ CorpusID:130346435.

[47] Wada T. Theory and technology to control the nutrient solution of hydroponics. In Plant factory using artificial light. Elsevier. 2019; 5–14. doi:10.1016/b978-0-12-813973-8.00001-4.

[48] Walker RL, Burns IG, Moorby J. Responses of plant growth rate to nitrogen supply: a comparison of relative addition and N interruption treatments. J. Exp. Bot. 2001; 52(355): 309–317. doi:10.1093/jexbot/ 52.355.309.

[49] Williams Ayarna A, Tsukagoshi S, Oduro Nkansah G, Lu N, Maeda K.Evaluation of tropical tomato for growth, yield, nutrient, and water use efficiency in recirculating hydroponic system. Agriculture. 2020; 10(7): 252. doi:10.3390/agriculture10070252.

[50] Wortman SE. Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. Sci. Hortic. 2015; 194: 34–42. doi:10.1016/j.scienta.2015.07.045.

[51] Pardossi A, Malorgio F, Incrocci L, Campiotti CA, Tognoni F. A comparison between two methods to control nutrient delivery to greenhouse melons grown in recirculating nutrient solution culture. Sci. Hortic. 2002; 92(2): 89–95. doi:10.1016/s0304-4238(01)00292-8.

[52] Valenzano V, Parente A, Serio F Santamaria P. Effect of growing system and cultivar on yield and water-use efficiency of greenhouse-grown tomato. J. Hortic. Sci. Biotechnol. 2008; 83(1): 71–75. doi:10.1080/14620316.2008.11512349.

[53] Velazquez-Gonzalez RS, Garcia-Garcia AL, Ventura-Zapata E, Barceinas-Sanchez JDO, Sosa-Savedra JC. A review on hydroponics and the technologies associated for medium-and small-scale operations. Agriculture. 2022; 12(5): 646. doi:10.3390/agriculture12050646.

[54] Verdoliva SG, Gwyn-Jones D, Detheridge A, Robson P. Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and β-carotene contents in hydroponically grown tomatoes. Sci. Hortic. 2021; 279: 109896. doi:10.1016/j.scienta.2021.109896.

[55] Vidhya R, Valarmathi K. Survey on automatic monitoring of hydroponics farms using IoT. In 2018 3rd International Conference on Communication and Electronics Systems (ICCES). IEEE. 2018; 125– 128. doi:10.1109/cesys.2018.8724103.

[56] Tatas K, Al-Zoubi A, Christofides N, Zannettis C, Chrysostomou M, Panteli S, Antoniou A. Reliable IoT-based monitoring and control of hydroponic systems. Technologies. 2022; 10(1): 26. doi:10.3390/ technologies10010026.

[57] Tomasi N, Pinton R, Dalla Costa L, Cortella G, Terzano R, Mimmo T. et al. New 'solutions' for floating cultivation system of ready-to-eat salad: a review. Trends Food Sci. Technol. 2015; 46(2): 267–276. doi:10.1016/j.tifs.2015.08.004.

[58] Pascual MP, Lorenzo GA, Gabriel AG. Vertical farming using hydroponic system: toward a sustainable onion production in Nueva Ecija, Philippines. Open J. Ecol. 2018; 8(01): 25. doi:10.4236/oje.2018. 81003.

[59] Pitakphongmetha J, Boonnam N, Wongkoon S, Horanont T, Somkiadcharoen D, Prapakornpilai J. Internet of things for planting in smart farm hydroponics style. In 2016 International Computer Science and Engineering Conference (ICSEC) Chiang Mai, Thailand. 2016; 1–5. doi:10.1109/icsec.2016.7859872.

[60] Putra PA, Yuliando H. Soilless culture system to support water use efficiency and product quality: A review. Agric. Agric. Sci. Procedia. 2015; 3: 283–288. doi:10.1016/j.aaspro.2015.01.054.

[61] Rahman KA, Zhang D. Effects of fertilizer broadcasting on the excessive use of inorganic fertilizers and environmental sustainability. Sustainability. 2018; 10(3): 759. doi:10.3390/su10030759.

[62] Rau AJ, Sankar J, Mohan AR, Krishna DD, Mathew J. IoT based smart irrigation system and nutrient detection with disease analysis. In 2017 IEEE Region 10 Symposium (TENSYMP) Cochin, India. 2017; 1–4. doi:10.1109/tenconspring.2017.8070100.

[63] Rijck G.D, Schrevens E. Application of mixture-theory for the optimization of the composition of the nutrient solution. Acta Hortic. 1995; 401: 283–292. doi:10.17660/actahortic.1995.401.34.

[64] Rodriguez-Ortega WM, Martinez V, Nieves M, Simon I, Lidon V, Fernandez-Zapata JC. et al. Agricultural and physiological responses of tomato plants grown in different soilless culture systems with saline water under greenhouse conditions. Sci. Rep. 2019; 9(1): 1–13. doi:10.1038/s41598-019-42805-7.

[65] Yanti CWB, Dermawan R, Nafsi NS, Bahrun AH, Mollah A, Arafat A. Response of kale (Brassica alboglabra L.) to various planting media and application of liquid inorganic nutrition in DWC (deep water culture) hydroponic systems. Earth Environ. Sci. 2020; 486: 012113. doi:10.1088/1755-1315/486/1/012113.

[66] Zamora-Izquierdo MA, Santa J, Martinez JA, Martinez V, Skarmeta AF. Smart farming IoT platform based on edge and cloud computing. Biosyst. Eng. 2019;177: 4–17. doi:10.1016/j. biosystemseng.2018.10.014.

[67] Zhang C, Xiao H, Du Q, Wang J. Hydroponics with split nutrient solution improves cucumber growth and productivity. J. Soil Sci. Plant Nutr. 2023; 23: 446–455. doi:10.1007/s42729-022-01056-8.

[68] Zhang H, Asutosh A, Hu W. Implementing vertical farming at university scale to promote sustainable communities: a feasibility analysis. Sustainability. 2018; 10(12): 4429. doi:10.3390/su10124429.

[69] Nicola S, Hoeberechts J, Fontana E. Ebb-and-flow and floating systems to grow leafy vegetables: Aa review for rocket, corn salad, garden cress and purslane. Acta Hortic. 2006; 747: 585–593. doi:10.17660/ actahortic.2007.747.76.

[70] Sanjuan-Delmas D, Josa A, Munoz P, Gasso, Rieradevall J, Gabarrell X. Applying nutrient dynamics to adjust the nutrient water balance in hydroponic crops. A case study with open hydroponic tomato crops from Barcelona. Sci. Hortic. 2020; 261: 108908. doi:10. 1016/j.scienta.2019.108908.

[71] Sanye-Mengual E, Orsini F, Oliver-Sola J, Rieradevall J, Montero JI, Gianquinto G. Techniques and crops for efficient rooftop gardens in Bologna, Italy. Agron. Sustain. Dev. 2015; 35(4): 1477–1488. doi:10.1007/s13593-015-0331-0.

[72] Sathyanarayan SR, Warke VG, Mahajan GB, Annapure US. Soil free nutrient availability to plants. J. Plant Nutr. 2023; 46(5): 801– 814. oi:10.1080/01904167.2022.2071736.

[73] Savvas D, Meletiou G, Margariti S, Tsirogiannis I, Kotsiras A. Modeling the relationship between water uptake by cucumber and NaCl accumulation in a closed hydroponic system. HortScience. 2005; 40(3): 802–807. doi:10.21273/hortsci.40.3.802.

[74] Schroder FG, Lieth JH. Irrigation control in hydroponics. Hydroponic production of vegetables and ornamentals. pp. 263–298. Seaman, C. 2017. Investigation of nutrient solutions for the hydroponic growth of plants. Sheffield Hallam University, UK. 2002; doi:10.7190/ shu-thesis-00042.

[75] Rosa-Rodriguez RDL, Lara-Herrera A, Trejo-Tellez LI, Padilla-Bernal LE, Solis-Sanchez LO, Ortiz-Rodriguez JM. Water and fertilizers use efficiency in two hydroponic systems for tomato production. Hortic. Bras. 2020; 38: 47–52. doi:10.1590/s0102-053620200107.

[76] Rouphael Y, Colla G. Growth, yield, fruit quality and nutrient uptake of hydroponically cultivated zucchini squash as affected by irrigation systems and growing seasons. Hortic. Bras. 2005; 105(2): 177– 195. doi:10.1016/j.scienta.2005.01.025.

[77] Rouphael Y, Colla G. Radiation and water use efficiencies of greenhouse zucchini squash in relation to different climate parameters. Eur. J. Agron. 2005; 23(2): 183–194. doi:10.1016/j.eja.2004.10.003.

[78] Rouphael Y, Colla G. The influence of drip irrigation or subirrigation on zucchini squash grown in closed-loop substrate culture with high and low nutrient solution concentrations. HortScience. 2009; 44(2): 306–311. doi:10.21273/hortsci.44.2.306.

[79] Rouphael Y, Cardarelli M, Rea E, Colla G. The influence of irrigation system and nutrient solution concentration on potted geranium production under various conditions of radiation and temperature. Sci. Hortic. 2008; 118(4): 328–337. doi:10.1016/j.scienta.2008. 06.022.

[80] Rouphael Y, Cardarelli M, Rea E, Battistelli A, Colla G. Comparison of the subirrigation and drip-irrigation systems for greenhouse zucchini squash production using saline and non-saline nutrient solutions. Agric.Water Manag. 2006; 82(1–2): 99–117. doi:10.1016/ j.agwat.2005.07.018.

[81] Rouphael Y, Colla G, Battistelli A, Moscatello S, Proietti S, Rea E. Yield, water requirement, nutrient uptake and fruit quality of zucchini squash grown in soil and closed soilless culture. J. Hortic. Sci. Biotechnol. 2004; 79(3): 423–430. doi:10.1080/14620316.2004. 11511784.

[82] Rouphael Y, Raimondi G, Caputo R, De Pascale S. Fertigation strategies for improving water use efficiency and limiting nutrient loss in soilless Hippeastrum production. HortScience. 2016; 51(6): 684– 689. doi:10.21273/hortsci.51.6.684.

[83] Massa D, Mattson NS, Lieth H. An empirical model to simulate sodium absorption in roses growing in a hydroponic system. Sci. Hortic. 2008; 118(3): 228–235. doi:10.1016/j.scienta.2008.05.036.

[84] Massa D, Incrocci L, Maggini R, Carmassi G, Campiotti CA, Pardossi A. Strategies to decrease water drainage and nitrate emission from soilless cultures of greenhouse tomato. Agric. Water Manag. 2010; 97(7): 971–980. doi:10.1016/j.agwat.2010.01.029.

[85] Martinez-Mate MA, Martin-Gorriz B, Martinez-Alvarez V, Soto-Garcia M, Maestre-Valero JF. Hydroponic system and desalinated seawater as an alternative farm-productive proposal in water scarcity areas: energy and greenhouse gas emissions analysis of lettuce production in southeast Spain. J. Cleaner Prod. 2018; 172: 1298–1310. doi:10.1016/j.jclepro.2017.10.275.

[86] Majid M, Khan JN, Shah QMA, Masoodi KZ, Afroza B, Parvaze S. Evaluation of hydroponic systems for the cultivation of Lettuce (Lactuca sativa L., var. Longifolia) and comparison with protected soil-based cultivation. Agric. Water Manag. 2021; 245: 106572. doi:10.1016/j.agwat.2020.106572

[87] Kwon MJ, Hwang Y, Lee J, Ham B, Rahman A, Azam H, Yang JS. Waste nutrient solutions from full-scale open hydroponic cultivation: Dynamics of effluent quality and removal of nitrogen and phosphorus using a pilot-scale sequencing batch reactor. J. Environ. Manage. 2021; 281: 111893. doi:10.1016/j.jenvman.2020.111893.

[88] Lee JY, Rahman A, Azam H, Kim HS, Kwon MJ. Characterizing nutrient uptake kinetics for efficient crop production during Solanum lycopersicum var. Cerasiforme Alef. Growth in a closed indoor hydroponic system. PLoS One. 2017; 12(5):e0177041. doi:10.1371/journal. pone.0177041.

[89] Ludwig F, Fernandes DM, Mota PR, Boas RLV. Electrical conductivity and pH of the substrate solution in gerbera cultivars under fertigation. Hortic. Bras. 2013; 31: 356–360. doi:10.1590/ s0102-05362013000300003

[90] Maboko MM, Du Plooy CP, Bertling I. Comparative performance of tomato cultivars cultivated in two hydroponic production systems. S. Afr. J. Plant Soil. 2011; 28(2): 97–102. doi:10.1080/02571862.2011. 10640019.

[91] Maggini R, Carmassi G, Incrocci L, Pardossi A. Evaluation of quick test kits for the determination of nitrate, ammonium, and phosphate in soil and in hydroponic nutrient solutions. Agrochimica. 2010; 54(6): 331–341.

[92] Eridani D, Wardhani O, Widianto ED. Designing and implementing the arduino-based nutrition feeding automation system of a prototype scaled nutrient film technique (NFT) hydroponics using total dissolved solids

(TDS) sensor. In 2017 4th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE), Semarang, Indonesia. 2017; 170–175. doi:10.1109/ icitacee.2017.8257697.

[93] Kannan M, Elavarasan G, Balamurugan A, Dhanusiya B, Freedon D. Hydroponic farming——a state of art for the future agriculture. Mater. Today: Proc. 2022; 68: 2163–-2166. doi:10.1016/j.matpr.2022. 08.416.

[94] Lee JY, Rahman A, Azam H, Kim HS, Kwon MJ. Characterizing nutrient uptake kinetics for efficient crop production during Solanum lycopersicum var. Cerasiforme Alef. Growth in a closed indoor hydroponic system. PLoS One. 2017; 12(5):e0177041. doi:10.1371/journal. pone.0177041.

[95] Ludwig F, Fernandes DM, Mota R, Boas RLV. Electrical conductivity and pH of the substrate solution in gerbera cultivars under fertigation. Hortic. Bras. 2013; 31: 356–360. doi:10.1590/ s0102-05362013000300003.

[96] Kwon MJ, Hwang Y, Lee J, Ham B, Rahman A, Azam H, Yang JS. Waste nutrient solutions from full-scale open hydroponic cultivation: Dynamics of effluent quality and removal of nitrogen and phosphorus using a pilot-scale sequencing batch reactor. J. Environ. Manage. 2021; 281: 111893. doi:10.1016/j.jenvman.2020.111893.

[97] Ko MT, Ahn TI, Son JE. Comparisons of ion balance, fruit yield, water, and fertilizer use efficiencies in open and closed soilless culture of paprika (Capsicum annuum L.). Hortic. Sci. Technol. 2013; 31(4): 423–428. doi:10.7235/hort.2013.13028.

[98] Ko MT, Ahn TI, Cho YY, Son JE. Uptake of nutrients and water by paprika (Capsicum annuum L.) as affected by renewal period of recycled nutrient solution in closed soilless culture. Hortic. Environ. Biotechnol. 2013; 54(5): 412–421. doi:10.1007/s13580-013-0068-0.

[99] Katsoulas N, Kittas C, Bartzanas T, Savvas D. Development and evaluation of a DSS for drainage management in semiclosed hydroponic systems. Acta Hortic. 2013; 1034: 509–516. doi:10.17660/ actahortic.2014.1034.64.

[100] Kim J, Kim HJ, Gang MS, Kim DW, Cho WJ, Jang JK. Closed hydroponic nutrient solution management using multiple water sources. Biosyst. Eng. 2023; 48: 215–224. doi:10.1007/ s42853-023-00182-0.

[101] Janeczko DB, Timmons MB. Effects of seeding pattern and cultivar on productivity of baby spinach (Spinacia oleracea L.) grown hydroponically in deep-water culture. Horticulturae, 2019; 5(1): 20. doi:10. 3390/horticulturae5010020.

[102] Incrocci L, Malorgio F, Della Bartola A, Pardossi A. The influence of drip irrigation or subirrigation on tomato grown in closed loop substrate culture with saline water. Sci. Hortic. 2006; 107(4): 365–372. doi:10.1016/j.scienta.2005.12.001.

[103] Jafarnia S, Khosrowshahi S, Hatamzadeh A, Tehranifar A. Effect of substrate and variety on some important quality and quantity characteristics of strawberry production in vertical hydroponics system. Adv. Environ. Biol. 2010; 3: 360–364

[104] Hooshmand M, Albaji M, zadeh Ansari NA. The effect of deficit irrigation on yield and yield components of greenhouse tomato (Solanum lycopersicum L.) in hydroponic culture in Ahvaz region, Iran. Sci. Hortic. 2019 ; 254: 84–90. doi:10.1016/j.scienta.2019.04.084

[105] Holmes SC, Wells DE, Pickens JM, Kemble JM. Selection of heat tolerant lettuce (Lactuca sativa L.) cultivars grown in deep water culture and their marketability. Horticulturae. 2019; 5(3): 50. doi:10.3390/ horticulturae5030050.

[106] Hershey DR. Solution culture hydroponics: History And inexpensive equipment. Am. Biol. Teach. 1994; 56(2): 111–118. doi:10.2307/4449764.

[107] Hebbar KB, Kannan S, Neenu S, Ramesh SV. Season and genotype effect on whole plant water use efficiency of coconut (Cocos nucifera L.) seedlings grown in a hydroponic system. Sci. Hortic. 2022; 303: 111198. doi:10.1016/j.scienta.2022.111198.

[108] Hashida SN, Johkan M, Kitazaki K, Shoji K, Goto F, Yoshihara T. 2014. Management of nitrogen fertilizer application, rather than functional gene abundance, governs nitrous oxide fluxes in hydroponics with rockwool. Plant Soil. 374(1): 715–725. doi:10.1007/ s11104-013-1917-4.

[109] Grewal HS, Maheshwari B, Parks SE. Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: an Australian case study. Agric. Water Manag. 2011; **98**(5): 841–846. doi:10.1016/j.agwat.2010.12.010

[110] Graham T, Zhang P, Woyzbun E, Dixon M. Response of hydroponic tomato to daily applications of aqueous ozone via drip irrigation. Sci. Hortic. 2011; **129**(3): 464–471. doi:10.1016/j.scienta.2011.04. 019.

[111] **Rajendran S**, Domalachenpa T, Arora H, Li P, Sharma A, Rajauria G. Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation. Heliyon. **2024**;10:e26823. https://doi.org/10.1016/j.heliyon.2024.e26823.

[112] Goins GD, Yorio NC, Wheeler RM. Influence of nitrogen nutrition management on biomass partitioning and nitrogen use efficiency indices in hydroponically grown potato. J. Am. Soc. Hortic. Sci. 2004; **129**(1): 134–140. doi:10.21273/jashs.129.1.0134

[113] Gillespie DP, Papio G, Kubota C. High nutrient concentrations of hydroponic solution can improve growth and nutrient uptake of spinach (*Spinacia oleracea* L.) grown in acidic nutrient solution. HortScience. 2021; **56**(6): 687–694. doi:10.21273/hortsci15777-21.

[114] Gillespie DP, Kubota C, Miller SA. Effects of low pH of hydroponic nutrient solution on plant growth, nutrient uptake, and root rot disease incidence of basil (*Ocimum basilicum* L.). HortScience. 2020; **55**(8): 1251–1258. doi:10.21273/hortsci14986-20.

[115] Fayezizadeh MR, Ansari NAZ, Albaji M, Khaleghi E. Effects of hydroponic systems on yield, water productivity and stomatal gas exchange of greenhouse tomato cultivars. Agric. Water Manag. 2021; **258**: 107171. doi:10.1016/j.agwat.2021.107171.

[116] Geary B, Clark J, Hopkins, BG, Jolley VD. Deficient, adequate and excess nitrogen levels established in hydroponics for biotic and abiotic stress-interaction studies in potato. J. Plant Nutr. 2015; **38**(1): 41–50. doi:10.1080/01904167.2014.912323

[117] Djidonou D, Leskovar DI. Seasonal changes in growth, nitrogen nutrition, and yield of hydroponic lettuce. HortScience. 2019; **54**(1): 76–85. doi:10.21273/hortsci13567-18.

[118] Domingues DS, Takahashi HW, Camara CA, Nixdorf SL. Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. Comput. Electron. Agric. 2012; **84**: 53–61. doi:10.1016/j.compag.2012.02.006.

[119] Jones JB Jr. Complete Guide for Growing Plants Hydroponically. GroSystems, Inc. Anderson, South Carolina, USA. CRC Press, CRC Press, Taylor & Francis Group, 6000 Broken Sound Parkway NW, Suite 300Boca Raton, FL 33487-2742. 2014

[120] Jensen MN. New developments in hydroponic systems, descriptions, operating characteristics, evaluations, pp. 1–25. In *Proceedings Hydroponic Where Is It Growing*? Hydroponic Society of America: Brentwood, CA. 1981.

[121] Jensen MN. Hydroponics of the future. In Proceedings of the 16th Annual Conference on Hydroponics, ed. M. Bates, 125–132. Hydroponic Society of America, San Ramon, CA. 1995.

[122] Conn et al. Protocol: Optimising hydroponic growth systems for nutritional and physiological analysis of Arabidopsis thaliana and other plants. Plant Methods. 2013; 9:4. doi:10.1186/1746-4811-9-4.

[123] Hershey DR. Solution culture hydroponics: history & inexpensive equipment. Am. Biol. Teacher. 1994; 56:111–118.

[124] Schlesier B, Bréton F, Mock H-P. A hydroponic culture system for growing Arabidopsis thaliana plantlets under sterile conditions. Plant Mol Biol Rep. 2003; 21:449–456.

[125] Shamshiri RR, Kalantari F, Ting KC, Thorp KR, Hameed IA, Weltzien C. et al. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. Int J. Agric & Biol Eng. 2018; 11(1): 1–22.

[126] **Zhao Z, Xu T** et al. Sustainable Nutrient Substrates for Enhanced Seedling Development in Hydroponics. ACS Sustainable Chem. Eng. 2022; 10: 8506–8516.

[127] Asaduzzaman M, Kobayashi Y, Mondal MF, Ban T, Matsubara H, Adachi F, Asao T. Growing Carrots Hydroponically Using Perlite Substrates. Sci. Hortic. 2013; 159: 113–121.

[128] Barbosa G, Gadelha F, Kublik N, Proctor A, Reichelm L, Weissinger E, Wohlleb G, Halden R. Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. Int. J. Environ. Res. Public Health. 2015; 12: 6879−6891.

[129] Massa D, Magán JJ, Montesano FF, Tzortzakis N. Minimizing Water and Nutrient Losses from Soilless Cropping in Southern Europe. Agric. Water Manag. 2020; 241:106395.

[130] Xiong J, Tian Y, Wang J, Liu W, Chen Q. Comparison of Coconut Coir, Rockwool, and Peat Cultivations for Tomato Production: Nutrient Balance, Plant Growth and Fruit Quality. Front. Plant Sci. 2017; 8: 1–9.

[131] Verdoliva SG, Gwyn-Jones D, Detheridge A, Robson P. Controlled Comparisons between Soil and Hydroponic Systems Reveal Increased Water Use Efficiency and Higher Lycopene and β-Carotene Contents in Hydroponically Grown Tomatoes. Sci. Hortic. 2021; 279: 109896.

[132] Walters KJ, Currey CJ. Hydroponic greenhouse basil production: comparing systems and cultivars. HortTechnology. 2015; 25(5):645–650. https:// doi. org/ 10. 21273/ HORTT ECH. 25.5. 645.

[133] AlShrouf A. Hydroponics, aeroponic and aquaponic as compared with conventional farming. American Academic Scientific Research Journal for Engineering, Technology, and Sciences. 2017; **27**(1): 247–255.

[134] Arora U, Shetty S, Shah R, Sinha DK. Automated dosing system in hydroponics with machine learning. *In* 2021 International Conference on Communication information and Computing Technology (ICCICT). Mumbai, India. 2021; doi:10.1109/iccict50803.2021. 9510115.

[135] Ahn TI, Son JE. Changes in ion balance and individual ionic contributions to EC reading at different renewal intervals of nutrient solution under EC-based nutrient control in closed-loop soilless culture for sweet peppers (*Capsicum annum* L.'Fiesta'). Hortic. Sci. Technol. 2011; **29**(1): 29–35.

[136] Al-Chalabi M. 2015**. Vertical farming**: Skyscraper sustainability? Sustain. Cities Soc. 2015; **18**: 74–77.

[137] Gumisiriza MS, Ndakidemi P, Nalunga A, Mbega ER. Building sustainable societies through vertical soilless farming: A cost effectiveness analysis on a small-scale non-greenhouse hydroponic system. Sustain. Cities Soc. 2022; **83**: 103923. doi:10.1016/j.scs.2022.103923.

[138] Martin M, Molin E. Environmental assessment of an urban vertical hydroponic farming system in Sweden. Sustainability. 2019; **11**(15): 4124. doi:10.3390/su11154124.

[139] Vertical Farming Case Study. Published by Alberta Agriculture, Forestry and Rural Economic Development 7000 – 113 Street Edmonton, Alberta Canada T6H 5T6. Prepared by Serecon Inc. Date of Publication April 2021.

[140] Bawa AK. Vertical Farming. Policy paper-89. Published by Dr Anil K. Bawa, Executive Director on behalf of **NATIONAL ACADEMY OF AGRICULTURAL SCIENCES,** NASC, Dev Prakash Shastry Marg, New Delhi - 110 012. India. Pp 1-19. May 2019.

[141] Ali F, Srivastava C. Futuristic Urbanism-An overview of vertical farming and urban agriculture for future cities in India. International Journal of Advanced Research in Science, Engineering and Technology. 2017; 4 (4), April 2017.

[142] Banerjee C. Up and Away! The Economics of Vertical Farming. Journal of Agricultural Studies. 2014; 2(1):40-60.

[143] Despommier D, Carter M. The Vertical Farm: Feeding the World in the 21st Century. UK: Picador. 2011.

[144] Hota S, Stobdon T, Chaurasia OP. **Aeroponics** and inflatable greenhouse in trans-Himalaya: Challenges and future perspective. New Age Protected Cultivation, ISPC. New Delhi. 2018; 4(2)18-20.

[145] Jain R, Janakiram T. Vertical gardening: A new concept of modern era. In: Commercial Horticulture, © 2016, Editors, N.L. Patel, S.L. Chawla and T.R. Ahlawat,*New India Publishing Agency*, New Delhi, India. 2016.

[146] Jankiram T, Bhaskar S. Recent advances in protected cultivation in China. New Age Protected Cultivation, ISPC, New Delhi. 2018; 4(2):25-30.

[147] Kheir Al-Kodmany. The Vertical Farm: A Review of Developments and Implications for the Vertical City. MDPI. 2018*:*1-36. (www.mdpi.com/journal/buildings).

[148] Kojai T, Niu G, Takagaki M. (ed). Plant factory an indoor vertical farming system for efficient quality food production. Academic Press. 2015; 432p.

[149] Pant T, Agarwal A, Bhoj AS, Joshi RP, Om Prakash K, Dwivedi SK. Vegetable cultivation under hydroponics in Himalayas- challenges and opportunities. Defence Life Science J. 2018; 3 (2):111-115.

[150] Rameshkumar DN, Jagathjothi S, Easwari R, Rajesh R, Naveen Kumar MP, Minithra R, Suresh R, Baladhandapani KK. Vertical Farming- Agriculture of the Future, Indian Farmer. 2020; 7(11) :1013-1017.

[151] Bhattacharya S. et al. VERTICAL FARMING A HOPE FOR INDIA TO ERADICATE THE CRISIS OF FOOD SHORTAGE. Galaxy International Interdisciplinary Research Journal. 2021;9(10): 529-535.

[152] Biksa E. Using CO_2 Successfully – Simply Hydroponics. 2024.

[153] The importance of gases in a hydroponic system - Produce Grower.

[154] What are greenhouse gases? | myclimate. 2024.

[155] How to Calculate and Measure Greenhouse Gas Emissions | Ecometrica.

[156] Calculating and reducing your carbon footprint | AHDB

[157] Greenhouse gas emissions and agriculture - Agriculture.Canada.ca. 2024.

[158] Download Vaisala's greenhouse CO_2 measurements document.

[159] Proper Application of CO_2 in Hydroponics (powerhousehydroponics.com).

[160] Carbon-Negative Farming: Is Hydroponics the Solution? | Eden Green.

[161] How to calculate the carbon emissions from your own farm business | Agriculture and Food.

[162] Poudel P, Ghimire A, Howard G, Evans B, Camargo-Valero MA, Mills F, Reddy O, Sharma S, Tuladhar S, Geremew A, Okurut K, Ngom B, Baidya M, Dangol S. Field-based methods for measuring greenhouse gases emissions from on-site sanitation systems: A systematic review of published literature. Heliyon. 2023; 7;9(9):e19947. doi: 10.1016/j.heliyon.2023.e19947.

[163] Greenhouse Carbon Dioxide Supplementation | Oklahoma State University (okstate.edu).

[164] Poudel M, Dunn B. Greenhouse Carbon Dioxide Supplementation. Oklahoma Cooperative Extension Service. HLA-6723. 2023. Division of Agricultural Sciences and Natural Resources • Oklahoma State University, USA.

[165] Karlowsky S, Gläser M, Henschel K and Schwarz D. Seasonal Nitrous Oxide Emissions From Hydroponic Tomato and Cucumber Cultivation in a Commercial Greenhouse Company. Front. Sustain. Food Syst. 2021; 5:626053. doi: 10.3389/fsufs.2021.62605.

[166] Nguyen NT, McInturf SA, Mendoza-Cózatl DG. Hydroponics: A Versatile System to Study Nutrient Allocation and Plant Responses to Nutrient Availability and Exposure to Toxic Elements. J Vis Exp. 2016; 13;(113):54317. doi: 10.3791/54317.

[167] Hydroponics. https://www.powerhousehydroponics.com/proper-application-of-co2-in-ydroponics/#:~:text=Co2%20controllers%20and%20monitors%20can,between%20.

[168] **Rajaseger G**, Chan KL, Tan YK, Ramasamy S, Khin MC, Amaladoss A, Kadamb Haribhai P. Hydroponics: Current trends in sustainable crop production. Bioinformation. **2023**; 30;19(9):925-938. doi: 10.6026/97320630019925.

[169] Lin D, Zhang L, Xia X. Model predictive control of a Venlo-type greenhouse system considering electrical energy, water and carbon dioxide consumption. Appl. Energy. 2021; 298: 117163.

[170] Kläring HP, Hauschild C, Heißner A, Bar-Yosef B, Model-based control of CO_2 concentration in greenhouses at ambient levels increases cucumber yield. Agric. For. Meteorol. 2000; 143: 208–216.

[171] Iddio E, Wang L, Thomas Y, McMorrow G, Denzer A. Energy efficient operation and modeling for greenhouses: A literature review. Renew. Sustain. Energy Rev. 2020; 117:109480.

[172] Lin D, Zhang L, Xia X. Model predictive control of a Venlo-type greenhouse system considering electrical energy, water and carbon dioxide consumption. Appl. Energy. 2021; 298: 117163.

[173] Wielemaker R, Oenema O, Zeeman G, Weijma J. Fertile Cities: Nutrient Management Practices in Urban Agriculture. Sci. Total Environ. 2019; 668: 1277–1288.

[174] Jones JB Jr: Hydroponics: Its history and use in plant nutrition studies. J. Plant Nutr. 1982; 5:1003–1030.

[175] Nutrient Solution For Hydroponics - The Ultimate Guide | Atlas Scientific (atlas-scientific.com). 2024.

[176] **Sangeetha T, Periyathambi E.** Automatic nutrient estimator: Distributing nutrient solution in hydroponic plants based on plant growth. Peer J. Comput Sci. **2024;** 23;10:e1871. doi: 10.7717/peerj-cs.1871.

[177] Mehra M, Saxena S, Sankaranarayanan S, Tom RJ, Veeramanikandan M. IoT based hydroponics system using Deep Neural Networks. Comput. Electron. Agric. 2018; **155**: 473–486. doi:10.1016/j. compag.2018.10.015.

[178] Cho WJ, Kim HJ, Jung DH, Kim DW, Ahn TI, Son JE. On-site ion monitoring system for precision hydroponic nutrient management. Comput. Electron. Agric. 2018;. **146**: 51–58. doi:10.1016/j. compag.2018.01.019.

[179] Hosny KM, El-Hady WM, Samy FM. Technologies, Protocols, and applications of Internet of Things in greenhouse Farming: A survey of recent advances. Information Processing in Agriculture. **2024**; https://doi.org/10.1016/j.inpa.2024.04.002.

[180] Maraveas C, Bartzanas T. Application of Internet of Things (IoT) for Optimized Greenhouse Environments. Agri Engineering. 2021; 3: 954–970. https://doi.org/10.3390/ agriengineering3040060.

[181] Blanco I, Luvisi A, De Bellis L, Schettini E, Vox G, Mugnozza SG. Research Trends on Greenhouse Engineering Using a Science Mapping Approach. Horticulturae. 2022; 8: 833. https:// doi.org/10.3390/horticulturae8090833.

[182] Zhou YH, Duan JG. Design and simulation of a wireless sensor network greenhouse-monitoring system based on 3G network communication. Int J Online Biomed Eng (iJOE). 2016; 12(5):48–5.

[183] Singh VK. Prediction of greenhouse micro-climate using artificial neural network. Appl Ecol Env Res. 2017; 15(1):767–778. https:// doi. org/ 10. 15666/ aeer/ 1501_ 767778.

[184] Ritchie H, Rosado P, Roser M “Greenhouse gas emissions” Published online at Our World In Data.org. Retrieved from: 'https://ourworldindata.org/greenhouse-gas-emissions' (Online Resource). 2020.

[185] **Farvardin M**, Taki M, Gorjian S, Shabani E, Sosa-Savedra JC. Assessing the Physical and Environmental Aspects of Greenhouse Cultivation: A Comprehensive Review of Conventional and Hydroponic Methods. Sustainability. **2024**; 16: 1273. https://doi.org/10.3390/su16031273.

[186] Nutrient Solution For Hydroponics - The Ultimate Guide | Atlas Scientific (atlas-scientific.com).

[187] Testing Hydroponic Nutrients | ZipGrow Inc.

[188] How can I measure individual nutrient levels digitally? : r/Hydroponics (reddit.com).

[189] pH, EC and temperature – Measuring and adjusting your fundamental parameters (bluelab.com). 2024.

[190] Hydroponics & Nutrient Application - Greenhouse Product News (gpnmag.com).

[191] Hydroponics Systems: Calculating Nutrient Solution Concentrations Using the Two Basic Equations (psu.edu). Penn State Extension, USA. 2024.

[192] How to Maintain a Hydroponic Nutrient Reservoir: 14 Steps (wikihow.com). 2024.

[193] Hydroponic EC Measuring Made Simple - NoSoilSolutions.

[194] Blom T, Jenkins A, Pulselli RM, van den Dobbelsteen AJF. The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. Journal of Cleaner Production. 2022; 377: 134443.

[195] **Estimating Greenhouse Gas Emissions in Agriculture** A Manual to Address Data Requirements for Developing Countries. **Food and Agriculture Organization of the United Nations.** Rome, 2015.

[196] Cassia R, Nocioni M, Correa-Aragunde N, Lamattina L. Climate Change and the Impact of Greenhouse Gasses: CO_2 and NO, Friends and Foes of Plant Oxidative Stress. Front. Plant Sci. 2018; 9:273. doi: 10.3389/fpls.2018.00273.

[197] Molin E, Martin M. Assessing the energy and environmental performance of vertical hydroponic farming. © IVL Swedish Environmental Research Institute 2018 IVL Swedish Environmental Research Institute Ltd. P.O Box 210 60, S-100 31 Stockholm, Sweden. Report number C 299.

[198] How To Calculate Your Farm’s Carbon Footprint — AGRITECTURE.

[199] Purdy D. No soil? No problem: Hydroponic farming could help combat climate change and food insecurity. - Climate360 News (lmu.edu). July 7, 2021.

[200] Casey L, Freeman B. et al., Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains. Journal of Cleaner Production. 2022; 369: 133214. https://doi.org/10.1016/j.jclepro.2022.133214.

[201] Oosterwyk J. Six Hard Truths about Vertical Farming – GROW magazine (wisc.edu). Food Systems, Front List, Summer 2022. College of Agriculture and Life Sciences. University of Wisconsin-Madison, USA.

[202] Assessing the energy and environmental performance of vertical hydroponic farming (ivl.se). 2024.

[203] Newell R, Newman L, Dickson M, Vanderkooi B, Fernback T, White C. Hydroponic fodder and greenhouse gas emissions: A potential avenue for climate mitigation strategy and policy development. FACETS. 2021; 6(1): 334-357. https://doi.org/10.1139/facets-2020-0066.

[204] Carbon-Negative Farming: Is Hydroponics the Solution? | Eden Green

[205] Wang C et al., Potential of technological innovation to reduce the carbon footprint of urban facility agriculture: A food–energy–water–waste nexus perspective. Journal of Environmental Management. 2023; 339: 117806 https://doi.org/10.1016/j.jenvman.2023.117806.

[206] https://www.ufv.ca/food-agriculture-institute/the-research/indoor- agriculture/hydroponic-fodder/.

[207] Oxygen and Hydroponics: How to Oxygenate Your System (ponicslife.com). Seattle, WA 98121, USA. March 28th, 2024.

[208] Are you maintaining the proper oxygen levels in your hydroponic production system? – Hort Americas.

[209] The Importance Of Dissolved Oxygen In A Hydroponic Solution - Pure Hydroponics.

[210] 5 Ways To Provide Oxygen To Your Hydroponic Plant's Roots - NoSoilSolutions.

[211] Oxygen and Hydroponic Nutrients (homehydrosystems.com).

[212] https://highvolumeoxygen.com/markets/horticulture/.

[213] Electrical-conductivity-and-ph-guide-for-hydroponics-hla-6722.pdf (okstate.edu). Oklahoma Cooperative Extension Service.

[214] Shrestha A, Dunn BL. Hydroponics | Oklahoma State University (okstate.edu). Published Apr. 2017|Id: HLA-6442. Oklahoma Cooperative Extension Service.

[215] Shrestha A, Dunn BL. hydroponics-hla-6442.pdf (okstate.edu). Oklahoma Cooperative Extension Service.

[216] Hydroponics | Oklahoma State University (okstate.edu). Oklahoma Cooperative Extension Service.

[217] Introduction to Hydroponics | OSU Continuing Education (oregonstate.edu).

[218] Singh H, Dunn BL. Oksa_HLA-6722_2016-10.pdf (shareok.org). Oklahoma Cooperative Extension Service.

[219] Thakulla D, Dunn BL, Hu B. Soilless-growing-mediums-hla-6728.pdf (okstate.edu). Oklahoma Cooperative Extension Service.

[220] Singh H, Dunn BL, Payton M. HYDROPONIC pH MODIFIERS AFFECT PLANT GROWTH AND NUTRIENT CONTENT IN LEAFY GREENS. Journal of Horticultural Research. 2019; 27(1): 31-36 DOI: 10.2478/johr-2019-0004.

[221] Poudal MR, Dunn BL. Greenhouse carbon dioxide supplementation. Oklahoma Cooperative Extension Service. 2017.

[222] Poudel MR, Dunn BL, C Fontanier C, VG Kakani. Effect of Supplemental CO_2 in Leafy Green Production in Hydroponics- 2017 ASHS Annual Conference, 2017.

[223] Singh H, Poudel MR, Dunn BL, Fontanier C, Kakani G. Effect of Greenhouse CO_2 Supplementation on Yield and Mineral Element Concentrations of Leafy Greens Grown Using Nutrient Film Technique. Agronomy. 2020; 10: 323; doi:10.3390/agronomy10030323.

[224] Khatri L, Kunwar A, Bist DR. Hydroponics: Advantages And Challenges in Soilless Farming. Big Data in Agriculture. 2024; 6(2): 81-88.

[225] Reddy K, Sreekumar G, Mishra R, Saikanth D. Future of Hydroponics in Sustainable Agriculture. 2023; 114–127.

[226] Kumar A, Thakur V, Singh J, Rohilla H. Hydroponics, a soilless gardening, a new way. 2024; 362–375.

[227] Muhasin HJ, Gheni AY, Tajuddin NII, Izni NA, Jusoh YY, Aziz KA. A systematic literature review for smart hydroponic system. Bulletin of Electrical Engineering and Informatics. 2024; 13: 656~664 ISSN: 2302-9285, DOI: 10.11591/eei.v13i1.4738.

[228] Regmi A, Rueda-Kunz D, Liu H, Trevino J, Kathi S, Simpson C. Comparing resource use efficiencies in hydroponic and aeroponic production systems. Technology in Horticulture. 2024; 4: e005. https://doi.org/10.48130/tihort-0024-0002.

[229] Naresh R, Jadav SK, Singh M, Patel A, Singh B, Beese S, Pandey SK. Role of Hydroponics in Improving Water-Use Efficiency and Food Security. Int. J. Environ. Clim. Change. 2024; 14: 2, 608-633.

[230] Start container farming - Freight Farms. 2024.

[231] Nirbita P, Chan KY, Thien GSH, Lee CL. Smart Hydroponic Farming System Integrated with LED Grow Lights. Pertanika J. Sci. & Technol. 2024; 32 (2): 685 - 701.

[232] Kadam SA, Kadam PS, Mohite DD. Design and experimental analysis of a closed-loop autonomous rotary hydroponics system for revolutionizing fenugreek yield and enhancing food security. Discov Sustain. 2024; **5**: 137. https://doi.org/10.1007/s43621-024-00339-7.

[233] Hydroponics Market Growth Research Report [2024-2032] | 250 Pages | LinkedIn. Emergen Research. 2024. Vancouver, BC, Canada.

[234] What is Hydroponics in 2024? | by Hydroponic Harmony | Medium.

[235] Hydroponics | National Agricultural Library (usda.gov). 2024.

[236] National Agricultural Library (usda.gov). 2024.

[237] What Is Hydroponics In 2024? (hydroponicharmony.com).

[238] Wastewater is a viable medium for growing lettuce in hydroponic systems | Science Daily. 2024.

[239] Hayashi S, Levine CP, Yu W, Usui M, Yukawa A, Ohmori Y, Kusano M, Kobayashi M, Nishizawa T, Kurimoto I, Kawabata S and Yamori W. Raising root zone temperature improves plant productivity and metabolites in hydroponic lettuce production. Front. Plant Sci. 2024; 15:1352331. doi: 10.3389/fpls.2024.1352331.

[240] Hydroponics Market Size, Share And Growth Report, 2030 (grandviewresearch.com).

[241] Sharma N, Acharya S, Kumar K, Singh N, Chaurasia OP. Hydroponics as an advanced technique for vegetable production: an overview. Journal of Soil and Water Conservation. 2018; 17:364–71.

[242] Kozai T, Niu G, Takagaki M. Plant Factory An Indoor Vertical Farming System for Efficient Quality Food Production. Cambridge: Academic Press. 2015; 423.

[243] Tiwari JK, Buckseth T, Singh RK, Zinta R, Thakur K, et al. Aeroponic evaluation identifies variation in Indian potato varieties for root morphology, nitrogen use efficiency parameters and yield traits. Journal of Plant Nutrition. 2022; 45:2696–709.

[244] Verdoliva SG, Gwyn-Jones D, Detheridge A, Robson P. Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and β- carotene contents in hydroponically grown tomatoes. Scientia Horticulturae. 2021; 279:109896.

[245] **Malabadi RB**, Kolkar KP, Chalannavar RK, Castaño- Coronado KV, Mammadova SS, Baijnath H, Munhoz ANR, Abdi G. Greenhouse farming: Hydroponic vertical farming- Internet of Things (IOT) Technologies: An updated review. World Journal of Advanced Research and Reviews. 2024; 23(02): 2634–2686.