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Greenhouse farming: Hydroponic vertical farming- Internet of Things (IOT) Technologies: An updated review

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Abstract

This review paper of literature highlights the importance of greenhouse urban farming technology, hydroponics, aeroponics, aquaponics, vertical farming and applications of Internet of Things (IOT) technologies. The greenhouse farming is a well known modern agriculture technology for optimal plant growth. Hydroponics, a soilless cultivation technique using nutrient solutions under controlled conditions, is used for growing vegetables, high-value crops, and flowers. Vertical farming is a popular trend in hydroponics that involves stacking multiple layers of plants in a vertical arrangement. This farming method saves space, reduces water usage, and increases yields per square foot of growing area. In comparison to conventional greenhouse cultivation, hydroponics requires less fertilizer, pesticides, and water due to the precise control over their distribution. The term "Internet of Things (IOT)" is a system of interconnected computing devices, sensors, objects, microcontrollers, and cloud servers that can transmit data across a network and control other devices remotely without human intervention. A better management of nutrient solution in hydroponic systems requires optimum pH, electrical conductivity (EC), or ions concentration. The three main greenhouse farming gases (GHGs) emissions in hydroponics hi-tech urban farming are nitrous oxide, methane and carbon dioxide (CO_2). To measure the levels of CO_2 in hydroponics, the more intermediate to advanced grower can use a CO_2 monitoring and controllers system. Hydroponic vertical farming is in infancy in India. Although hydroponic vertical farming units for production of crops like strawberry, lettuce and other leafy vegetables, foliage and flowers are functioning in major metros of India. However, the organized hydroponic vertical farms for production of food crops are not available in India. Therefore, only a few successful hydroponic vertical farms have been built in India mainly due to the initial high price tag on construction and the cost of maintaining them afterwards. Another disadvantage is carbon footprint of hydroponic vertical farming is very high, and discourages its applications.

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1. Introduction

Greenhouse hydroponic farming is one of the modern agricultural technique for growing plants without soil but with nutrient solutions under controlled conditions [1-3-9]. The nutrient solution supplies the essential elements containing macro- and micronutrients with optimum concentrations for plant growth and metabolism [3-9]. Hydroponics has multiple advantages compared to open field soil-based agricultural farming [12-29]. Hydroponic growth systems are a convenient platform for studying whole plant physiology [3-9, 12-29, 34]. Hydroponics cultivation has great prospects for Indian agriculture [27]. It is one of the potential technologies for doubling farmers income. In the changing scenario of food habits and growing fad for green vegetables, herbs and fruits, hydroponics technology is going to play a major role for sustainable year round production in urban areas [3-9, 12-29, 34]. 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 [3-9, 12-29, 34]. Hydroponics is derived from the Greek words that mean, consisting of "hydro" which means water, and "ponos" means labour. The word hydroponics was coined by Professor William Gericke in the 1930s [1- 34]. Similar to hydroponics, the floating gardens of Babylon, Egypt, and Mexico in the Aztecs times indicated that water gardens have been practiced for centuries. In 1887, the first nutrient solution for soilless cultivation systems was developed by Sachs and Knop [3-9, 12-29, 34-340]. 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.), Fenugreek (*Trigonella foenum-graecum*) and strawberry (*Fragaria ananassa)* [3-9, 12-29, 34-340].

Greenhouse cultivation systems increase water and fertilizers productivity compared with open-field soil-based cultivation systems due to better control of environmental conditions and inputs [3-9, 12-29, 34]. Hydroponics, a soilless cultivation technique using nutrient solutions under controlled conditions, is used for growing vegetables, high-value crops, and flowers [1- 34]. It produces significantly higher yields compared to conventional agriculture despite its higher energy consumption. The success 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 [3-9, 12-29, 34-379].

One of the promising approaches to boost vegetable production to enhance food security is growing vegetables in hydroponics [3-9, 12-29, 34-340]. The cultivation of plants in nutrient solution and a soilless growing medium under controlled environmental conditions [3-9, 12-29, 34-379]. The hydroponics, an agricultural method that dispenses with soil, provides a viable alternative to address this problem [3-9, 12-29, 34-379]. Although hydroponics has proven its effectiveness on a large scale, there are still challenges in implementing this technique on a small scale, specifically in urban and suburban settings [1-3 13-33-340]. Also, in rural communities, where the availability of suitable technologies is scarce [3-9, 12-29, 34]. Paradigms such as the Internet of Things (IOT) technologies and Industry 4.0, promote Precision Agriculture on a small scale, allowing the control of variables such as pH, electrical conductivity, temperature, among others, resulting in higher production and resource savings [3-9, 12-29, 34-379].

There are many reasons why greenhouse farming is adopted due to increasing world populations, there might be a shortage of water, food and agricultural land [3-9, 12-29, 34, 35-340]. Additionally, excessive use of fertilizer can increase the cost of production, plant toxicity, and environmental pollution and decrease crop quality [3-9, 12-29, 34, 35]. On the other hand, climate change will bring drought or uneven precipitation, negatively affecting agricultural activity and productivity [1-3 13-33, 35]. One of the biggest challenges will be meeting the demand for food, as farmland is being lost due to climate change, water scarcity, soil pollution, and other factors [1-3 13-33]. Among the main factors fuelling urban population growth are natural increase, migration from rural to urban locations, and reclassification [1-3 13-33]. Therefore, geographic expansion of urban settlements at the expense of rural localities through annexation and transformation [1-3 13-33]. The first step towards addressing 2050 human feeding needs is to embrace sustainability in all critical human activities, agriculture being one of them [1-3 13-33]. The soil quality has been degraded to catastrophic levels, with minimum production, pressing for innovative, sustainable food systems [1-3 4-33]. This is mainly due to over use of fertilizers, chemicals and pesticides, and insecticides etc[1-3 13-33]. Climate change and global population growth are straining global food production systems [3-33, 35]. Global responses to the COVID-19 pandemic, including the shutdown of international trade and human travel, highlight a need to safe out world food security [1-3 13-33, 124-125]. One notable obstacle facing the expansion of the greenhouse industry is the large capital investment required to develop indoor growing systems as compared to traditional agriculture[1- 33-340].

To meet this increasing populations' food and feed demands, there is an urgent need to use innovative approaches to enhance the availability of fresh food produced across the globe [1-3 13-33]. Therefore, the nutrient solution is a substantial factor in hydroponics[1-3 4-33].Thus, proper nutrient solution management is essential to improve nutrient use efficiency and water use efficiency in hydroponic cultivation systems [3-33]. A hydroponic system is essential in improving agricultural productivity as a sustainable and resource efficient system to achieve food security[1-3 4-33-368].

When compared with traditional farming, hydroponics can produce higher yield by exploiting not only the horizontal surface area, but also the vertical space [1-3 4-34-368]. Therefore, effectively increasing the number of plants per unit area, and leaning towards hydroponic vertical farming to meet daily consumer demands for nutritious fresh products in and around densely populated areas [1-3 4-34]. Additionally, hydroponics makes it possible to harvest several crops throughout the year, without chaotic discharges of either pesticides or fertilizers to the environment [1-3 13-33]. Hydroponics uses less land and water than traditional open-field agriculture [1-3 4-33-353-368]. Indeed, by using smart greenhouses equipped with several technologies to control critical parameters for healthy plant physiology [10, 11, 13-33]. Furthermore hydroponics optimizes the use of water and chemicals to eliminate potentially hazardous waste and residuals [1-34, 35-368]. Large-scale hydroponics facilities operate under controlled conditions of climate, lighting, and irrigation, rendered by numerous sensors, web platforms, software and mobile applications available now a days [10, 11, 30]. 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 [1-3 13-33].

The hydroponic systems employ different techniques to supply nutrient solution, such as deep water culture (DWC), Ebb and flow system, nutrient film technique (NFT), wick system, and drip [1-3 13-34]. The DWC technique is one of the most common hydroponic methods in which the plant roots are submerged in an aerated nutrient solution [1-34]. The ebb and flow system is a flood and drain hydroponic system in which the roots are periodically flooded with the nutrient solution through a water pump[1-3 13-33]. A water pump supplies nutrient solution to plants, and the roots are allowed to absorb moisture and uptake nutrients [1-34]. Furthermore, the excess nutrient solution drains to a reservoir, and the roots can take oxygen during this draining time [1-3 13-34].

However, hydroponics has a few limitations, including high initial setup cost, energy, vulnerability to power outage due to water and air pump utilization, and technically trained manpower is needed for operation and maintenance [1-3 13-34-353]. Moreover, higher energy consumption in hydroponic systems may increase greenhouse gas emissions, which can be optimized using longer service life materials and renewable energy[1-34, 35]. High fuel and electricity utilization, machinery, irrigation systems, and transportation increase energy consumption, which may lead to high greenhouse gas emissions [1-3 13-33, 35].

In the following section, the greenhouse farming methods such as hydroponics, aeroponics, aquaponics, vertical farming and applications of IOT technology has been discussed.

2. Greenhouse Farming: Why Adopted

Greenhouse farming is an innovative farming model and a tool for achieving sustainable food production [1-34]. It can also be described as a system that allows the cultivation of crops in a protected environment with enclosed structures, away from extreme weather conditions, pests and diseases, and other unfavorable factors [2-34]. These unfavorable factors that have been addressed by greenhouse farming usually lead to a reduction in yield, quality and quantity in conventional farming [1-34]. This ultimately affects the quality of produce and the projected income of the farmer, thereby, hindering sustainable production [1-34]. The varieties of crops can now be grown in their unnatural regions without compromising on their quality. Therefore, desirable crops can now be produced without hindrance [1-34]. For instance, tropical crops can now be grown in cold regions while temperate crops can be grown in hot regions [3-34].

Greenhouse farming is an agricultural management system that has demonstrated its efficiency in intensifying food production [1-35]. Greenhouse farming has grown rapidly, particularly in higher-income countries such as USA, Canada, UK, France, Germany, The Netherland (Dutch), Denmark, Spain, Australia, Hungary, Switzerland, Russia, New Zealand, Israel, Japan, Middle East (Bahrain, Kuwait, Qatar, Oman, the Kingdom of Saudi Arabia, and Dubai, United Arab Emirates), urban areas in Asia (India, China, Singapore, Malaysia, Taiwan, Thailand etc), in the global production of nutritious foods such as fruits and vegetables [1-34]. Green house farming is also developed to meet current food demand in Azerbaijan, Brazil, Iran, Colombia and South Africa. However, greenhouse farming are often used to produce fruits, medicinal plants and vegetables nutritious products, because of their relatively high price and limited seasonal availability[1-34]. These greenhouse farming systems constitute a feasible alternative for ensuring food supply, which is one of the greatest challenges faced by humankind in the twenty-first century [1-34]. As a result of its numerous advantages over conventional farming, greenhouse farming is now a widely adopted technology [1-34]. A major advantage of greenhouse farming production is its year-round productive capacity and smaller exposure to environmental risks, as it reduces the dependency on, and disruptions by, natural factors and cycles, such as temperature and light, water and rain, and pests and diseases [4-34]. Greenhouse farming cultivation is a great solution to overcome the challenges of field production, such as loss of crops, poor weather and insects. Greenhouse farming is fully protected from the outside environment [3-34]. Greenhouse farming creates an ideal ecosystem for growing crops by controlling factors like temperature, sunshine, fertilization and irrigation, all helping to greatly reduce the risk of lost crops [3-34-300]. Greenhouses help to protect plants from diseases and outdoor pests [1-34]. They also reduce the impact of outdoor conditions like rain, droughts, high winds, cold temperatures and snow [1-34]. The food security is a global concern facing now a days many challenges such as climate change, population growth, economic development, and the change in diet which consequently are putting pressure on resource availability[1-34-300].

Greenhouse farming is now a well adopted technology and influenced by many factors such as climate change, building construction, industrialization, mining, forest fires, commercial logging and rapid growth of the world population, agricultural land and forest area is decreasing worldwide [1-34, 36]. Population growth and migration to urban areas are two interrelated aspects while referring to the hazardous impact of urbanization on the environment [1-34]. Urbanization has long been associated with human development and progress, but recent studies have shown that urban settings can also lead to significant inequalities and health problems [1-34, 36]. Consequently, the demand for food has been steadily increasing [1-34]. According to United Nations Food and Agriculture Organization (FAO) research, 9.73 billion people will populate the earth by 2050 [2-34], which urges attention to agriculture and scientists to meet global food demands[2-34]. In developing countries, deforestation is rising at an alarming rate [1-34, 36]. Factors like urbanization, industrializations, agricultural activities, commercial logging, mining and forest fires, all seem to stem from the increased demand for goods and services borne out of population growth [1-34, 36]. In the short term, deforestation is caused due to population growth (developmental activities) and agricultural expansion, aggravated over the long term by wood harvesting for fuel and export [1-34]. With the onset of the industrial revolution as well as the green revolution in India, there was a sharp fall in the forest cover of country [1-34]. The natural forests have been cleared out for agricultural uses, urban development, industrializations and methods like shifting cultivation have led to a decline in soil fertility [1-34]. Moreover, with the rise in population, followed by the rise of urbanization, the unorganized expansion of the settlement areas have occurred at the cost of the environment and ecology [1-34, 36]. Similarly, the rise of industries, mining activities and lack of strict regulation has heavily contributed to deforestation and loss of agricultural land [1-34, 36]. The main aim of greenhouse farming is to offer an appropriate environment for high-yield production while protecting crops from adverse climate conditions, hi-tech greenhouses provide precise regulation and control of the microclimate variables by utilizing the latest control techniques, advanced metering and communication infrastructures, and smart management systems thus providing the optimal environment for crop development [1-34].

3. Greenhouse Farming: Challenges

The greenhouse farming is a self-tracking, self-regulating, and micro climatically controlled environment for optimal plant growth [1-34-340]. In the agricultural field, the frame structure is covered with a transparent or green shady mesh material. There is a room to cultivate plants in the shade [1-34]. Sensors manage the state of the inside environment entirely or partially, based on the requirements of agriculture [10,11, 30]. The agriculture sector required the development of greenhouse technology [10,11, 30-250]. Temperature, carbon dioxide and oxygen levels, humidity, soil, and air pressure are all varied for each culture [1-34]. The increasing reliability of the smart greenhouse and growing energy demand from emerging nations are the major factors driving market expansion[1-34]. Population growth has increased the demand for food production around the world. Farmers may face enormous pressure to boost crop yield by clearing area for crop cultivation or implementing innovative technologies such as smart greenhouses and vertical farming [1-34]. Due to the general scarcity of arable land in metropolitan settings, farmers have turned to innovative solutions such as hi-tech greenhouses and vertical farming to produce fresh vegetables [1-34].

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 [1-34, 36]. Increasing population, decreasing land and water holding, urbanization, industrialization, global warming are some of the major impediments for the country [1-34, 36]. Various biotic and abiotic stress factors are threatening the open field agricultural production systems throughout the world in varying degrees [1-34, 36]. The soil fertility status has attained almost the saturation level in most parts of the country as the productivity is not rising with the amount of inputs [1-34, 36]. The consumer demand for locally sourced, fresh produce has led to increased willingness to pay for high-quality, sustainably grown fruits and vegetables [1-34, 36]. Technological advancements, including automation and improved crop management, are enhancing productivity and quality, attracting both investors and farmers[1-34, 36]. Greenhouses also contribute to sustainable agriculture practices, aligning with global environmental goals [1-34]. More than 6 million ha area has been affected by salinity and alkalinity apart from other factors continually degrading the soil health [1-34, 36]. Under these circumstances, it would become increasing by difficult to provide quality nutritive food for the burgeoning population in the near future [1-34]. The demand for fresh and green horticultural produce, mainly vegetables, fruits and flowers, is rising sharply particularly in peri-urban and urban areas [1-34, 36]. Sustainable agricultural practices safeguard the food supply, the land, and ensure global food security by addressing the challenges posed by climate change [1-34].

Rapid urbanization and widespread urban sprawl have depleted green cover and increased urban vulnerability to climate change [1-34, 36]. Urbanization is one of the primary characteristics of a rapidly developing economy like India [1-34, 36]. Urbanization is a form of social transformation from traditional rural societies to modern, industrial and urban communities [1-34, 36]. It is a long term continuous process. It is the progressive concentration of population in urban units [1-34, 36]. This increasing rate of migration of the population from rural areas to urban areas has resulted due to the overall desire to achieve better standards of living [1-34, 36]. This includes not only basic necessities like adequate housing, clothing, healthcare, education, transportation and increased employment opportunities but also improved social status in accordance with the societal norms [1-34, 36]. The unregulated rise in construction activities, in and around farmlands and suburbs of the city is undoubtedly contributing to the loss of green cover of the city in India [1-34, 36]. Due to the rush of migrants to urban areas, an expansion of urban settlements is being observed [1-34, 36]. This augmentation, accumulation and spatial extension of urban settlements into rural areas have led to several socio-economic and environmental changes [1-34, 36]. The occupational shift from the primary sector to secondary and majorly tertiary/service sector has severely impacted the land-use in a country like India with the decrease in farmlands and the increase in the influence of industrialization [1-34]. Logging is the commercial felling of trees to manufacture products [1-34]. Deforestation, on the other hand, is defined as the complete removal of the forest and all of its associated life forms. In other words, logging is an action and deforestation is the end result [1-34, 36].

The rise of Indian population to approximately 1.5 billion demands more food, water and quality life particularly in the urban areas [1-34, 36, 38]. Emergence of urban clusters and their expansion consumes significant proportions of agricultural land and substantially impacts biological diversity [1-34, 36, 38]. Population growth is intrinsically linked to increased demand for energy and food [1-34, 36]. Increase in population has adversely affected the green cover in urban India [36]. The shrinking of residential gardens adds to environmental degradation [1-34, 36]. The observed change in lifestyle at the expense of garden space indicated devaluation of urban green cover [1-34, 36]. Increased impact of climate change is a major threat to Indian economic growth [1-34, 36]. Since India exhibits a mix of climatic characteristics ranging from hot and dry to cold and cloudy, the greenhouse farming strategy should be reflective of the local climatic conditions [1-34, 36, 38].

Moreover, additional challenges like lack of labor, sudden weather changes, and water scarcity put more pressure on farmers [3-10, 36]. Global challenges linked to population growth, urbanization, and climate change have led to bringing innovative features to conventional greenhouse cultivation techniques [1-34, 36]. In fact, over the past few years, the greenhouse industry has been transformed to include modern technologies allowing farmers to grow a consistent product all year round using far fewer resources than conventional production [1-34, 36].Traditional farming methods are increasingly being pushed to their limits, necessitating the adoption of innovative technologies and practices to meet the world's food production needs [1-34]. Greenhouse farming has emerged as a leading solution in modern agriculture, offering numerous advantages that are transforming the way to produce food and cultivate crops [1-34]. Greenhouse farming is an innovative farming model and a tool for achieving sustainable food production [1-34]. These unfavorable factors that have now been addressed by greenhouse farming usually lead to a reduction in yield quality and quantity in conventional farming [1-34].

Climate change resulting in different weather patterns can threaten food production as both plant and animal productivity are affected [1-34]. Crop yields are reduced, infectious diseases and pests are prevailing, frequent occurrence of environmental contaminants and chemical residues are observed along the food chain hampering food safety and security [1-34]. Therefore, it is evident that traditional agricultural systems are insufficient to meet the increasing food demand. Hence there is an urgent need for a transition to sustainable and precision agriculture taking advantage of the technological progress to increase crop productivity while preserving the existing resources [1-34]. Controlled greenhouses farming are key solutions to overcome these challenges as they can optimize crop production by manipulating the indoor climate while mitigating the climate change effect [1-34]. The traditional agriculture must transform significantly to produce ecological and sustainable food [1-34]. Therefore, greenhouse agriculture is one of the feasible future alternatives for socio-ecological sustainability [1-34].

4. Advantages of Greenhouse Farming

- Plants can be grown all year round. Hence crops are no longer considered seasonal as they can be available at all times due to continuous production made possible by greenhouse farming [1-34]. For instance, tropical crops can now be grown in cold regions while temperate crops can be grown in hot regions[1-34-340].
- Greenhouse farming can protect the plants from unfavorable climatic factors. Extreme weather conditions such as frost, rain, heavy snowing storm, wind, and temperature affect crops and lead to loss of crops or reduction in crop quality[1-34, 80].
- Control of pests and diseases. However, the extreme weather conditions, pests and diseases can lead to the loss of crops [1-34,80]. However, using a control measure such as greenhouse farming keeps the crops away from the attack of pests and diseases. Greenhouses can give the freedom to grow organic, above ground crops, in addition to protecting crops from insects and outdoor pollution such as pesticide drift. Greenhouses greatly support integrated pest management systems and offer greater biological control by protecting crops from pests [1-34,80]. The result is significant savings on pesticides, less time is needed to treat plants and super crop quality[1-34,80].
- Immediate access to fresh and quality produce. Crops can be grown within the cities in large quantities [1-34,80]. Therefore, there will be no loss in the quality of produce resulting from the transportation of produce over long distances between the farm land and the city[1-34,80].
- Efficiency and conservation of resources. Greenhouse farming helps farmers to determine plant requirements in the right dosage including water, nutrients, pesticides, etc. This prevents unnecessary costs and helps to maximize minimal resources[1-34,80].
- Access to safe and healthy food. When the attack of pests and diseases is prevented, it reduces the use of pesticides on crops, resulting in safe produce [1-34,80]. Also, the application of the right dosage of nutrients to plants supplies the right nutrition to the human body when the produce is consumed [1-34,80].
- Yield and profit maximization. Greenhouse farming helps plants to produce more, and increases the quality of the produce [1-34]. This reduces loss of produce using the best greenhouse practices [1-34,80]. Therefore, there is an increase in the profitability of farmers compared to open-field farming. Greenhouses can be automated at different levels to increase productivity, to improve crop quality and yield, to reduce labor costs and to maximize efficiency [1-34,80].
- Land maximization. Greenhouse technology helps farmers to maximize land space for food production, especially in vertical farming systems [1-34,90]. In vertical farming, plants are grown and stacked vertically to maximize space [1-34]. Therefore, multiple crops are grown in layers allowing more crops to be produced on a small area of land [1-34,80].
- Year round Continuous production, which is also a key element in sustainable food production can be achieved through greenhouse farming. Greenhouse production allows to grow throughout the year in climate-controlled conditions, generally doubling annual yield compared to field crops [1-34,80]. Growing in a greenhouse will increase crop annual yield. However, one need to master conditions like climate, irrigation and fertilization of crops [1-34,80].

5. Greenhouse Farming: Success Stories

Greenhouse farming is essential in increasing domestic crop production in countries with limited resources, limited agricultural land use, transportation problem, and a harsh climatic conditions like Qatar, Bahrain, Saudi Arabia, Kuwait, Singapore, Dubai (UAE), Canada and some parts of India [1-43]. Greenhouse farming development is even more important to overcome these limitations and achieve high levels of food security. Food security is a growing societal challenge [1-43]. The pressure to feed a projected global population of 9.6 billion by 2050 will continue to be limited by decreasing arable land [1-43]. The recent disruptions in international trade resulting from responses to the COVID-19 pandemic have highlighted the importance of regional self-reliance in food production[1-43, 123]. There are more than 50 countries now in the world where cultivation of crops is undertaken on a commercial scale under cover [1-43]. United States of America has a total area of about 4000 ha under greenhouses mostly used for floriculture with a turnover of more than 2.8 billion US $ per annum and the area under greenhouses is expected to go up considerably, if the cost of transportation of vegetables from neighboring countries continues to rise [1-43, 51]. The area under greenhouses in Spain has been estimated to be around 25,000 ha and Italy 18,500 ha used mostly for growing vegetable crops like watermelon, capsicum, strawberries, beans, cucumbers and tomatoes[1-43]. In Spain simple tunnel type greenhouses are generally used without any elaborate environmental control equipments mostly using UV stabilized polyethylene film as cladding material [1-43].

Globally, greenhouse cultivation is increasing rapidly, according to a new study from the University of Copenhagen that maps the global extent of greenhouses [37]. But the majority of this boom is happening outside of Europe, it is taking place in low- and middle-income countries in the Global South [37]. Using a combination of deep learning algorithms and modern sources of satellite imagery, the researchers mapped the amount of land used for greenhouse cultivation worldwide [37]. Their mapping shows that greenhouse cultivation, whether it takes place in glass houses or open fields wrapped in plastic films covers at least 1.3 million hectares of the Earth's surface [37]. The new figure is nearly three times more than previous estimates. Greenhouse cultivation is spread over 119 different countries, of which China accounts for an entire 60.4% of the total area [37]. Spain and Italy occupy second and third place with 5.6% and 4.1% of global greenhouse coverage respectively [37]. Whereas large clusters of greenhouses in the Global North were established in the 1970's and '80s, they began to spring up in the Global South two decades later[37]. And while there has been some stagnation in the Global North, the trajectory of growth continues in Asia, Africa and Central and South America [37]. Indeed, greenhouses in the Global South account for 2.7 times as much area as in the Global North [37]. "Greenhouse cultivation has become a global phenomenon and there is every indication that it will continue to expand [37]. Until now however, this phenomenon is rapidly rising under the radar and research have had large gaps in our knowledge of the dynamics that drive this phenomenon [37].

The present agricultural scenario in **India** is a mixture of outstanding achievements and missed opportunities [3, 4, 15, 27, 38-44]. One such technology is the green house technology. Although it is centuries old, it is new to India [3, 4, 15, 27, 38-44]. In India, till today, 99% of agriculture is traditional open farm land based [3, 4, 15, 27, 38-44]. If India has to emerge as an economic power in the world, Indian agricultural productivity should equal those countries, which are currently rated as economic power of the world [3, 4, 15, 27, 38-44]. While greenhouses have existed for more than one and a half centuries in various parts of the world, in India use of greenhouse technology started only during 1980's and it was mainly used for research activities [3, 4, 15, 27, 38-44]. This may be because of our emphasis, so far had been on achieving self-sufficiency in food grain production [3, 4, 15, 27, 38-44]. However, in recent years in view of the globalization of international market and tremendous boost and fillip that is being given for export of agricultural produce, there has been a spurt in the demand for greenhouse technology [3, 4, 15, 27, 38-44]. The National Committee on the use of Plastics in Agriculture (NCPA-1982) has recommended location specific trials of greenhouse technology for adoption in various regions of the India [3, 4, 15, 27, 38-44].

The surge of greenhouse farming in India is not just an isolated trend [3, 4, 15, 27, 38-44]. It is a progressive response to the escalating challenges of climate change, population growth, and food security[3, 4, 15, 27, 38-44]. Greenhouses are being built in the Ladakh region, Himachal Pradesh, Sikkim and Rajasthan for extending the growing season of vegetables from 3 to 8 months [3, 4, 15, 27, 38-44]. In the North-East, greenhouses are being constructed essentially as rain shelters to permit off-season vegetable production [3, 4, 15, 27, 38-44]. In the Northern plains, seedlings of vegetables and flowers are being raised in the greenhouses either for capturing the early markets or to improve the quality of the seedlings [3, 4, 15, 27, 38-44]. Propagation of difficult-to-root tree species has also been found to be very encouraging [38-43]. Several commercial floriculture ventures are coming up in Maharashtra, Tamil Nadu, Delhi and Karnataka states to meet the demands of both domestic and export markets[3, 4, 15, 27, 38-44].

The commercial utilization of greenhouses started in India from 1988 onwards and now with the introduction of Government's liberalization policies and developmental initiatives, several corporate houses have entered to set up 100% export oriented units [3, 4, 15, 27, 38-44]. In just four years, since implementation of the new policies in 1991, 103 projects with foreign investment of more than Rs.800 crores have been approved to be set up in the country at an estimated cost of more than Rs.5000 crores around Pune, Bangalore, Hyderabad and Delhi [3, 4, 15, 27, 38-44]. Thus the area under climatically controlled greenhouses of these projects is estimated to be around 3000 ha [3, 4, 15, 27, 38-44]. Out of which many have already commenced exports and have received very encouraging results in terms of the acceptance of the quality in major markets abroad and the price obtained. Climatic change is a significant challenge for the farmer [38-43, 44]. More than 99% of farmer uses the traditional farming technique in India [3, 4, 15, 27, 38-44].

In Canada, the greenhouse industry caters both to the flower and off-season vegetable markets [20, 45-46]. The main vegetable crops grown in Canadian greenhouses are tomato, cucumbers and capsicum [20, 45-46]. Hydroponically grown greenhouse vegetables in Canada find greater preference with the consumers and could be priced as much as twice the regular greenhouse produce [20, 45-46]. The greenhouse vegetable sector is both the largest and fastest growing area of Canadian horticulture [20, 45-46]. Common vegetables grown in Canadian greenhouses include tomatoes, cucumbers, lettuce, peppers, green beans, eggplant, herbs, and microgreens [20, 45-46]. However, tomatoes, cucumbers, and peppers represent an overwhelming majority. Collectively, tomatoes, cucumbers, and peppers represent 96% of the total harvested area (16.8 million square meters), 98% of production by metric tonne, and 95% of total farm gate value of all Canadian greenhouse vegetables [20, 45-46]. According to the recent report by Ashton L , 2024, (RBC, Climate Action Institute, June 2024), Canada, greenhouse vegetables account for 39% of Canada's fresh produce exports, 99.5% of which are U.S.-bound [20, 45-46]. Canadian greenhouse fruit and vegetable products are consumed in the east from New York to Florida. Canada is not only a leader in greenhouse productivity but also in innovation [20, 45-46]. Canadian greenhouses energy use is primarily powered by natural gas, which means high energy use equates to high greenhouse gas (GHG) emissions[20, 45-46]. In Canada, there are 920 greenhouses specializing in fruits and vegetables, spanning more than 5,000 acres[20, 45-46]. These greenhouses produce more than 800,000 tonnes of tomatoes, cucumbers, peppers, lettuce, strawberries, and other produce, and are mainly made of glass, polycarbonate, or polyethylene, with different growing mediums depending on the crop[20, 45-46]. Canada is also home to greenhouse production for flowers and cannabis [20, 45-46]. There are more than 1,500 operations growing flowers and plants generating a farm gate value of $2.1 billion in 2023[20, 45-46]. Technologies such as greenhouse farming play an important role in raising agricultural productivity and decoupling production from land use [20, 45-46]. The report by Ashton L , 2024, (RBC), Canada also highlighted that Canada's greenhouse production boasts the highest yields per area of land among top greenhouse nations[20, 45-46, 123]. Canada produces 4.6 times more per area of land than Spain, is slightly more productive than the Netherlands, and 2.6 times more than Mexico[20, 45-46, 123]. Ontario continues to lead the Canadian greenhouse vegetable sector, accounting for 68% of total operations, 70% of total harvested area, and 960 million CAD in farm gate value in 2018[20, 45-46]. The continued expansion of the Canadian vegetable greenhouse industry provides an opportunity for Canada to increase its domestic food supply, especially in times of unforeseen border closures where a large portion of Canada's food supply could be halted[20, 45-46, 123]. If the Canadian greenhouse industry is to expand to better sustain Canada's domestic food needs, a multifaceted approach capitalizing on existing strengths while addressing gaps in our produce supply is needed[20, 45-46]. The Canadian greenhouse industry has the potential to increase production of current top-producing crops and diversify to include other crops for which domestic markets exist[20, 45-46]. Existing greenhouse operations in highly productive regions can increase efficiency and productivity with the incorporation of novel agricultural technologies[20, 45-46].

Globally, population growth is expected to rise to 9.7 billion in 2050, with food demand rising around 56% by 2050 from 2010 level [1-20, 45-46]. Canada's greenhouse vegetables account for 39% of all fresh produce exports, valued at over $1.4 billion. Ontario is responsible for 88% of this export value, predominantly to the U.S. (99.5%), but also to Japan, France, and Taiwan [20, 45-46]. Meeting future food demand is a challenging task amid rising food insecurity. In Canada, greenhouse tomatoes, peppers, cucumbers, lettuce, okra, and strawberries together produce around 8.5 times more per area of land compared to Canadian field production, demonstrating strong productivity[20, 45-46]. The cost of the food is very expensive due to several factors, including poor growing conditions, supply chain issues, and high input costs[20, 45-46]. Canada is second to Mexico in U.S. imports of greenhouse tomatoes by some distance[20, 45-46]. In Ontario, the top producers of greenhouse tomatoes, cucumbers, and peppers had gross margins of approximately 80 to 90% between 2017 and 2021, growing in greenhouses sized at approximate 29, 117 and 49 acres on average, respectively[20, 45-46]. These factors present a challenge for the agriculture sector to innovate and advance climate resilient, efficient systems that bring more of the food produced to people's plates at an affordable price[20, 45-46]. Canada's greenhouses are well positioned to help meet the challenge because of their high land use and input efficiency, potential to shorten supply chains for Canadians, and a strong history of growth and innovation[20, 45-46]. Canadian greenhouse industry has the potential to be a key component of Canada's growth towards a more self-reliant food production system[20, 45-46]. According to report by Ashton L , 2024, (RBC, Climate Action Institute, June 2024) [45], two-thirds of greenhouse production of fruits and vegetables in Canada takes place in Ontario and is mostly concentrated in Essex County in the province's southwest[20, 45-46]. On the basis of report by Ashton L , 2024, (RBC), Canada, Leamington, Ontario, or the "Sun Parlour" of Canada, is in Essex County and home to North America's largest concentration of greenhouses growing fruits and vegetables[20, 45-46]. Essex County benefits from warmer temperatures, long sunny days, a great Lakes-induced microclimate that creates ideal growing conditions[20, 45-46].

According to report by Ashton L , 2024, (RBC, Climate Action Institute, June 2024) [45], Canada, Canadian greenhouse operators are actively exploring approaches to integrate the use of artificial intelligence (AI) in greenhouse operations to centralize data and optimize growing conditions in real-time[20, 45-46]. Canada's greenhouse sector is a success story in growth and productivity. According to report by Ashton L , 2024, (RBC, Climate Action Institute, June 2024) [45], Canada, Canadian greenhouses have demonstrated their global leadership in productivity per area of land[20, 45-46]. By providing local sources of fresh foods year-round, the greenhouse vegetable industry holds strong potential to overcome future food supply shortages and could become a critical contributor to self-sustainable food production in Canada[20, 45-46]. Many challenges, however, surround the Canadian greenhouse industry. In Canada, the vegetable greenhouse industry may present an option for potential solutions[20, 45-46].

Canada also exports a significant number of vegetables internationally[20, 45-46]. In 2018, over half (51.2%) of the total fresh vegetable exports from Canada were grown by greenhouse operations, contributing approximately 1.95 billion CAD to the Canadian economy[20, 45-46]. As well as being Canada's largest supplier of vegetables, the USA remains

Canada's largest importer. In 2018, the USA imported 97.8% of Canada's total vegetable exports, amounting to values of approximately 1.91 billion CAD[20, 45-46]. Additionally, increasing the production capacity of commodities already grown in greenhouses, such as lettuce, beans, eggplants, strawberries, and microgreens, could reduce Canada's trade reliance and promote a self sustaining vegetable supply [20, 45-46]. The global community has been impacted by the effects of both climate change and COVID-19 on food security. Many countries have recently put a heightened focus on domestic supply, including greenhouse vegetable cultivation[20, 45-46, 124-125].

Increased operating expenses are a common obstacle experienced by the Canadian greenhouse industry[20, 45-46]. Another area contributing to increased costs is integrated pest management. Labor- and time-intensive crop protection practices, such as pesticide applications, biological control agents (BCAs), and sanitization and maintenance procedures, are necessary to limit crop destruction by pests and pathogens[20, 45-46]. Labor shortages present a long-standing challenge for Canadian vegetable agriculture in both greenhouse and field operations, though greenhouses' labour needs are higher, partly due to their longer growing season[20, 45-46].

There are added challenges for more northern countries with harsher climates, such as Canada, to increase greenhouse vegetable production[20, 45-46]. Finland, Sweden, Norway, Iceland, and Russia are looking to improve upon their existing greenhouse industries, which, like Canada, also commonly grow cucumbers, tomatoes, and peppers. In fact, the Russian cucumber market is already almost 100% supplied by domestic greenhouse production[20, 45-46]. In these northern regions, the major challenge for greenhouse production is the high energy requirements for year-round heating. Countries across the Americas and Europe have developed large-scale rooftop greenhouses[20, 45-46].

The longevity of the greenhouses themselves is a concern to many regions with harsh conditions, including Canada [20, 45-46]. Adaptations to limit hurricane impacts and earthquakes could be applied for some of Canada's extreme weather events [20, 45-46]. Greenhouses can emerge as a pillar of Canada's agri-food growth and sustainability ambitions over the next decade and towards 2050[45]. The sector is set to double in acreage over the next 10 years, deliver more diversity of products, and improve yields [45]. The real challenge for Canadian greenhouses in meeting demands in growing markets and overcoming rising resource constraints will be developing infrastructure that spurs growth and decarbonization, and enables rural communities to thrive [45].

In Germany, the first supermarket with a greenhouse roof was built, which utilizes an aquaponic system, using fish bio-waste to fertilize the plants, serving as a bio-filter to clean the water and return it to the fish tank [47-50]. The REWE green farming store, Germany is not just a supermarket, but also a production facility in the middle of the city [47-50]. On the rooftop farm, which is operated by REWE's partner ECF Farmsystems, 800,000 basil plants can be grown annually using aquaponics, which use dung from the fish that REWE farms on site as fertilizer [47-50]. No pesticides are used in this process. This is the first supermarket with a rooftop greenhouse in Europe and it combines retail with a basil farm and fish farm [47-50].

Another notable aquaponic urban greenhouse exists in Sweden, where tropical commodities, including bananas and mangoes, are being locally grown [52]. The use of regionally advantageous technological developments is driving greenhouse operations for food sustainability[52]. MOA JOHANSSON is one of three co-founders of the start-up Containing Greens. Based in Luleå, Sweden, the company uses waste heat to grow vegetables that will help feed communities in northern Sweden year-round [52]. For example, initiatives to help address food insecurity in mountainous regions of India and Nepal are challenging due to a lack of financial feasibility [53-59]. In the rural far-northern regions of Russia, the potential for vertical farming using hydroponic systems to locally supply produce has been supported by significant federal financial incentives [46, 60-61]. Iceland's computerized geothermal climate control systems supporting automated hydroponic and soilless greenhouses have been successful, though they still depend on government funding and tariffs to compete economically with imported vegetables [46, 53-59-61].

The Netherlands (Dutch) is the traditional exporter of greenhouse grown flowers and vegetables all over the world [62-81]. With about 89,600 ha under cover, the Dutch greenhouse industry is probably the most advanced in the world [62-81]. Dutch greenhouse industry however relies heavily on glass framed greenhouses, in order to cope up with very cloudy conditions prevalent all the year round [62-81]. A very strong research and development component has kept the Dutch industry in the forefront[62-81]. According to the Washington post, The Dutch has nearly 24,000 acres — almost twice the size of Manhattan — of crops growing in greenhouses[62-81]. These greenhouses, with less fertilizer and water, can grow in a single acre what would take 10 acres of traditional dirt farming to achieve. Dutch farms use only a half-gallon of water to grow about a pound of tomatoes, while the global average is more than 28 gallons [62-81]. Fifteen out of the top 20 largest agri-food businesses — Nestlé, Coca-Cola, Unilever, Cargill and Kraft Heinz — have major research and development centers in the Netherland [62-81]. The Netherlands has used advances in vertical farming, seed technology and robotics to become a global model [62-81]. In 2019, the Netherlands exported agriculture goods worth of €94.5 billion and this number is increasing every year [62-81]. The Dutch agriculture is very efficient and the Dutch have become masters at increasing their food productivity per hectare, animal and or labour unit reducing the costs with new and innovative green house technologies [62-81]. After the United States, the Netherlands is the biggest exporter of agricultural produce in the world [62-81]. The Dutch agricultural sector exports some € 65 billion of agricultural produce annually [62-81]. This is 17.5% of total Dutch exports. One quarter goes to its largest trade partner, Germany. Accounting for 10% of the Dutch economy and employment, the agricultural and horticultural sectors play a crucial role [62-81].

Dutch greenhouse horticulture is a major sector, with more than 3,300 specialized companies representing an export value of €10.8 billion[62-81]. This makes greenhouse horticulture as one of the most important sectors within Dutch agribusiness[62-81]. Annually greenhouse contributes €7.9 billion to the Dutch economy accounting for 1% of the gross domestic product[62-81]. A majority of exports valued at €10. 8 billion consisting of fruit and vegetables, flowers and plants, are available for immediate neighbors in Western Union [62-81]. This vibrant greenhouse farming industry is not just a significant player on the economic front but also a leader in innovation and sustainability[62-81]. This sector is also working on the path of achieving 100% organic crop protection by 2030 and aims to become completely climate neutral by 2040. The driving force behind this wave of innovation is the Triple Helix model, a synergistic collaboration among governments, universities and businesses[62-81].

The greenhouse sector is one of the largest industrial sectors in the Netherlands [62-81]. In 2003, about 9500 companies owned a total area of 10,500 hectares, but the number of companies dropped to 6250 in 2009, due to take-overs and voluntary company closures[62-81]. About half of the total cultivated area produces tomatoes, peppers and other vegetables with the other half dedicated to flowers and plants[62-81]. The sector is renowned as technologically sophisticated and innovative, with advanced systems for controlling temperature, air quality, energy production, lighting, irradiation, water provision, pest management, sewerage, waste disposal, crop harvesting and product packaging[62-81]. Fruits, vegetables, house plants, cut flowers: with about two thousand companies and a total area of about ten thousand hectares in greenhouses. The Dutch greenhouse horticulture sector represents more than one percent of the Dutch economy and the Dutch labour market [62-81]. About eighty percent of the annual production value of six billion euros is exported. But the international competition is increasing [62-81]. For this reason, Glastuinbouw Nederland, the leading entrepreneurial network in the Dutch greenhouse horticulture sector, maintains that the sector must continue to innovate[62-81]. Glastuinbouw Nederland stands at the forefront of the Dutch greenhouse horticulture sector as a paramount entrepreneurial network [62-81]. This has represented the 75% of the country's greenhouse horticulture acreage, and embodies the collective force of Dutch growers dedicated to responsibly producing vegetables, flowers and plants [62-81].

The development of greenhouses in Gulf countries is primarily due to the extremity in the prevailing climatic conditions [82-88]. Israel is the largest exporter of cut flowers and has wide range of crops under greenhouses (15,000 ha) and Turkey has an area of 10,000 ha under cover for cultivation of cut flowers and vegetables[82-88]. In Saudi Arabia cucumbers and tomatoes are the most important crops contributing more than 94% of the total production. The most common cooling method employed in these areas is evaporative cooling [82-88].

Egypt has about 1000 ha greenhouses consisting mainly of plastic covered tunnel type structures[1- 82-88]. Arrangements for natural ventilation are made for regulation of temperature and humidity conditions. The main crops grown in these greenhouses are tomatoes, cucumbers, peppers, melons and nursery plant material[1-82-88].

In Asia, China and Japan are the largest users of greenhouses. The development of greenhouse technology in China has been faster than in any other country in the world[1-82-88]. With a modest beginning in late seventies, the area under greenhouses in China has increased to 48,000 ha in recent years[1-82-88]. Out of this 11,000 ha is under fruits like grapes, cherry, japanese persimon, fig, loquot, lemon and mango. The majority of greenhouses use local materials for the frame and flexible plastic films for glazing. Most of the greenhouses in China are reported to be unheated and use straw mats to improve the heat retention characteristics[1-82-88].

Japan has more than 40,000 ha under greenhouse cultivation of which nearly 7500 ha is devoted to only fruit orchards[1-82-88]. Greenhouses in Japan are used to grow wide range of vegetables and flowers with a considerable share of vegetable demand being met from greenhouse production[1-82-88]. Even a country like South Korea has more than 21,000 ha under greenhouses for production of flowers and fruits[1-82-88]. Thus, greenhouses permit crop production in areas where winters are severe and extremely cold as in Canada and USSR, and also permit production even in areas where summers are extremely intolerable as in Israel, UAE, and Kuwait[1-82-88]. Greenhouses in Philippines make it possible to grow crops in spite of excessive rains and also in moderate climates of several other countries[1-82-88]. Thus, in essence greenhouse cultivation is being practiced and possible in all types of climatic conditions [1-82-88].

Qatar is a small country in terms of land area located in the Arabian Gulf with an arid desert climate [89-94]. Agricultural food production in Qatar faces many challenges such as scarce freshwater, limited arable land and a climate that is not favoring agriculture as the summers are long, hot, and humid with low annual rainfall and often dust storms [89-94]. Therefore, in the last decade between 2010 and 2019, the greenhouse and open field production of the most consumed vegetables in the country has increased from 31.573 tons to 66.500 tons, recording an approximate 110% increase (Planning and Statistics Authority in Qatar) [89-94]. Moreover, the Qatar greenhouse market is a developing sector, expected to mark double-digit growth during the near future and reach a value of approximately 259 million US$ by 2025 [89-94]. Considering climate change, shortage of resources, population growth, and harsh climate, the agricultural sector in Qatar is encountering several challenges in ensuring its growing food needs[89-94]. Advanced technological solutions such as active smart greenhouses, IOT and precision agriculture, as well as alternative sources for water and energy, can support the state of Qatar to achieve its National Vision 2030, particularly the food security, environmental and sustainability challenges [89-94].

By 2019, Saudi Arabian enterprise Mishkat had already accomplished a notable milestone. The vertical farm was believed to be the first to earn organic certification [94-98]. This recognition was founded on their sophisticated use of organic pest management, including sticky traps, bumblebee pollination, and the introduction of predatory insects [94-98]. However, in response to changing operational needs, Mishkat is now shifting from an 'organic' label to a 'pesticide-free' marketing model [94-98].

The Middle East is known for its extreme weather conditions, characterized by scorching summers and high temperatures that can approach and even exceed 40 degrees Celsius[1-94-98]. These climatic conditions can be a significant challenge for agriculture in the region. Extreme heat, combined with water scarcity in many areas, poses a double challenge for farmers[1-94-98]. Extreme heat has a direct impact on plant growth and crop productivity in the Middle East[1-94-98]. One of the key players in the fight against extreme heat in agriculture is the cooling system, which controls temperature and humidity inside greenhouses [94-98]. Another is the use of double plastic covering, a system that provides thermal insulation and humidity control[94-98]. This advanced equipment helps to create a controlled environment in greenhouses and agricultural structures, counteracting the adverse effects of extreme heat [94-98]. Together, they enable a more efficient, resilient and productive crop, which is critical in a region like the Middle East where high temperatures are a constant [94-98]. Cooling System technologies has led to a substantial increase in productivity. Farmers have witnessed more abundant harvests and an improvement in the overall quality of their produce. In addition, a greenhouse dedicated to flower production has seen a similar transformation thanks to these solutions[94-98]. Flowers, which once struggled under the scorching heat, now bloom with more vibrant colors and extended shelf life [94-98].

Middle East and Africa smart greenhouse market is flourishing because of growing adoption of rooftop farming, increasing popularity of organic food, and rising convenience of crop monitoring and harvesting [94-98-108]. BlueWeave Consulting, a leading strategic consulting and market research firm, in its recent study, expects Middle East & Africa smart greenhouse market size to grow at a CAGR of 8.4% during the forecast period between 2023 and 2029. Major factors for expansion of Middle East and Africa smart greenhouse market include rising food consumption due to an immensely growing population, as well as indoor farming trends due to changing consumer preferences[94-98-108]. The increasing necessity fresh food in the Middle East region has contributed to the region's potential for urban gardening. The most pivotal elements driving the market's growth are the expanding trend of rooftop farming, as well as the rising population[94-98-108]. Adopting an innovative approach to vertical farming might provide access to safe, nutritious, and inexpensive food, create thousands of jobs, provide ample financial opportunities, and benefit the environment. Crops, fruits, and vegetables, among other things, can be grown under regulated conditions in a greenhouse, and the produce can be gathered throughout the year regardless of season or weather differences. Therefore, this factor is expected to boost the market growth during the forecast period. However, high-cost investment in smart greenhouse is anticipated to hinder the growth of Middle East and Africa smart greenhouse market[94-98-108].

Based on technology, Middle East and Africa smart greenhouse market is divided into HVAC, LED Grow Light, Irrigation System, Material Handling, and Valves segments[94-98-108]. The LED grow light segment dominates the market during period in analysis because smart greenhouses necessitate the installation of costly systems, such as HVAC, control systems, LED grow lights, and sensors[94-98-108]. LED grow light units are made up of an array of LEDs that are specifically intended for smart greenhouse applications. LED grow lights are pricey, but they are an essential component of a smart greenhouse. The units contain several types of LED lights that range in terms of power and wavelengths required to provide the necessary light for the respective plant species[94-98-108].

Producing food sustainably in the Middle East has always been a challenge due to the region's predominant desert climate and limited freshwater supplies[94-98-108]. With approximately 85% of food consumed in the United Arab Emirates being imported, HDR worked with a joint venture between Emirates Flight Catering, a subsidiary of the Emirates Group, and Crop One Holdings, Inc. to bring forward an imaginative and sustainable solution. HDR was commissioned to lead the design, provide site supervision and office support for construction of the world's largest vertical farming facility in Dubai[94-98-108]. The three-story, 330,000-square-foot facility provides a controlled environment for producing more than 6,500 pounds of leafy greens every day, unaffected by outside factors such as weather or pests[1-94-98-108]. Using hydroponics technology, the vertical farm does not need soil, natural sunlight or pesticides. Amid global food scarcity, a large share of the produce will be for the consumer retail market, meeting a valuable need in the region[1-94-98-108]. Since July 2022, the produce is also being used as part of onboard catering by Emirates Airlines, the largest airline in the Middle East. Typically, the biggest challenge may have seemed keeping heat outside the building, Dubai averages almost 110 degrees Fahrenheit (43 degrees Celsius) in the summer [94-98-108]. Interestingly, the climate inside posed the bigger challenge. To simulate daytime conditions, hundreds of LED lights sit above the crops, producing heat and evaporating water, causing a rise in humidity[94-98-108]. There is no water evaporation into the atmosphere; hence vertical farming uses a fraction of the water required for traditional farming methods[1-94-98-108]. The majority of water used is recovered, treated and recycled [94-98-108]. Following strict quality requirements, the team designed a water treatment facility on site to facilitate this process. Water is treated close by, then recycled back to the grow rooms. The building is also capable of generating almost a third of its required energy from solar panels located on the roof, adding to the facility's sustainability credentials[1-94-98-108].

Dutch adaptive technology and resilient farming methods present opportunities to overcome obstacles which are faced in the Middle East, like water scarcity and climate change[1-94-98-108]. The shortage of skilled labor poses a significant obstacle to the adoption of advanced farming techniques[1-94-98-108]. Plantlab will collaborate with Saudi Greenhouses to build indoor farms throughout the Middle East and North Africa. Recently a cooperation agreement was signed by both companies. The first location opens in Q1 of 2024, in Riyadh, Saudi Arabia, adjacent to the Saudi Greenhouses greenhouse complex [1-94-98-108].

Innovative farming entrepreneurs hold the future of The Gulf region. Dutch Greenhouse Delta is here to navigate these visionaries to food security, recognizing the challenges and opportunities for modern agriculture. Dutch Greenhouse Delta platform represents the entire ecosystem of horticultural excellence in the Netherlands, consisting of leading companies, academia and government [1-94-98-108]. Dutch Greenhouse Delta integrated approach provides a comprehensive farmer solution, offering sustainability and efficiency throughout the entire value chain [1-94-98-108]. Dutch Greenhouse Delta takes the lead in orchestrating efforts to address the evolving needs of the Gulf nations, aligning Dutch horticultural excellence with the food safety strategy of Bahrein, Kuwait, Qatar, Oman, the Kingdom of Saudi Arabia, and the United Arab Emirates[1-94-98-108].

Azerbaijan has three major greenhouse vegetable production areas: the western part of the country (mainly Ganja and Shamkir regions); the central region (mainly Absheron peninsula); and the southern region Lankaran and Astara area [109-113]. Of the about 280 hectares of greenhouses in Azerbaijan, about 20% are antiquated Soviet style greenhouses, many of which are currently being updated and repaired by their owners[109-113]. New structures of Israeli, Dutch, Turkish and Italian companies have been built or are in the planning stages of construction [109-113]. Finally, about 30% are home built polyethylene covered greenhouses with mixed wooden and steel frame materials, while low tunnels also exist [109-113]. The majority of greenhouse cultivation systems in Azerbaijan, regardless of geographic location, consist of fundamental climate control components, and depending on their design and complexity, they can provide a greater or lesser amount of climate control, and subsequent plant growth and productivity [109-113-131]. Over the past 5 years, Azerbaijan experienced a boom in greenhouse constructions. A lot of modern glass greenhouses have been built over the past five years from Phoenix Greenhouse Solutions in Azerbaijan [109-113].

Azerbaijan is a country with a rich agricultural history, and has plenty of opportunities. For instance, strawberry, raspberry, banana, and avocado could be quite profitable businesses[109-113]. Plant diseases, gas, and fertilizer expenses are the most challenging factors nowadays, especially rising prices for fertilizers and agrochemical products increase the cost of the end product[109-113]. The greenhouse company (JSC "GREEN WORLD") is situated in the settlement of Zira, the Absheron peninsula and specialized in growing tomatoes. Zira is historically known to be a perfect place to grow vegetables and other agricultural products[109-113]. This is the reason why this location was home to dairy-vegetable state farm, which used to supply Azerbaijan as well as other republics of post-soviet space with its produce for a long time other[109-113]. Grow Group Azerbaijan is one of the first and leading companies in country engaged in modern greenhouse activities [109-113]. Operating since 2009, Grow Group Azerbaijan contributes to the development of the non-oil industry, to the growth of production and export in the country, as well as to the further development and recognition of the Made in Azerbaijan brand [109-113]. Built by Grow Group Azerbaijan, greenhouse systems are equipped using high quality materials that meet world standards [109-113]. Grow Group Azerbaijan, is a leader in the application of advanced technologies in Azerbaijan, annually participates in agricultural exhibitions both in country and abroad, sharing its experience, the latest methods and instruments with local farmers to increase the quality and export volumes of vegetables[109-113]. The Baku Greenhouse Complex is Engaged in production of tomatoes and other vegetables on an area of 20 hectares[109-113]. Another company, Growers Market - Supplies all types of greenhouses, located inside and outside the country, with the necessary equipment, systems and materials[109-113]. The Tolze Caspian - Local representative of Stolze International BV, one of the most successful companies in Europe for irrigation, climate control and heating systems for greenhouses. Grow Group is also a representative of RICHEL is one of the most advanced companies in France and Europe for the production of structures for glass and plastic greenhouses[109-113]. Grow Construction - Turnkey[109-113]. This is involved in the construction of new greenhouse complexes, as well as construction and installation of various greenhouse systems separately[109-113].

The Brazilian commercial greenhouse market is predicted to grow at a CAGR of 2.62% from US$36.593 million in 2021 to US$43.868 million by 2028 [115-113]. Brazil has a diverse climate. As a result, a variety of agricultural soils and climates can be effectively produced in greenhouses throughout the nation[115-113]. In Brazil, over a million individuals are working in the greenhouse business. Numerous crops, including ones that might not be ideal for conventional farming techniques, can be grown in this region due to the favorable environment[115-113]. Brazil has a sizable population, which means that many customers are interested in purchasing goods from a greenhouse farm[115-113]. Additionally, the high humidity levels in Brazilian greenhouses aid in protecting plants from the adverse weather conditions outside [115-113].

Brazil's greenhouse farming is expanding as the country experiences warmer temperatures and drier soil [115-113-131]. The practice of cultivating plants in a controlled environment was first pioneered in the Netherlands and has since grown to be a significant agricultural sector in many nations[1-115-113]. With greenhouse farming, there are several things to consider, including crop kind, climate, and location. In Brazil, places with high temperatures and fertile soils are best for greenhouse farming. Further, Brazil is one of the world's top producers of greenhouses[115-113]. In Brazil, there are currently around 6,000 greenhouses in use, producing an estimated 1.5 million metric tons of tomatoes and other crops annually as per the 2022 article by AgriFarming [115-113-131].

The commercial greenhouse industry in Brazil is seeing significant trends in technical breakthroughs like artificial intelligence, smart irrigation systems, pH monitors, and temperature control software [10, 11, 132, 115-118, 160-178, 187, 199, 200. 204. 207, 213]. They address issues like disease prevention and insect management, indoor farmers may use technology like artificial intelligence, automated irrigation systems, pH detectors, and climate change [115-118]. For instance, researchers at Embrapa and their collaborators created a methodology in September 2021 for the remote and automated satellite monitoring of the growth of areas in Brazil using integrated agricultural production systems [115-118].

Iran is characterized by its diverse climate, with hot summers, cold winters, and significant climatic variability [119-122]. However, J. Huete Greenhouses has developed a greenhouse system that adapts to these extreme climatic conditions. Out of the 190,000 hectares of farmlands in Tehran province, 5,000 hectares are under greenhouse cultivation [119-122]. J. Huete Greenhouses' project in Iran goes beyond just the greenhouses[119-122]. This comprehensive and cutting-edge approach positions the project as a benchmark in Iran's agricultural industry [119-122]. J. Huete Greenhouses has made its mark in Iran with a high-tech greenhouse project that has overcome climatic challenges and redefined agricultural production in the country [119-122]. Through the implementation of advanced technologies and sustainable practices, they have created an optimal environment for vegetable cultivation in extreme climatic conditions [119-122]. This project is a testament to J. Huete Greenhouses' commitment to innovation and excellence in protected agriculture in Iran [119-122-131].

According to the report titled, Colombia Indoor Farming Market Overview, 2027, the indoor farming market in Colombia is expected to grow rapidly over the forecast period [132-140]. Indoor farming is a method of growing fresh vegetables and other plants that uses a variety of facilities such as vertical farming, hydroponics, and indoor greenhouses [132-140]. Vertical farms are plants that are piled on levels and are frequently integrated into other structures such as shipping containers, skyscrapers, or warehouses [132-140]. In Colombia, the main hydroponic systems used are the drip irrigation and NFT system for growing tomato, beans, pepper, cucumber, strawberry and lettuce etc [132-140]. In Andean countries like Peru, Bolivia, Colombia and Ecuador, aeroponics is being developing to obtain basic potato tuber seed, free of virus [123, 132-137-140]. Brazil and Mexico are the more representative hydroponic countries in Latin

America [1-132-140]. Finally, it is necessary to obtain a hydroponic certification, as well as the organic products, to support the hydroponic growers in Colombia [132-140]. Colombia is a global powerhouse when it comes to agriculture with all regions of Colombia producing approximately 73 million tons of agricultural products annually [132-140]. Simplified hydroponics underwent development in Colombia during the 1980s as an alternative way of growing crops [132-140]. This method of farming was designed to function as a solution to increasing food demands from a growing global population and future lack of land, as these factors will only heighten food insecurity over time [132-140]. Simplified hydroponics not only uses up to 90% less water and 75% less land than traditional farming but produces a higher quality crop [132-140]. This method does not require herbicides and increases the crop's quality by producing food with a higher nutrient value than food grown using traditional farming [132-140].

6. Greenhouse Farming : Economics

Agricultural productivity demands a revolutionary change in attitude to adopt advanced technologies to sustain, and greenhouse technology promises a solution [141-152, 354]. High yield of quality vegetables, flowers and fruits can be grown intensively out of season at year-round excellence that cannot be achieved in the open field [141-152]. Climate, though sometimes hostile, will not interrupt and limit production. Space and water are efficiently utilized in its fullest resulting to the cutting cost of electricity, labour, time and water [141-152, 153-159]. Greenhouse farming requires a heavy expenditure on infrastructure, equipment, labor, and raw material [1-141-152]. To become successful, a greenhouse farmer needs to have knowledge in three areas – technical, economic, and marketing – to be successful [141-152]. They need to complete a training program before they start their own business. The choice of crops plays a pivotal role in determining the profitability of greenhouse farming [141-152]. According to market analysis, high-value crops such as tomatoes, peppers, and herbs are not only popular choices for greenhouse cultivation due to market demand but also enable farmers to command premium prices [141-152, 153-159]. A mutual understanding of consumer preferences and market trends is essential for maximizing profits [141-152]. Moreover, the versatility of greenhouse farming enables the cultivation of specialty or out-of-season crops, providing a competitive advantage in catering to markets that traditional farming methods might struggle to access[141-152].

Acknowledging challenges is crucial for a realistic understanding of greenhouse farming economics [141-152, 354]. Pest management, diseases, and the energy costs associated with maintaining optimal conditions are common concerns [141-152]. However, the implementation of integrated pest management strategies, adoption of sustainable practices, and exploration of renewable energy sources can effectively mitigate these challenges, enhancing the overall economic outlook of greenhouse farming[141-152]. Forming business relationships with vegetable buyers is a significant milestone in the success of a vertical farming operation [141-152, 153-159]. The keys to maintaining this relationship are to produce safe, high quality vegetables that are reliably supplied [141-152]. If quantity or quality were to dwindle or degrade, it could put the business relationship at risk[141-152]. In order to maintain the quality of vegetables, growing guidelines and legislation are set out to ensure that quality parameters are met[141-152]. In order to consistently supply safe, high quality vegetables, it is important to implement Standard Operating Procedures (SOPs) to maintain the desired quality[141-152, 153-159].

The economic benefits of greenhouse farming extend to environmental sustainability, aligning with the growing consumer preference for eco-friendly and locally sourced products [141-152]. Consumers are increasingly willing to pay a premium for produce that is not only fresh but also grown using sustainable practices[141-152, 153-159]. Greenhouse farming, with its reduced water usage, minimal pesticide reliance, and lower carbon footprint, aligns with these eco-conscious preferences [141-152]. This alignment translates into market advantages, allowing greenhouse farmers to tap into consumer segments that prioritize both product quality and environmental responsibility [141-152, 153-159]. The economics of greenhouse farming demand a nuanced perspective that encompasses initial investments, operational efficiency, crop selection, and market dynamics [141-152, 153-159]. Greenhouse farming emerges not just as a means of cultivation but as a holistic approach to sustainable and economically viable agriculture [141-152]. As technology continues to advance, and awareness of sustainable farming practices grows, the economic benefits of greenhouse farming are poised to shape a resilient and prosperous agricultural landscape, defining the future of food production[141-152].

The India Greenhouse Horticulture Market is estimated to witness a rise in revenue from US$ 190.84 Millions in 2021 to US$ 271.25 Million by 2030 [1-141-152]. The market is registering a CAGR of 4.19% during the forecast period 2022-2030. In terms of volume, the market is registering a CAGR of 3.37% during the forecast period 2022-2030 [141-152]. Agriculture is the backbone of India's economic activity and experience during the last 50 years has demonstrated the strong correlation between agricultural growth and economic prosperity [1-141-152]. By adopting greenhouses, there is no doubt that in the near future, there will be more food and jobs [141-152]. Sustained production of quality fruits, flowers and vegetables will eventually cause lesser importation as local farmers can produce these all season of the year [141-152]. Farmer's income will be improved and sustained ultimately making economy stable [141-152, 354].

The vegetable greenhouse industry must overcome unique challenges to expand. Increasing operating expenses, economic losses due to pest incidence, labor shortages, wasted crops, and a lack of publicly available industry data are explored, as they relate to the productivity and sustainability of the greenhouse industry [141-152]. Another major problem is the cost of production of greenhouse farming vegetables is very high resulting in the higher price of the end product. There is also fear that loss of the jobs by using modern computerized greenhouse farming. 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) [331]. The rapid growth in this sector is linked to the expanding utilization of hydroponic systems in the indoor cultivation of vegetables [331]. The literature survey with many examples confirmed that hydroponics often provides a better Return On Investment [ROI] than conventional farming methods because of its greater productivity and quicker harvest times [146-147].

7. Greenhouse Farming: Internet of Things (IOT) Technologies

Greenhouse farming is considered as one of the precision and sustainable forms of smart agriculture [1-141-152]. There is an urgent need to explore climate-resilient alternative agriculture production systems that focus on resilience, resource efficiency, and disease management [1- 141-152]. Hydroponics, a soilless cultivation system, gaining interest as it reduces the dependency on agricultural land, and pesticides, and can be implemented in areas with poor soil quality, thus mitigating the negative effects of extreme weather events [1-152]. The greenhouse gases can support off-season crops inside the indoor environment, monitoring, controlling, and managing crop parameters at greenhouse farms more precisely and securely is necessary, even in harsh climate regions [1-152]. Traditional agriculture is characterized by unnecessary human interaction resulting in higher labor costs and susceptibility to severe weather events due to limited integration of data-driven decision support systems [160-178]. Internet of Things (IOT) technologies offers a reprieve through AI and machine learning-based energy- and water-saving measures, automated farm operations, and mechanization to resolve crop monitoring challenges [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346].

The evolving Internet of Things (IOT) technologies, including smart sensors, devices, network topologies, big data analytics, and intelligent decision-making, are thought to be the solution for automating greenhouse farming parameters like internal atmosphere control, irrigation control, crop growth monitoring, and so on [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. The term "Internet of Things (IOT)" is a system of interconnected computing devices, sensors, objects, microcontrollers, and cloud servers that can transmit data across a network and control other devices remotely without human intervention [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. Therefore, smart greenhouses can aid farmers in raising the yield of their crops[160-178]. The sensors capture the data inside and outside the greenhouse and automatically transmit them to a central cloud server for storing and archiving [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].These data can be accessed by end-users devices and benefit from the generated knowledge of their crops, suitable harvesting time, and energy consumption [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Additionally, cloud edge points can be used for storing the data for more rapid processing [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. The implementation of intelligent agriculture, Artificial Intelligence (AI), big data, robotics, and IoT in agriculture accelerated the transition from Agriculture 3.0 to Agriculture 4.0 [160-178, 346]. Smart farming (represented in Agriculture 4.0) provides a path to sustainability by applying information and communication technology (ICT) with technologies like cloud computing [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. IoT, AI, and robotics technologies in the cyber-physical cycle of farm management [160-178, 346].

In one of the study reported by Sangeetha and Periyathambi (2024) [346] 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[346]. This program uses multiple data sources to make informed conclusions about the plant's age[346]. Environmental sensors, such as those that measure temperature, humidity, and light intensity, provide real-time information on growing conditions[346]. Furthermore, nutrient sensors monitor the composition of the hydroponic solution, providing information about the plant's nutritional requirements[346]. This abundance of data is processed by the algorithm, which then applies programmed growth patterns appropriate to the farmed plant species[346]. In hydroponic farming practices, this dynamic and adaptable technique guarantees that plants receive personalized nourishment throughout their lifecycle, optimizing their health and productivity [346]. While supplying nutrients, the system executes the Growth Stage Identification algorithm to identify the age of the plant and provide the correct quantity of nutrients accordingly [346].

The experimental results of Sangeetha and Periyathambi (2024) [346] showed that the Growth Stage Identification algorithm achieves a 97.5% accuracy rate for the first 5 weeks with 1,715 ppm of nutrition consumption which identify the vegetative state[346]. A total of 97.5% accuracy rate for the 6–9th week with 2,380 ppm of nutrition consumption, which identify the flowering stage, and 99.4% accuracy rate for the last 10–15th week 2,730 ppm of nutrition consumption, which determine the fruiting location of the plant [346]. In the future, integrating machine learning for area computation of the complete plant bush and real time monitoring seems like a really promising improvement[346]. Utilizing sophisticated algorithms and real-time video feeds, the system provides current data on plant development and well-being, enabling informed choices and accurate system operation [346]. Therefore, this study by Sangeetha and Periyathambi (2024) [346] demonstrated the advantages of merging robotics, IoT, and data analysis for optimal plant cultivation and agricultural practice optimization [346].

Precision farming is a sustainable solution that optimizes performance by providing each plant or animal exactly what it demands to survive and reduce waste and inputs[160-178]. Also, agriculture 4.0 is essential for optimizing greenhouse agriculture resources, especially energy and water [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. This survey presented the Internet of Things (IOT) technologies applications for smart greenhouse farming, including monitoring, controlling, tracking, and predicting applications [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Furthermore, various Internet of Things (IOT) technologies communication protocols, sensors, devices, and technologies are introduced [160-178]. There are multiple emerging technologies that are predicted to significantly impact the future of precision agriculture[160-178]. The technologies that would have the most notable impact include cloud computing, edge computing, fog computing, embedded software, embedded systems, cyber-physical systems (CPS),Wireless Sensor Networks (WSN), Big Data Gateway, Machine to Machine (M2M), Human to Machine (H2M), LoRa Protocol (LoRaWAN), ZigBee/Z-Wave Radio Frequency Identification (RFID), Gateway General Packet Radio Service (GPRS), Application Programming Interface (API), Advanced Encryption Standard (AES), and Digital Twins [[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346].

The focus on Internet of Things (IOT) technologies is grounded on the immense contribution of technology to modern civilizations after computers and the internet [160-178, 346]. The immense contribution of IOT in agriculture and commercial greenhouses could be linked to the integration of intelligent machines, actuators, sensors, unmanned aerial systems, radio frequency identification (RFID) devices, big data analytics, artificial intelligence, and satellites, and this has facilitated its widespread application in various agricultural and non-agricultural applications, including intelligent farming and frost prevention in greenhouses, intelligent control of greenhouse structures, fire hazard prevention, transition to agriculture 4.0, precise-control of nutrients in soilless greenhouse cultivation, smart cities, emission monitoring, distributed/decentralized energy storage, solar-powered sensors, smart feeding, shading and lighting control, and security [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. The widespread adoption of Internet of Things (IOT) technologies in smart greenhouses and precision agriculture has been partly augmented by the development of highly efficient communication protocols such as MQTT Protocol (Message Queuing Telemetry Transport), which have gradually phased out HTTP (Hypertext Transfer Protocol) [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. MQTT is capable of running on lower bandwidth, which translates to lower overhead protocols [160-178]. Cloud computing has been proven useful in smart greenhouses and precision agriculture [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].The storage of sensor data in the cloud and the integration with smart technologies for the remote monitoring of plant water levels, nutritional content, soil pH, humidity, and temperature, has translated to significant cost savings and improvements in yields [160-178].

Sensor development should focus on novel and creative sensitive materials, methods, technologies, and approaches with minimal cost and energy consumption [160-178]. Aside from that, the deployment of sensors must be accelerated. There is a need to expedite the deployment of sensors[160-178]. By widely introducing IOT sensors, it would be beneficial to establish a virtualized sensor system that allows farmers to remotely manage and monitor their greenhouse farms based on IOT technology[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].

Implementing advanced agro-technology and automation can enhance productivity and decrease labor demands in the agricultural sector[[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. The implementation of IOT-based systems, sensors, and data analytics are being researched to monitor and control environmental parameters, detect crop health issues, and optimize resource usage. Implementing automated processes, such as robotic seeding, harvesting, and maintenance, has the potential to address labor limitations [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. The implementation of advanced agro-technology and automation has been shown to impact productivity and labor requirements in agriculture positively. Implementing IOT-based systems, sensors, and data analytics can be utilized to monitor and control environmental parameters, detect crop health issues, and optimize resource usage[160-178]. Implementing automated processes, such as robotic seeding, harvesting, and maintenance, can potentially address labor limitations [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].

Getting large-scale and small-scale farmers to accept smart farming techniques in the greenhouse is the most difficult task[160-178]. Furthermore, local farmers are apprehensive about using smart farming technologies based on IOT, citing cost, literacy, privacy, and security as important research gaps[160-178]. Managing privacy and implementing transparent policies are vital to gaining farmers' trust. Devices with average computational power must provide farmers with cost-effective options[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346].

IOT in greenhouse farming has significantly increased cyber security incidents, including attacks, threats, and vulnerabilities [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. While intrusion detection systems (IDS) have been created to address these security issues by examining network traffic and identifying compromised devices, none offer tailored solutions for smart farming[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Consequently, there is a need for further research into the development of machine learning-based IDS and specialized access control methods specifically designed for agricultural environments[160-178]. IOT technologies that use the medium of internet connection can send data to a cloud server or receive instructions to operate [160-178]. Most IOT technologies use an open internet connection medium to perform these processes [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346].When an IOT device uses an open internet connection, it will expose to dangers such as information theft or system hacking[160-178]. Therefore, developing a secure indoor hydroponic monitoring device with multi-factor authentication (MFA) method is proposed [160-178].

Now-a-days, the hydroponic farming system with the Internet of Things (IOT) technology is increasingly becoming a trend for researchers to produce a more capable farming device or remote monitoring system[160-178]. However, this intelligent system is not controlled securely and will be dangerous when system hacking occurs[160-178]. Also, the technical challenges existing in IOT-based greenhouse agriculture are analyzed[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. In addition, there are countries already using IOT in greenhouse farming [160-178]. Lastly, future research suggestions in greenhouse farming based on IOT have been introduced [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Therefore, implementing IOT and associated technologies in greenhouse systems has the potential to user in a new era of economic growth in agriculture, primarily due to its ability to provide precise measurements at any location and time, all while being cost-effective[160-178]. Therefore, enhancing crop production, monitoring conditions of growth, such as humidity, temperature, and nutritional composition, and early detection of plant diseases through these technologies can provide a path to sustainability in agriculture[160-178]. More research on greenhouse farming data and environmental parameters is required to use AI to model diseases for efficient plant growth. It is recommended that data analytics techniques must be developed to process massive amounts of greenhouse farming data at a faster rate [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].

The general architecture is required for all plants and crops, quality of service (QOS), implementation of explainable artificial intelligence (XAI) for crop growth monitoring, and pest control [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. XAI is critical for understanding and analyzing the reasons behind specific decisions. XAI enables farmers to move away from traditional farming methods and better understand the factors influencing their outcomes[160-178]. Machine learning (ML) algorithms also need much computer power and storage. As a result, lightweight AI and ML algorithms are required to build using novel automated strategies [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Precision agriculture, a newer concept known as smart agriculture, uses cyber-physical techniques to combine information and communication technology (ICT) in all phases of the farm management cycle [160-178]. Sensors and data analysis tools can be used throughout the culture for real-time plant growth monitoring[160-178]. Robots using position-based visual feedback could improve smart hydroponic farming[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Smart hydroponics might help to find the best way to grow a plant by combining hardware setup with a software tool replicating the plant's growth trajectory [160-178].

Nutrient and light sensors are now used in artificial intelligence (AI)-assisted hydroponics [160-178]. One can gather information via sensors installed in the gadget to gather data—for example, shifts in temperature, humidity, and light intensity[[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. When the AI computer visualizes the developing plant's colors, it identifies the parameters to be executed, like providing nutrients to the soil based on the specific colors upon recognition[160-178]. The parameters of hydroponic solutions may be self-calibrated and managed using machine-learning algorithms based on sensor data [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. The AI system directly delivers the nutrient solution, water, and light to plant roots using sensors. However, as sensor technology develops, more data is being created, making it challenging to utilize them correctly [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. Innovative technologies, including smart home technology (domotics), IOT automated growing techniques, and AI-based systems, have increasingly entered the mainstream recently and, to add to that, have relevant applications in indoor hydroponic productions [10, 11, 132, 160-178, 187, 199, 200, 204. 207, 213, 346]. The amount and accessibility of knowledge on the web means that increasing numbers of individuals are starting to explore these growth strategies for various motives, and both hydroponic and indoor cultures are growing in popularity with farmers [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].

Glenn Dbritto *et al.* have researched land and water conservation using an artificial intelligence system in the hydroponic cultivation of Tomato F1 hybrid Suhyana seed [160-178]. The system provides a controlled environment where a combination of water, nutrient solution, and light is autonomously supplied to the plant roots[160-178]. This approach aims to optimize plant growth while minimizing water usage and promoting sustainable land use practices [160-178].

A Deep neural network (DNN) was implemented in a study by Mehra et al., 2018 [164] to regulate the hydroponic system's efficacy parameters (environmental conditions) [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. Sensors linked to both an Arduino and a Raspberry Pi 4 have been integrated into a prototype indoor IOT-based hydroponic control system for the nutrient film technique. This will automatically adjust and manage the nutrient and pH levels in the study system [10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. A recent study conducted by Sun Park involved the development and implementation of an integrated system that utilizes IOT-Edge-AI-Cloud to track environmental data in strawberry hydroponics to identify optimal harvest times[160-178]. The monitoring system is suggested to gather, organize, and visualize data related to the circumstances in which strawberries are grown[160-178]. Additionally, a deep learning algorithm was utilized to classify the maturity level of strawberries in images[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213]. An integrated interface was employed to visualize the monitoring and analysis results, offering fundamental data for strawberry cultivation [160-178]. Authors demand that even if the area used for strawberry farming grows, the suggested system, which is based on a virtualized container and the IOT-Edge-AI-Cloud idea, may be readily scaled and flexible[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213, 346]. The hydroponic strawberry atmosphere was monitored for 4 months to verify the effectiveness of the monitoring system[160-178, 346]. Furthermore, the verification of the harvesting was decided by utilizing strawberry images obtained from Smart Berry Farm[10, 11, 132, 160-178, 187, 199, 200. 204. 207, 213].

8. Greenhouse Farming: Hydroponic

Hydroponics is an advanced system in agriculture that has been widely applied in urban farming for soil-less food production [1-179-289, 344-345]. Hydroponics is a soilless Agri-production system widely suitable for the cultivation of greenhouse crops[179-289, 344-345]. Hydroponic is defined as the science of growing or the production of plants in nutrient-rich solutions or moist inert material, instead of soil [1-179-289, 344-345]. Hydroponics means growing plants without soil, with the sources of nutrient elements as either a nutrient solution or nutrient-enriched water; an inert mechanical root support (sand or gravel) may or may not be used [1-179-289]. Hydroponics as “the science of growing plants without the use of soil, but by the use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, or sawdust, to which is added a nutrient solution containing all the essential elements needed by the plant for its normal growth and development [179-289]. Hydroponics, as a convenient means for studying plants in the laboratory and for growing commercial crops, was a term first coined by William F. Gericke in 1929, yet it is a documented technique dating back to the late 17th century [179-289]. Its advantages include the potential for accessibility to all plant tissues and the easy manipulation of the nutrient profile of the growth medium when compared to soil [179-289]. Urban agriculture refers to food production systems inside city boundaries or densely populated areas. In the context of climate change and global industrialization, urban agriculture has drawn increasing interest to achieve global food security [179-289]. COVID-19 pandemic has further driven food insecurity concerns as regional transport of foods has been impeded by pandemic-induced controls, but this has also highlighted one of the biggest advantages of urban agriculture: the ability to produce food locally[123, 179-289].

The modern hydroponic system was developed in the middle of the 20th century as a solution to boost food production in locations with limited resources and space [1-179-289]. It is believed that the Hanging Gardens were created utilizing the first known application of hydroponic cultivation. The concept of soilless agriculture owes a great deal to Gericke's research, which also laid the framework for modern Hydroponics[1-179-289]. Hydroponics is now widely utilized in commercial and domestic settings to cultivate various products, from leafy greens to tuber crops to tomatoes and herbs. Its promise to boost food production and sustainability, decrease water consumption, and raise crop yields has recently increased in popularity[1-179-289].

Hydroponics is the practice of growing plants in a nutrient-rich water solution instead of soil [1-179-289]. Peat moss, charcoal, gravel, rock wool, perlite, coco peat, and coconut coir are only some of the inert media used in hydroponic systems to support plant roots [1-179-289]. The system may be engineered to give the plants the optimal quantity of water, nutrients, and oxygen for optimal development[1-179-289]. Since the hydroponics system utilizes only water and nutrient solution without the involvement of soil, any failure or problem in the nutrient distribution, water pump, or nozzle clogging will lead to rapid death of the growing plants[1-179-289]. Special attention is required to ensure real-time monitoring of the growth and development of the plant[1-179-289].

9. Hydroponic: Essential Nutrient Elements

Currently 17 elements are considered essential for most plants, these are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, copper, zinc, manganese, molybdenum, boron, chlorine and nickel [179-289]. With the exception of carbon (C) and oxygen (O), which are supplied from the atmosphere, the essential elements are obtained from the growth medium [179-289]. Other elements such as sodium, silicon, vanadium, selenium, cobalt, aluminum and iodine among others, are considered beneficial because some of them can stimulate the growth, or can compensate the toxic effects of other elements, or may replace essential nutrients in a less specific role [179-289]. The most basic nutrient solutions consider in its composition only nitrogen, phosphorus, potassium, calcium, magnesium and sulphur and they are supplemented with micronutrients[179-289-340].

10. Hydroponic: Choice for Sustainable Agriculture

Hydroponics is one of the rapidly growing fields in agriculture and could be the alternate choice for sustainable agriculture[1-179-289-340]. The world's population is growing faster than ever before, and this has led to the development of hydroponics, a potential method of growing vegetables without soil in cities[1-179-289]. Controlled conditions, nutrient substrate and solid support pave the way for the development of hydroponics systems across the world, even in agro-climatic zones[1-179-289]. Hydroponic, is an alternative agriculture production system that focuses on climate resilience, efficient resource utilization, and disease-free crop production [1-179-289-340]. In hydroponics, instead of soil, plants receive a nutrient-rich water solution directly, providing them with the essential elements they need for growth[1-179-289]. This method has several advantages, including better control over nutrient levels, more efficient use of water, and the ability to grow plants in areas with poor soil quality[1-179-289]. The most significant limitation of using soil as a growing medium is the difficulty in managing weeds and disease prevalence [1-179-289]. However, the economic implications of soilless agriculture as a replacement are significantly raised because it decreases soil disinfection and boosts water usage efficiency [1-179-289].

Hydroponics, a soilless system, has recently attracted researchers to overcome the limitations faced in traditional soil-based cultivation since it can be used for the production of crops irrespective of soil environment[1-179-289]. Hydroponic systems, other than providing disease-free mini tubers, can provide multifold yield of seed potato as compared to the conventional methods[1-179-289-340]. Additionally, smart agriculture may make it possible for farmers to use cutting-edge technologies like artificial intelligence (AI), nanoparticles (NPs), plant growth-promoting rhizobacteria (PGPR), and aeroponics [1-179-289-340]. Drought, unpredictable weather, contaminated water sources, and under nutrition crops compelled producers to look for alternatives to soil-based agriculture[1-179-289]. In response, soilless agriculture, a revolutionary crop cultivation method, has been adopted by growers for the past few decades to overcome the shortcomings faced by soil-based cultivation [1-179-289]. In comparison to soil-based cultivation, the soilless technique is considered safer since it contains fewer or no soil-borne pathogens and pests [1-179-289]. In the soilless system, cultivation occurs in a nutrient solution or a customized cultivation substrate, including minerals [1-179-289]. The cultivation depends on using proper equipment, and the crops that are produced may generate higher yields if the system is appropriately managed [1-179-289]. Similarly, mini tubers are produced in a controlled environment with the help of soilless substrates, beds, containers, and nutrient solutions (hydroponics) [1-179-289].

As a result of hydroponics technology, it is possible to produce food crops in harsh environments such as hilly areas too high to cultivate, mountain regions, deserts, concrete school playgrounds, and arctic settlements[1-179-289]. Beyond staple crops and vegetables, hydroponics may also produce specialty crops like salad leaves, spices, and ornamental plants in urban locations where land prices have replaced conventional farming [1-179-289]. Artificial lighting, agricultural plastics, and pest and disease-resistant cultivars will enhance crop yields and cut production unit costs[1-179-289]. Waste heat from industry and power plants is now used in hydroponic greenhouses as an emerging trend to enhance energy efficiency. Hydroponic systems are used commercially and in private homes to cultivate a wide variety of plant life, including vegetables, fruits, herbs, and flowers [1-179-289-340].

Hydroponic systems may be closed or open depending on the growth medium used and the mechanism of nutrient circulation[1-179-289-340]. Closed hydroponic systems do not need a growth medium. However, nutrient imbalances may occur in this system as time progresses if not maintained appropriately [1-179-289]. Thus, hydroponic nutrient solutions must be examined regularly, which makes them challenging to manage due to the varying mineral components. Specifically, in potato cultivation, plants absorb significant potassium (K) amount from the nutrient solution, resulting in a disproportion in the solution's potassium content [1-179-289]. In contrast, open systems continually recycle, monitor, and adjust nutrient concentrations[1-179-289].

Commercial firms have recently cantered their efforts on hydroponics, which has risen fivefold in the last decade and has a global market value of up to $8 billion US dollars [1-179-289]. According to estimates, the global hydroponics sector is predicted to reach $17.9 billion by 2026 [1-179-289]. Environmental parameters such as dissolved oxygen, nutrient concentration, pH, and temperature typically affect the growth of hydroponic culturing plants[1-179-289]. Hence, sensors are necessary to monitor real-time measurements. Electrical conductivity sensors may be used to monitor nutrient concentrations because an increase in ionized nutrient content increases electric current [1-179-289]. Numerous crops have been produced via the hydroponic system in developed countries to fulfill customer demands[1-179-289-340]. Researchers are concentrating their efforts on whole-plant potato physiology to optimize massive hydroponic systems used for commercial mini-tuber production, easing the gathering of physiological and anatomical samples for study [1-179-289].

11. Hydroponic System Substrates

Hydroponic systems are categorized into two types: solution and medium-culture hydroponics[1-179-289]. The latter is the dominant type and requires growth media (solid substrates) to support seed germination and crop growth[1-179-289]. Currently, hydroponic substrates are largely based on inert materials such as rockwool, expanded clay, perlite, coconut chips, glass wool, and phenolic foam [1-179-289]. However, each of these substrates has its own drawbacks[1-179-289]. For example, rockwool is prone to producing small dust particles that could cause human health issues upon inhalation. It is also non-biodegradable and hence not environmentally friendly. Perlite only retains water for a short time and needs to be watered frequently[1-179-289]. Phenolic foam is not readily biodegradable, resulting in plastic pollution upon disposal. Additionally, the foams may contain toxic constituents that can be released during their lifetime. In particular, the above mentioned substrates only serve as inert physical supports for plants and do not deliver nutrients/agrichemicals in a controllable manner to crops, leading to unnecessary pollution and waste in hydroponic systems[1-179-289].

12. Hydroponics: Keratin and cellulose

Keratin and cellulose [353] are two natural biopolymers which are plentiful in bio-wastes such as hair, poultry feathers, wood shavings, and vegetable trimmings [353]. In one of the study, these waste-derived biopolymers are converted into bioactive nutrient substrates that can support crop development in hydroponic culture systems[1-179-289]. Functional experiments using the model plant Arabidopsis and crops including Bok Choy (*Brassica rapa*) and Arugula (*Eruca vesicaria*) indicated that these substrates have the potential to be customized for enhanced seedling development in comparison to conventional substrates [353]. One of the study demonstrates the feasibility and potential of up-cycling and repurposing keratinous and cellulosic wastes to provide a sustainable solution for targeted nutrient delivery to crops [353]. Therefore, keratin and cellulose materials were converted into hydroponic substrates for use as a platform in sustainable agriculture[353]. In addition to being a physical carrier for supporting crop growth, the keratin-cellulose substrates also demonstrated potential as a smart platform to control the release of macronutrients through keratin degradation and also the release of cationic micronutrients through the formation of chemical bonds between cationic ions and active thiol groups of keratin during synthesis[353]. Plant growth experiments confirmed that the keratin-cellulose substrates can promote greater seedling development compared to conventional commercial hydroponic substrates[353].

13. Hydroponics: Influencing Factors

Plant growth primarily depends on the availability of 17 essential nutrients and can be broadly classified into macronutrients and micronutrients [1-179-289]. The importance of both for the nourishment and growth of plants cannot be overstated. 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[1-179-289]. Plants acquire carbon, hydrogen, and oxygen through natural means, specifically from the air and water they consume, with the remainder obtained from the soil[1-179-289]. The roots obtain nutrients from nutrient solutions or aggregate media in hydroponic systems[1-179-289]. 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[1-179-289].

The criticality of the nutrient solution composition, regular monitoring of the nutrient solution and plant nutrient status is a significant aspect to consider[1-179-289]. The major salt deficiencies that a hydroponic system may encounter include nitrogen, calcium, iron, magnesium, and boron deficiencies[1-179-289]. 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[1-179-289]. Insufficient leaching during the process of fertigation in hydroponics can lead to the accumulation of soluble salts in the medium due to water evaporation [1-179-289]. Nutrient antagonism and interaction is a crucial parameter that warrants serious consideration in the context of hydroponic systems[1-179-289]. Research suggests that plants tend to absorb nutrients proportionally to their presence in the nutrient solution[1-179-289]. 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[1-179-289]. The nutrient levels in the nutrient solution may not necessarily guarantee optimal plant growth and development[1-179-289]. Despite sufficient nutrient supply, plant nutrient deficiency may still occur. In instances of nitrogen deficiency, the color of leaves may change to a lighter shade of green or, in severe cases, a yellow hue[1-179-289]. Observations can be made from stunted development and discoloration, specifically a slight purple tint, on the stems and undersides of leaves[1-179-289]. Whereas if the feeding solution includes excessive nitrogen, roots become stunted, causing blossoming to be delayed[1-179-289]. Boron deficits are rare and often accompany calcium shortages, mainly in the case of plant's deficit with water[1-179-289]. Boron generally improves root uptake of potassium and phosphorus and keeps plant cell walls intact and functioning[1-179-289]. Hydroponic production requires a full hydroponic nutrient solution, which includes Mg as one of the key ingredients[1-179-289]. 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 [1-179-289]. It was found that the total extractable pigments of red fruits and their surface color remained unaffected by iron treatment[1-179-289]. 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[1-179-289].

pH indicates the solution's acidity or alkalinity. 0–14, with 7 neutrals[1-179-289]. Maintaining nutrition solution pH levels in the optimal range increases nutrient availability. Soilless culture nutrient solutions should have a pH between 5 and 7 (typically 5.5) as they are weakly neutralized and needs automated pH adjustment to keep the root environment between 6 and 6.5 [1-179-289]. Even though phosphorous (H_2PO_4 to HPO_4) buffers pH, pH between 1 to 10 mM, it is harmful to plants[1-179-289]. A circulating solution with around 0.05 mM has substantially less buffering power than the new replenishment mixture that replaces transpiration losses because plants actively absorb phosphorus[1-179-289].

The significance of light in photosynthesis cannot be overstated, as it is the primary source of energy for plants to synthesize organic compounds[1-179-289]. Through this process, plants convert light energy into chemical energy, which is then utilized to support their metabolic processes and promote growth[1-179-289]. Artificial lighting systems such as LED lights can be utilized in smart hydroponics to regulate light's intensity, spectrum, and duration meticulously[1-179-289-340]. 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[1-179-289]. The light requirements of plants vary depending on the species, with some requiring specific amounts of red and blue light[1-179-289-340]. 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 [1-179-289].

Temperature plays a significant role in plant growth and metabolic processes[1-179-289]. In smart hydroponics, the temperature can be precisely regulated to create an ideal plant environment [1-179-289]. Each plant species has an optimal temperature range for growth and development, including germination, root growth, and flowering [1-179-289]. Maintaining the appropriate temperature range can enhance enzymatic activity, nutrient uptake, and overall plant performance[1-179-289]. 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 [1-179-289-340].

The term humidity pertains to the quantity of water vapor in the atmosphere[1-179-289]. The careful management of humidity in smart hydroponics can lead to the creation of an optimal growing environment[1-179-289-340]. 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. Research has shown that high humidity levels can lead to the development of fungal diseases[1-179-289]. 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[1-179-289]. The manipulation of humidity levels by growers can facilitate an optimal environment for plants, fostering robust growth and mitigating the likelihood of pathogenic infections [1-179-289]. In smart hydroponics, the ability to control and optimize physical factors gives growers greater precision and flexibility in creating an ideal growing environment[1-179-289]. By fine-tuning light, temperature, and humidity, growers can mimic optimal conditions for specific plant species, growth stages, and environmental preferences[1-179-289]. Hydroponic systems are highly space-efficient and require less land[1-179-289]. Hydroponic Vertical growing techniques maximize production in limited areas. Suitable for urban farming, rooftops, or areas with limited agricultural space[1-179-289].

Hydroponics uses up to 90% less water than soil-based farming[1-179-289-379]. Recirculating systems minimize water wastage and evaporation[1-179-289]. Water is efficiently delivered directly to plant roots, reducing water usage[1-179-289]. Enhanced nutrient delivery promotes healthy plant growth[1-179-289-340]. Higher concentrations of desired compounds in herbs and medicinal plants with improved flavour, aroma, and nutritional value has been reported[1-179-289]. Plants grow faster in hydroponics due to optimized growing conditions[1-179-289-340]. Shorter crop cycles and faster harvest times. Quick turnaround and increased production capacity. Soil-free environment minimizes the risk of soil-borne diseases and pests. Easier monitoring and management of plant health. Reduced reliance on chemical treatments[1-179-289]. Hydroponic systems can be scaled up or down to suit different needs[1-179-289-340]. Versatile setups accommodate various plant species—adaptability to different growing environments and locations[1-179-289]. By harnessing these advantages, hydroponics could offer a highly efficient and sustainable method of cultivation, enabling growers to maximize yields, optimize plant quality, and minimize environmental impact [1-179-289-340].

14. Types of Hydroponics

Multiple types of hydroponic systems 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), Aeroponics, Aquaponics, Fogoponics, Kratky, and Drip irrigation system are the most popular hydroponics systems[1-179-289].

Wick system hydroponics: For indoor hydroponics, the wick method is the most straightforward. The system is passive, since it lacks a water pump, and it is regarded as a self-feeding system [1-179-289]. With the aid of a wick (usually nylon), the nutrient solution from the reservoir is transported into the growth media via capillary action [1-179-289]. Wick hydroponics was used by Kim et al [1-179-289] to examine how the number of wicks affected seed potato development and yield. The growing medium used in that study was a 1:2 perlite and peat moss mixture[1-179-289]. The prime factors for considering this hydroponics approach include operation without the involvement of pumps, electricity, or aerators with low maintenance [1-179-289]. Furthermore, because it does not rely on electricity for the transportation of nutrients, it can be used in places where electricity is a major concern [1-179-289]. The Wick system is appropriate for herbs, small plants and spices[1-179-289]. Even though the wick system is simple and affordable, nutrient recycling is impossible since water is transported to the plants by capillary action, either by open or closed circulation [1-179-289]. Limited oxygen access, slower growth rate, and easily prone to algal growth are the significant limitations to using this system in a wide range of commercial applications [1-179-289]. Moreover, the system is suitable only for small-scale crops with extensive periods that cannot be cultivated [1-179-289]. Similarly, many plants may consume the nutrient solution before replenishing it with the wicks. So, cultivating plants that require a high amount of water is tedious[1-179-289].

Drip system hydroponics: Drip system of hydroponics uses pipes, hoses, and a growing media to provide regular nutrition and watering [1-179-289]. This technology is like drip irrigation in soil gardening, gaining popularity and becoming the industry standard in hot and dry locations[1-179-289]. Long pipes and hoses irrigate crops, save water, and decrease evaporation [1-179-289]. Using an automated timer, a pump distributes water or fertilizer solution to individual plants or pots [179-289]. Presently, Big Data and IOT (Internet of Things) are employed in smart farming to modernize conventional agricultural farming to conserve nutrients and water[1-179-289]. Sensors could help in monitoring the parameters such as temperature and soil moisture [1-179-289].

The significant advantage of this method is less water consumption. A drip system can survive equipment failures and short-term power. Moisture levels can be easily controlled in a drip system [1-179-289]. Enough oxygen transfer favors crop cultivation in soil and hydroponic systems [1-179-289]. Recirculation of excess nutrients is also possible in this system. Crops like cucumbers grow very well in the drip irrigation system [1-179-289]. Similarly, superior tomatoes and peppers typically grow higher in the drip system when compared to other systems because they provide enough stability [1-179-289]. The major limitation of the drip system includes being easily prone to algal growth and clogging. Hence regular cleaning is mandatory[1-179-289].

Ebb and flow (or flood and drain) hydroponics system: It is considered a more popular system in which plants are kept in large grow beds, usually filled with growing medium[1-179-289]. A pump generally coupled to a timer is used to accomplish this. The timer regulates the flow of nutrient solutions in the environment [1-179-289]. If the timer puts the pump on, it allows the nutrient solution in the growth tray, and if it shuts off, it pumps the nutrient solution back into the reservoir [1-179-289]. In this approach, one must rinse roots often for brief intervals[1-179-289]. So, it is unnecessary to endure extended exposure to the water, and they may remain wet, ensuring they can breathe. Nevertheless, continual observation is necessary to monitor water flow to the system[1-179-289].

The ebb and flow system is affordable, enhances nutrient recirculation, and requires low maintenance. It is the preferred choice for growing celery and melons [1-179-289]. The primary limitations include the formation of root rot and crop loss due to technical failure[1-179-289]. In addition, it is easily prone to algal growth[1-179-289]. In order to overcome this, the system can be improved, and the filtration unit can be incorporated. Another method is Dutch Bucket method is also used [1-179-289].

Deep water cultivation (DWC) hydroponics system: DWC is a modified hydroponic system with an air stone, reservoir, air pump, tubing, and floating platform [1-179-289]. This system includes a tank (generally called a grow tank) containing the nutrient solution and a pump to supply oxygen to the roots [1-179-289]. In the presence of an air pump, more plants can be cultivated in a single grow tank. Plant roots usually float in nutritional solutions for water, oxygen, and nutrients [1-179-289]. Oxygen, pH, and fertilizer levels must be monitored to optimize salinity[1-179-289].

The system is reliable and cheap, and an air pump uninterruptedly supplies oxygen to the crop root zone [1-179-289]. A simple experimental setup in plastic boxes, glass basins, ice boxes, and fish ponds is enough for crop cultivation [1-179-289]. Deep water cultivation is best suited for producing cherry tomatoes, cucumber, Chinese cabbage, lettuce, spinach, and radish [1-179-289]. However, crop cultivation using this method has not been commercialized extensively because of a few limitations, such as contact area between air and water and oxygen transfer efficiency [1-179-289]. Moreover, a few parameters, such as concentration of the nutrients and oxygen, salinity, and pH, must be critically monitored to evade algal and mold growth in the reservoir [1-179-289].

Nutrient film technique (NFT) hydroponics system*:* NFT technique requires only a thin layer of solution at the bottom of a deep tank (a "film" in actuality) [1-179-289]. Consequently, the lower half of the roots will receive food and water, while the upper half will be allowed to breathe [1-179-289]. This technique is used when plants respond by producing roots that reach the film and then extend horizontally when it is initially produced [1-179-289]. This system exposes the root surface to the air during nutrient solution circulation [1-179-289]. The pump is generally in mode to monitor the nutrient solution constantly. In the NFT, the roots are constantly submerged in a thin flowing nutrient solution[1-179-289]. One of the simplest types of hydroponic systems is the wick system in which the nutrient solution is delivered to the roots through wicks via capillary action [1-179-289]. Indeed, wicks distribute nutrient solutions from the reservoir to the growing media[1-179-289]. In a drip hydroponic system, the nutrient solution is applied directly to the growing media through drippers, and plant roots absorb water and nutrients from the media [1-179-289].

The NFT hydroponic system enhances the recirculation of excess solution of nutrients and aids in the proper oxygen supply [1-179-289]. Also, it is economical since it can be organized in multilevel, matrix farming, and vertical orientation[1-179-289]. In addition, it minimizes land usage, labor and fertilizers compared to other systems [1-179-289].Water consumption is also very minimal, and it is climate resistant[1-179-289]. It is most suitable for smaller and fast-growing plants such as lettuce, and is the most preferred technique for the cultivation of tomatoes[1-179-289]. Blueberries, strawberries, and melons can be cultivated in NFT since it provides an ideal environment [1-179-289]. Herbal plants like chives prone to drought stress can be cultivated better in NFT. Despite the fact that NFT is one of the most widely used hydroponics techniques, a lot of studies are concerned that exposing tuber roots to an excessive amount of salt from the nutrition may harm their periderm tissue[1-179-289]. Thus, aeroponics has been promoted and applied in an effort to boost productivity[1-179-289].

15. Hydroponics: Role of Liquid Media

Hydroponics utilizes liquid media as the source of micro- and macronutrients that plants required for growth rather than the soil used in traditional systems [1-179-289-379]. There are a number of different systems and techniques used that fall into the category of "hydroponics" [1-179-289]. Hydroponic techniques have been divided into two categories: solution culture and media culture, and their differences are outlined as follows [1-179-289].

In solution culture, the roots of plants are placed directly into liquid. Solution culture can be further subdivided into circulating and non-circulating systems [1-179-289]. In circulating systems, nutrient solution is pumped from a reservoir into a tank, which then flows back into the reservoir[1-179-289]. The nutrient film technique (NFT) utilizes a tank on a slope which allows a shallow flow of water over the roots of the plant [1-179-289]. Contrastingly, in the deep flow technique (DFT), the tray is filled with solution and the roots are completely submerged [1-179-289]. Non-circulating systems are not pumped from a reservoir, and the nutrient solution simply sits within the culture tank and is then replaced when the nutrient concentration is inadequate or the pH or electrical conductivity (EC) are unsuitable[1-179-289]. Examples of non-circulating systems include the root dipping technique (RDT), floating technique (FT) and capillary action technique[1-179-289]. The root dipping technique uses plants suspended over nutrient solution while only the bottom portion of the roots are within the nutrient solution, while the floating technique sees the roots fully submerged, analogous to NFT and DFT [1-179-289]. When the capillary action technique is used, nutrient solution is provided either via placing the pot into a very shallow container, where the solution then makes its way through the media by capillary action, or is transported from a reservoir to the media via wicks [1-179-289]. Finally, the ebb and flow technique is similar to DFT, but the nutrient solution is periodically drained from the culture tray and then re-added [1-179-289].

16. Advantages of Hydroponics

- Crops can be grown where no suitable soil exists or where the soil is contaminated with disease.
- Labor for tilling, cultivating, fumigating, watering, and other traditional practices is largely eliminated.
- Maximum yields are possible, making the system economically feasible in high-density and expensive land areas.
- Conservation of water and nutrients is a feature of all systems. This can lead to a reduction in pollution of land and streams because valuable chemicals need not be lost.
- Soil-borne plant diseases are more readily eradicated in closed systems, which can be totally flooded with an eradicant.
- More complete control of the environment is generally a feature of the system (i.e., root environment, timely nutrient feeding, or irrigation), and in greenhouse-type operations, the light, temperature, humidity, and composition of the air can be manipulated.
- Water carrying high soluble salts may be used if done with extreme care. If the soluble salt concentrations in the water supply are over 500 ppm, an open system of hydroponics may be used. Further if care is given to frequent leaching of the growing medium to reduce the salt accumulations.
- 8.The amateur horticulturist can adapt a hydroponic system to home and patio-type gardens, even in high-rise buildings. A hydroponic system can be clean, lightweight, and mechanized.
- Hydroponics increases water and fertilizer productivity due to better control of environment and water and nutrient management by recirculating the nutrient solution. Two main hydroponic systems are based on recirculating the nutrient solution, that is, open- and closed-loop hydroponic systems.

17. Open- and Closed-loop Hydroponic Systems

Two main hydroponic systems are based on recirculating the nutrient solution, that is, open- and closed-loop hydroponic systems. In open hydroponic systems, the nutrient solution is drained after passing through the crop root zone, and the nutrient solution is not re-circulated back to the root zone after usage[1-179-289]. Nevertheless, a proper hydroponic system that can reduce water and nutrient application and negative environmental impacts is essential [1-179-289]. A closed-loop hydroponic system is an effective nutrient solution management approach in which leachate is reused and reduces the negative aspects such as the disposal of nutrient solution to the environment [1-179-289]. The open hydroponic system can be run as a drip, NFT, or DWC system. The nutrient solution application in a closed-loop system can be carried out in the form of drip, NFT, DWC, or ebb and flow system [1-179-289]. On the other hand, open hydroponics are easy to manage compared to closed-loop hydroponics, as the used nutrient solution is drained[1-179-289]. A new nutrient solution is prepared and supplied. However, the discharge of nutrient solution, especially containing nitrate nitrogen (NO_3 −−N) and phosphorous, contaminates water resources, which may cause eutrophication in the surface water bodies as well as some diseases such as blue baby syndrome because of high NO_3 −−N concentration in drinking water [1-179-289]. Moreover, open hydroponics indicates low water and nutrients productivity and economic returns due to the high cost of reduction with increased hydroponics inputs[1-179-289]. However, an open hydroponic system prevents salt accumulation in the root zone and growing media[1-179-289]. Although an open hydroponic system has some advantages, the major disadvantages of using the open system are waste of water and fertilizer along with the environmental pollution resulting from used nutrient solution discharge[1-179-289]. Studying the possibility of reusing nutrient-rich hydroponic waste to cultivate plants in hydroponics can introduce an environmentally friendly cultivation system [1-179-289]. Next to nitrogen, phosphorus and potassium are essential nutrients for plant growth and productivity, and their limitation affects crop yield and quality[1-179-289]. Therefore, phosphorus and potassium need to be investigated to control the nutrient solution along with nitrogen to maximize the hydroponic performance 1-179-289].

Accordingly, the closed-loop hydroponic system was able to enhance water and fertilizer savings without a significant crop yield reduction compared to the open hydroponic system[1-179-289]. Furthermore, the closed-loop system reduced fertilizers consumption (2.53 kg) during the entire crop cycle by 96% compared to the open system (4.95 kg) [1-179-289]. The closed-loop system produced 9.5% lower biomass, compared to the open system. However, the open system consumed two-fold water (41 L) to produce 1 kg of fresh tomatoes than the closed-loop system with 22 L of water consumption. Furthermore, fertilizers consumption was around 59%–75% lower in the closed-loop system[1-179-289].

The advantages of closed-loop hydroponic systems over open systems include reduced water use, nutrient usage, and environmental pollution [1-179-289]. However, the recycling of nutrient solution in closed-loop hydroponic systems can cause excess ions accumulation, such as sodium and chloride, in the substrates and the root zone, resulting in higher salinity [1-179-289]. High consumption of nutrients by crops from highly concentrated nutrient solutions in a closed-loop system may cause negative effects such as nutrient toxicity and reduction in yield and crop quality[1-179-289]. The closed-loop system is more economically efficient than open hydroponics in terms of water and fertilizer savings, up to 90% and 85% in closed-loop versus 85% and 68% in open systems[1-179-289].

Nutrient imbalance often occurs in closed-loop hydroponic systems [1-179-289]. Nutrient concentration can rise in the nutrient solution over time due to water loss by evapo-transpiration, which increases the electrical conductivity (EC) of both the nutrient solution and the growing media[1-179-289]. Therefore, the regular monitoring of ions concentrations or electrical conductivity in the nutrient solution in a closed-loop system is extremely important [1-179-289]. The ion imbalance commonly occurs in a long term crop growth cycle, which leads to a crop yield reduction due to deficiency or toxicity of nutrients [1-179-289]. Therefore, the recycled nutrient solution should be refreshed or changed periodically. Moreover, high electrical conductivity can cause extreme osmotic conditions and plants stomatal conductance reduction [1-179-289].

18. Hydroponics: pH and Electrical conductivity (EC)

Optimal nutrient solution management can lead to a high water and nutrient efficient system[1-179-289]. A better management of nutrient solution in hydroponic systems requires optimum pH, EC, or ions concentration [1-179-289-340]. The pH of a nutrient solution is one of the most important factors affecting nutrient availability, uptake, and solubility[1-179-289-340]. The optimum pH range for plants is between **5.5 and 6.5** in which the plants have readily available nutrients [1-179-289-340]. 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[1-179-289-340]. This also inhibits the absorption of micronutrients such as iron, copper, zinc, and manganese [1-179-289-340]. On the other hand, low pH decreases the absorption of macronutrients, including nitrogen, phosphorus, potassium, calcium, and magnesium [1-179-289]. 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 [1-179-289-340]. 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 [1-179-289]. Therefore, an optimum pH range should be maintained for proper plant growth [1-179-289-340]. Adopting the optimal nutrient solution management strategy to reduce water and nutrient consumption and the cost of production to increase crop growth is essential [1-179-289-340].

The Electrical conductivity(EC)-based strategy is the simplest method. However, it cannot follow the nutrient variations in the solution over time [1-179-289]. Hence, ion-based strategies have been studied to improve the quality of the nutrient solution, thus increasing the yield[1-179-289-340]. 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[1-179-289]. The nutrient-based strategy can reduce water and nutrient consumption by up to 60% more than the electrical conductivity (EC)-based technique[1-179-289].

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 [1-179-289-340]. Nutrient concentration alteration occurs over time due to plant nutrient uptake, crop growth, and evaporation[1-179-289-340]. 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 [1-179-289-340]. 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 [1-179-289-340]. However, plants uptake more water than mineral nutrients which may 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[1-179-289-340]. 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 [1-179-289-340]. 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 [1-179-289].

The conventional approach of monitoring the hydroponic nutrient solution using electrical conductivity measurement may not provide precise information about ion concentrations, potentially resulting in poor yields or excessive fertilizer usage [1-179-289-340]. To overcome these limitations, alternative management strategies have been developed to enable more accurate monitoring and efficient management. One such strategy is the **nitrogen-based** approach, where nitrogen concentration becomes the primary controlled element in the nutrient solution and leads to nutrient use efficiency (NUE) and water use efficiency (WUE) development by prolonging nutrient solution recirculation [1-179-289]. Furthermore, various methods have been devised to improve nutrient solution strategies[1-179-289]. These include using ion-selective electrodes to measure individual ions in the hydroponic nutrient solution, using sensors to monitor substrate moisture content, estimating water requirements, and implementing programmed nutrient addition methods [1-179-289]. An effective alternative to manage the nutrient solution in hydroponics is the measurement of macronutrients in the solution, which will help to understand useful information on the main ions in the nutrient solution [1-179-289-340].The essential nutrients such as $NO_3{}^{-}$−N, phosphorous, and potassium can be controlled using ion-selective electrodes, which efficiently control macronutrient supply [1-179-289]. This nutrient solution management technique may decrease water and nutrient consumption by prolonging the recirculation of the solution in closed-loop hydroponic systems [1-179-289].

19. Hydroponics: Hi-tech Urban Agriculture

Hydroponics holds immense promise for the future of agriculture. This innovative cultivation method offers a range of advantages that address the challenges faced by traditional farming practices[1-179-289, 345].With its ability to maximize resource efficiency, enable year-round crop production, and enhance yields. Hydroponics has the potential to revolutionize the way to grow food [1-179-289, 345]. By utilizing hydroponics, one can optimize water, nutrients, space, reducing waste and promoting sustainability[1-179-289]. The controlled environments of hydroponic systems allow for precise control over growing conditions, resulting in accelerated growth rates and higher crop yields [1-179-289]. This, in turn, contributes to food security, reduces dependence on imports, and increases the availability of fresh, locally-grown produce [1-179-289]. Moreover, hydroponics offers a pathway to environmental sustainability by reducing soil erosion, minimizing chemical inputs, and integrating with eco-friendly pest control methods[1-179-289]. It also opens up possibilities for urban agriculture, allowing for food production in limited spaces and bringing farming closer to urban centers [1-179-289]. As technology advances, integrating smart technologies, automation, and data analytics with hydroponics further enhances its potential [1-179-289]. This integration enables real-time monitoring, precise control, and automation of various processes, leading to greater efficiency, reduced labour requirements, and improve overall productivity[1-179-289].

The combination of hydroponics with smart technology in farming is novel and has promise as a method for effective and environmentally friendly crop production[1-179-289]. This technology eliminates the need for soil and reduces water usage by providing nutrients straight to the plant's roots[1-179-289]. The Internet of Things (IOT), sensors, and automation are all used in "smart farming," which allows for constant monitoring of soil conditions, nutrient levels, and plant vitality to facilitate fine-grained management and optimization[1-179-289]. The technology-driven strategy improves crop output, quickens growth rates, and keeps conditions ideal all year round regardless of weather or other environmental circumstances[1-179-289]. In addition, smart farming lessens the need for organic chemical inputs, promotes environmentally safe methods of pest management, and minimizes the amount of waste produced [1-179-289]. This ground-breaking strategy may significantly alter the agricultural sector by encouraging regionalized food production, enhancing food security, and adding to more resilient farming practices[1-179-289].

20. Disadvantages of Hydroponics

- The original construction cost per acre is very high and found expensive.
- Trained personnel must direct the growing operation. Knowledge of how plants grow and of the principles of nutrition is important.
- Introduced soil-borne diseases and nematodes may be spread quickly to all beds on the same nutrient tank of a closed system.
- Most available plant varieties adapted to controlled growing conditions will require research and development.

- The reaction of the plant to good or poor nutrition is unbelievably fast. The grower must observe the plants every day.

21. Aeroponics

Aeroponics is an indoor horticulture technique that suspends plant roots in a nutrient-rich mist, allowing maximum oxygenation and nutrient uptake[1-179-289]. This highly efficient farming method can result in faster plant growth and higher yields. The aeroponics technology is modern, relevant, and novel[1-179-289]. For reforestation of damaged land in humid climates, it can cultivate plants in huge quantities and tree seedlings linked to soil microorganisms, such as AM fungi [1-179-289]. Plants produced by aeroponics thrive in an air or thick fog environment. It involves spraying a nutrient-rich water solution onto the plant's hanging roots [1-179-289]. Lower stems occur in a closed or semi-closed environment using a high-pressure sprayer with a micro inject nozzle and an electronic timer [1-179-289]. It provides highly oxygenated nutrients to the plants [1-179-289]. However, it is essential to customize the misting cycles for plants since their roots are exposed to the air and will dry rapidly [1-179-289]. In addition, outside temperatures can easily affect the mist and make the system more challenging to operate in frigid conditions [1-179-289]. Several countries (including Japan, South Korea, New Zealand, China, Africa, Spain, and Latin America) have used aeroponics to grow mass amounts of potato mini-tubers [1-179-289]. Aeroponics is the future of soil-free agriculture. Growing tubers and rhizomes in an aeroponic system have the potential to be more profitable than growing them in a hydroponic or soil system [1-179-289]. Mini-tubers cultivated aeroponically are also harvested differently than those grown conventionally [1-179-289]. The fundamental distinction is in the sequential harvests of aeroponic plants[1-179-289]. There is only one final harvest in the conventional system, while depending on the cultivar, up to ten or more harvests are possible using aeroponics [1-179-289]. Aeroponics is the most popular hydroponics system in the world. Its application in tropical regions such as **Brazil** has attracted much attention since it improved the production of virus-free seed potatoes [1-179-289].

Aeroponics farming requires less water and no soil, so it is a prudent option for promoting mini tuber production in challenging potato cultivation environments, such as deserts, cold steep terrains, and coastal regions[1-179-289]. Aeroponics-based crop production in interplanetary colonies or space stations may soon be the subject of enthralling research projects [1-179-289]. However, the technology is still in its infancy and has room for development [1-179-289]. The system still requires a good environment and appropriate techniques, and hence more elaborative research is warranted [1-179-289].

22. Aquaponics

Aquaponics is the method of cultivating plants and animals **[**often fish**]** close to one another [290-297]. Bacteria convert noxious fish wastes like ammonia into plant-friendly nitrates and nitrites [290-297]. Aquaponics relies on fish waste as its primary food supply[290-297]. Hence understanding this concept is essential. In turn, the plants filter the water, making it safe for the fish [290-297]. This approach is beneficial since it helps to save money and biological resources by reducing waste [290-297]. The aquaponics system allows the use of fish waste as nutrients for plants, which in this process purify the water to be pumped back again to the fish tanks [290-297]. Aquaponics combines hydroponics and aquaculture [290-297]. Crops are grown in a hydroponic system and share the same water environment with fish growing [290-297]. In this process, water is carefully re-circulated in order to achieve the best balance. Hence plants can purify the fish waste coming from the fish tanks while being fertilized by the same waste [265, 290-297]. Aquaponics combine the fishes and plants in one ecosystem, wherein fishes grow in indoor ponds producing nutrient-rich waste that acts as a food for the plants grown in vertical farms [290-297]. The plants purify and filter the waste water that is recycled directly to the fish ponds [290-297]. There is need of using Re-circulatory Aquacultures System (RAS) in the Vertical Farming [265, 290-297]. The **pisciponics -** cultivating fishes, prawns and snails with plants (vegetables, fruits, herbs or flowers) in a symbiotic environment with RAS in vertical farming is coming up in Kerala, India [290-297]. This closed-cycle system has potential to become popular in coming days [290-297].

23. Use of Nanoparticles in Hydroponics

Nanoparticles (NPs) are used in agriculture to increase nutrient management and crop production [259, 265, 298-304, 348-352]. Nanoparticles were also used in the production of vaccine development against COVID-19 [298-304]. Nanoparticles have also shown antimicrobial properties[298-304]. Due to their large surface area and relevant reactivity, NPs offer the plant readily accessible nutrients by enhancing the soluble and available forms of nutrients [259, 265, 298-304, 348-352]. Precipitation and insolubilization processes are often related to bulk fertilizers[298-304].The use of nanoparticles as a delivery mechanism promises to be significantly more efficient than current approaches [259, 265, 298-304, 348-352]. **Nanoparticles** have been shown to alter critical responses in plants, such as germination, seedling vigour, root development, and photosynthesis [259, 265, 298-304, 348-352]. Additionally, several studies revealed that nanoparticles might provide plants with a better defense against oxidative stress since these particles can imitate antioxidant enzymes, viz., superoxide dismutase, catalase, and peroxidase [259, 265, 298-304, 348-352]. It has been shown that nanoparticles can be used to reduce the impacts of temperature, salt, and drought stress on plants by enhancing their tolerance to these stresses [259, 265, 298-304, 348-352]. Benefits arising from this technology are relevant not only for soil but also for soilless systems[259, 298-304, 348-352]. Nanoparticles were utilized in hydroponics systems to accelerate the development of various plants such as spinach and tomato [259, 265, 298-304, 348-352]. The introduction of nanoparticles produced promising plant growth and disease resistance outcomes[259, 298-304, 348-352]. In a study conducted by Bagherzadeh Homaee and Ehsanpour (2015)[352], the effects of silver nanoparticles (AgNPs) or silver nitrate ($AgNO_3$) on *in vitro* culture of potato plants were investigated [259, 298-304, 348-352]. It was observed that growth parameters, such as leaf area, root length, shoot dry weight, and root dry weight, increased in the plants treated with $AgNO_3$ and AgNPs[259, 298-304, 348-352]. Plants treated with $AgNO_3$ or AgNPs at two mg/L had significantly more chlorophyll than control plants [259, 298-304, 348-352]. All indicators exhibited substantial growth and pigment differences treated with nanoparticles except for shoot length[259, 298-304, 348-352]. Since nanotechnology is still in its infancy, close attention needs to be paid to the toxicity and trophic transmission of nanoparticles in our surroundings [259, 298-304, 348-352].

24. Hydroponic Vertical Farming

With rising urbanization a worldwide phenomena, it has been estimated that most of the world's population (>60%) by 2030 will shift to cities for urban dwelling [1-305-319]. Interestingly in the same period (by 2030), the human population is expected to reach 8.6 billion from the current 7.6 billion, and expected to rise further exponentially to 9.8 billion by 2050 and explode to 11.2 billion by 2100 [1-305-319]. Cultivable land has become a limiting factor and land prices are skyrocketing in recent years [305-319]. The transportation of food to cities from rural production sites will add to the problem, compounded further in perishable and semi-perishable food especially from horticultural crops having shorter shelf life [305-319]. One innovation that has potential to partly manage the above problem is by production of food items in cities itself in residential buildings, roof tops, and public spaces [305-319]. However, the present improved agriculture practices put immense pressure on finite resources with diminishing returns on land, water, and energy [305-319]. The innovative technology of vertical farming is expected to relieve this pressure to a large extent [305-319]. Vertical farming generally refers to the growing of crops mostly vegetables, ornamentals, and herbs on stacks of indoor shelves using artificial light and nutrient solutions, without much sunshine and soil [305-319]. Such vertical farms are not dependent on seasons/controlled environment and have ability to enhance production round the year with little risk of crop failure [305-319]. Further vertical farms give fresh quality produce without depending on favourable climate, healthy soil, high water consumption and saves on labour [305-319]. Vertical farming has potential to sustain ever increasing world population especially in the urban areas with nutritional supplement thus providing food security [305-319]. Vertical production of mushrooms, hydroponic green fodder, some vegetables and fruits and even poultry birds are either already in vogue or at advanced stage [305-319]. Vertical gardens in ornamental horticulture, a component of vertical farming are also known as green walls, living walls, bio walls or vertical garden [305-319]. It is a free-standing space or part of a building that is partially or completely covered with attractive vegetation luxuriantly growing in an organic or inorganic medium [305-319]. Hydroponics and vertical farming address the need of safe and healthy, pesticide/ acaricides/ insecticide free, natural antioxidant rich produce with low carbon and water foot print [305-319].

25. Hydroponic Vertical Farming Layers

Vertical farming is a popular trend in hydroponics that involves stacking multiple layers of plants in a vertical arrangement [305-319]. This farming method saves space, reduces water usage, and increases yields per square foot of growing area [305-319]. In response to increased demand for agricultural productivity, vertical farming is a new technology that aims to boost crop yield per unit of land[305-319]. Vertical farming is a technically challenging and pricey crop production method that uses protected horticulture systems like glasshouses and controlled environment facilities along with numerous layers of growth surfaces and/or inclined production surfaces [305-319]. As a result, vertical farming requires a scientific approach that considers various elements, including lighting, crop nutrition, growing systems, energy efficiency, construction, and site selection [305-319].

Compatible crops for vertical agriculture today include lettuce, broccoli, spinach, chard, chive, palak (beet leaf), mustard greens, amaranths, parsley, coriander, mint, kale, basil and other herbs (rosemary, fennel, thyme, oregano and others), strawberries, mushrooms, micro greens and sprouts, summer squash, peppers, eggplants, tomatoes, cucumbers, muskmelon, algae, crop nurseries, ornamental foliage and flower and medicinal plants [305-319]. Micro greens can be produced by vertical farming indoor, outdoor, on and off season, in home and on farm [305-319]. They are preferred by chefs and consumers to enhance the flavour, colour, and texture of a dish [305-319]. Micro greens of the genus *Brassica* mainly broccoli have become popular due to their ease of germination, relatively short production time (7 to 21 days), and offering of intense flavours, colours and medicinal values [305-319]. Commercial growers are currently producing micro greens in greenhouses in vertical system using soilless media in trays [305-319]. Micro greens are also produced hydroponically using capillary mats placed in troughs, similar to those used in a nutrient film technique system [308-310, 313, 317-319]. Mushrooms do not require lots of light to grow and are nutritious food that cycle up organic waste[308-310, 313, 317-319]. Mushroom producers have been using vertical farming much longer than the plant producers [305-319]. It is amenable to urban or indoor farming in vertical beds and is being practiced in several metros and peri-urban areas [308-310, 313, 317-319]. Mushroom production is an apt example of successful, economical and sustainable vertical farming [308-310, 313, 317-319].

Garden wall–a type of vertical farming (garden) is popular throughout the world including India [308-310, 313, 317-319]. Vertical gardens can be seen on public places mainly on airports, metro pillars/stations, river bridges, elevated roads, etc., in many metro cities in India [308-310, 313, 317-319]. Multicolour evergreen foliage plants are preferred, although flowers and even leafy vegetables find place in these wall gardens [308-310, 313, 317-319].However, their maintenance is costly and proving un-sustainable [308-310, 313, 317-319]. Orchids, which do better on tree trunk and its branches, can be grown vertically under controlled climatic conditions especially in temperate and sub-temperate climate [308-310, 313, 317-319]. Garden walls with seasonal leafy vegetables are the best option for indoor gardens [305-319]. Availability of all season plants, growing media, fertilizers and watering are issues that need to be addressed for their commercialization [308-310, 313, 317-319]. Strawberries are commercially grown in environment controlled structures in different gutter systems by keeping distance between two gutters approximately 100 cm. A gutter system enables correct amount of drainage water to irrigate [308-310, 313, 317-319].

26. Hydroponic Vertical Farming: Internet of Things (IOT) Technology

The Internet of Things (IOT) technology is used in vertical farming to monitor environmental conditions and collect data on individual plants [1-305-319]. IoT systems use this information to formulate accurate recommendations for the amounts of light, water, and nutrients that should be provided to each plant[1-305-319]. An IOT device prototype for smart vertical farming with LED lights, sensors, a wooden board, and a battery is presented as essential components [305-319]. The prototype is equipped with sensors such as a light-detection resistor (LDR), soil moisture sensor (SMS), and LM35 temperature sensor (TMS), which together gather data on plant development, then analyze and showed that data in a web application for optimal efficiency [305-319]. Recently, there have been reports of a smart phone app developed in Android Studio that allows users to regulate and track plant development in hydroponic vertical farming systems [305-319]. Using Internet of Things technology, sensors are used to monitor environmental and dietary factors including temperature, humidity, TDS, pH, and water level [1-305-319].

27. Hydroponic Vertical Farming: Sustainable Urban Agriculture

Vertical farms is one of the modern urban agriculture technology used for growing leafy vegetables, medicinal and ornamental plants. This type of agriculture is safe, efficient, durable, elegant, economical and ecologically sustainable [305-319]. There are many factors influencing the vertical farming, heating, ventilation, air conditioning (HVAC), uniformity of the environment, optimal delivery of carbon dioxide (CO_2), shelf spacing, design and smart LED lighting are important in hi-tech controlled vertical farms allowing optimum interaction of crops and surrounding climate [305-319]. Since seed germination, rooting, vegetative growth, flowering, fruiting, flavor and color development are directly related to photo period. Therefore, duration, intensity, spectrum, etc., are crucial to maximize yield and quality of produce [305-319]. LED, red and blue light alone and their combinations have direct influence on the crop growth [305-319]. The growing beds are suitably designed to utilize maximum space combining ease of irrigation/fertigation and other operations [305-319].

In vertical farming, the elevation difference between first row (*bottom one*) and top row (*upper one*) is considerable and this difference affects the water emission rate from dripper [305-319]. For quality production, irrigation water needs to be free from undesirable chemicals and pathogens, while fertigation can save as much as 60% fertilizers [305-319]. Essentially the drainage and recirculation of water/ nutrients solution needs to be monitored for its electrical conductivity (EC) and pH [305-319]. The type of growing media, providing needed nutrition to the relatively shallow depth/ limited volume in containers, is the most important component in vertical farming [305-319]. Field soils are generally unsatisfactory for the production of plants in containers[305-319]. On the basis of literature survey, mixing coco peat, vermiculite and perlite in the ratio of 3:1:1 on volume basis was observed to be one of the best growing media [305-319].

28. Hydroponic Vertical Farming: Electrical conductivity (EC) and pH

The success story of hydroponics depends on two important parameters such as electrical conductivity (EC) and pH [1-305-319-340]. The EC values of specific crop are from 1.5 to 2.5 ds/m for hydroponics depending on environment [305-319]. Higher EC increases osmotic pressure and hinders nutrient uptake while lower EC severely affects the plant growth and yield [305-319]. Another important fact is that reduction in water uptake is strongly correlated to EC [305-319]. The pH value determines the nutrient availability for the plants [305-319]. Therefore, it needs daily adjustment due to the lower buffering capacity of soilless systems [305-319]. Regulation of pH can also be carried out by using nitric, sulphuric or phosphoric acid, either individually or in combination by using pH meter [305-319]. Furthermore, oxygen is essential for cell growth and activity, the roots require oxygen to absorb water and nutrients [1-305-319]. Therefore, aeration, is an important factor that influences root and plant growth in hydroponic system [305-340]. Maintenance of proper balance of water and oxygen in plant roots is very important in vertical farming and requires standardization [1-305-319]. Prevention and management of bio-stress in vertical farming is as important as in any other farming system [305-319].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 [305-319].

29. Hydroponic Vertical farming in India

Vertical farming and rooftop gardens should be extensively explored due to the limited availability of land [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. Vertical farming involves growing crops in vertically stacked layers, enabling optimal utilization of space [3, 4, 15, 273, 4, 15, 27,305-319]. Establishing rooftop gardens on buildings has been identified as a potential method for expanding areas available for food production[38-44, 308-310, 313, 317-319]. Vertical farming is still infancy in India [3, 4, 15, 27, 308-310, 313, 317-319]. 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 [308-310, 313, 317-319]. However, the organised vertical farms for production of food crops are not available in India [3, 4, 15, 27, 38-44,308-310, 313, 317-319]. The production of button mushrooms and orchids on large scale in vertical system are success stories in India [3, 4, 15, 27, 308-310, 313, 317-319]. Lack of research on hi-technologies involved in vertical farming system is lacking particularly in public sector in India [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. Most of the components require support both in terms of human resource, infrastructure and financial stability [38-44,308-310, 313, 317-319]. Vertical farming being highly technical requires intensive research [3, 4, 15, 27, 308-310, 313, 317-319]. India is yet to undertake major initiative on much needed research projects of vertical farming or urban farming [38-44, 308-310, 313, 317-319]. Being a highly populated of 1.5 billion with continuous migration of people to cities/urban areas, India would no longer be a country of villages but of cities and metros [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. Hence due emphasis on urban farming/vertical farming is needed both by research as well as development organizations/ ministries [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. Vertical farming engages multiple disciplines of natural sciences (mainly horticulture), architecture, engineering and affects both people and the environment [308-310, 313, 317-319]. The two major problems have been financial and technological feasibility in its popularization and spread[3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. Since vertical farming or indoor farming requires contemporary building materials and renewable energy systems such as light shelves, light pipes and fibre optics, which deliver natural light deep into buildings to provide energy for photosynthesis, and skilled workers [38-44, 308-310, 313, 317-319]. Therefore, its rate of return does not seem profitable to investors [308-310, 313, 317-319]. Whereas on the other hand, conventional farming does not require either of it, but if one sees from the point of future then Z-farming (Zero-Acreage) and vertical farming can become the lucrative option for potential investors[3, 4, 15, 27, 38-44, 308-310, 313, 317-319].

The length of distance that food travels in cities from source of production will increase many folds in future, if cities continue to depend for food on rural farming (most of the food in cities is imported from far off places) [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. In this scenario, future cities would have to produce their own food[308-310, 313, 317-319]. However, conventional land farming would not be possible in cities and peri-urban areas with prohibitive land prices[3, 4, 15, 27, 38-44,308-310, 313, 317-319]. The vertical or roof top farming (also called zero-acreage farming) would be the only possible future approach and solution for providing food/nutrition to cities[3, 4, 15, 27, 38-44, 308-310, 313, 317-319].

The hydroponic vertical farming technology today in the Indian scenario is costly and consequently, its produce [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. Thus, it is difficult as of today to compete with the market price obtained from the modern geoponic agriculture [38-44, 308-310, 313, 317-319]. However, the produce of vertical farming do have sizeable market only in the Indian metros, mainly in the high end hotels and well-to-do (high income) population [3, 4, 15, 27, 38-44, 308-310, 313, 317-319]. The ground reality is that soilless vertical farms for greens (leafy vegetables, strawberries and herbs) are largely owned by hotel industry that also supply quality fresh food to other industrial houses and financially well off people [3, 4, 15, 27, 38-44,308-310, 313, 317-319]. On Research and Development (R&D) and human resource fronts, the two pillars of any successful venture, this technology is unfortunately still in infancy in India [38-44,308-310, 313, 317-319]. Its status either as 'organic' or 'inorganic' is also controversial [38-44,308-310, 313, 317-319]. Currently, hydroponic vertical farming is not amenable to major food crops [3, 4, 15, 27, 308-310, 313, 317-319]. Lack of expertise, research, education, training, economics, standards and regulations are some of the major obstacles coming in the way of commercial exploitation of vertical farming in Indian cities [38-44, 308-310, 313, 317-319]. Compared to Europe, USA, Canada, China and Singapore where hydroponic vertical farming has shown good progress, it is still restricted to a few individually driven projects/hobbies mainly in Bengaluru, Pune, Delhi, Mumbai, Hyderabad and few other cities in India [3, 4, 15, 27, 38-44, 308-310, 313, 314, 317-319]. In spite of numerous inherent benefits enumerated earlier, the technology needs institutional support to generate mass interest to stabilize in India [3, 4, 15, 27, 38-44,308-310, 313, 314, 317-319]. Vertical farming envisages production of food inside walls, ensuring that cities start the process of becoming self-sustaining and less reliant on the global and national systems that provide their food [3, 4, 15, 27, 38-44,308-310, 313, 314, 317-319]. Spoilage and food waste would be reduced and fresh food would be available using recycled water [38-44,308-310, 313, 314, 317-319]. These are only a few of the environmental and social benefits that hydroponic vertical farms seek to provide to city dwellers [3, 4, 15, 27, 308-310, 313, 317-319]. Vertical farming in addition, would eliminate agricultural runoff that harms biodiversity in our oceans, eliminate weather and climate change related crop failures and convert farmland back to nature in rural areas (restoring ecosystems) [3, 4, 15, 27, 38-44, 308-310, 313, 314, 317-319]. Despite these benefits, 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 maintaining them afterwards [3, 4, 15, 27, 38-44,308-310, 313,314, 317-319].

30. Hydroponic Vertical Farming Categories

Vertical farming can be classified into two main categories, one is multiple levels/rows of growing platforms/units, and second one is located on a vertical surface such as on rooftops [305-319]. The pre-fabricated units could be placed on the rooftop of a building [305-319]. The vertical farming sector suggests that lettuce, basil and micro-greens are the most commonly produced leafy green vegetables in the emerging vertical farming sector [305-319]. The LED light technology being developed is ideally suited to growing leafy greens [305-319]. Currently, there have been increasing in demand, especially basil and micro-greens production using vertical farming [305-319]. In vertical farming system, the nutrient solution is delivered to the top and drained under gravity to the bottom of the vertical hydroponic system [305-319]. Furthermore, vertical hydroponics appears to be a encouraging system for urban areas to increase land and crop productivity and support local food security targets [305-319]. Vertical farming systems generated a greater amount of crop per unit of cultivation space compared to the horizontal hydroponic system [1-305-319]. In addition, vertical farming systems may be a good agro-based system for horizontal hydroponic development [305-319]. Hydroponic growth of the plants are protected from pests and illnesses, lowering the demand for chemical pesticides [305-319].

31. Hydroponics: Emission of Greenhouse Gases

On the basis of literature survey it is confirmed that greenhouse gases are those gases in the atmosphere that have an influence on the earth's energy balance [320-336]. They cause the so-called greenhouse effect[35, 320-336]. It is found that climate change is one of the biggest issues facing countries around the world. The challenge for the agriculture and agri-food sector is to reduce greenhouse gases (GHG). This is the biggest challenge for agri-food sector and adapt to the impacts of climate change without affecting food security [35, 320-336]. The best known greenhouse gases, carbon dioxide (CO_2), methane and nitrous oxide, can be found naturally in low concentrations in the atmosphere [35, 320-336]. However, the proportion has increased significantly since the beginning of the last century due to various man-made sources [35, 320-336]. Greenhouse gases (GHGs) are gases in the earths atmosphere that absorb and trap heat from the sun [320-336]. However, it is a fact that without the presence of greenhouse gases (GHGs), the earth could not sustain its livable temperature [35, 320-336]. Hence with rapid industrialization of the global economy and the resulting release of great volumes of man-made greenhouse gases (GHGs), the planet has experienced abnormal levels of warming [35, 320-336]. As greenhouse gases (GHGs) accumulate, prompting a rise in temperatures, there has been a significant shift in the climate system and weather patterns [35, 320-336]. This shift has the potential to devastate economic and social structures and human health [35, 320-336]. Therefore, it is critical that corporate and public bodies seek to limit the amount of greenhouse gases (GHG)[35, 320-336].

The three main greenhouse gases (GHGs) emissions in agriculture are nitrous oxide(N_2O), methane and carbon dioxide (CO_2) [35, 320-336]. Carbon dioxide (CO_2) is the greenhouse gases (GHG) primarily responsible for climate change [35, 320-336]. Not due to its potency but because it is the most abundant greenhouse gases (GHG) in the atmosphere[320-336-340]. CO_2 is emitted from a number of different sources including, sites burning fossil fuels, damaged natural carbon sinks such as forests after wildfires and eroded soil beds[35, 320-336].

Nitrous oxide (N_2O) is considered as the most critical greenhouse gas (GHG) emitted by agricultural and horticultural food production [35, 320-336]. Hydroponic vegetable cultivation in greenhouse systems has a high potential for N_2O emissions due to the intense application of nitrogen-containing fertilizers[35, 320-336]. Nitrous oxide (N_2O) is another greenhouse gas (GHG) emitted from greenhouse farms[35, 320-336]. This gas, familiar to us as laughing gas, is produced in nature by microbes as they process nitrogen in soils[320-336]. Further, 40 percent of nitrous oxide (N_20) emissions globally come from human activities frequently related to the agricultural sector[320-336]. The impact of a single pound of nitrous oxide is 300 times the impact of carbon dioxide. Also, once released, the gas can last over 100 years in the atmosphere [35, 320-336].

Methane (CH_4) gas comes from livestock farms, natural gas systems and landfill sites[35, 320-336]. Although methane has a shorter lifespan in the atmosphere than CO_2, it is more efficient at trapping radiation [320-336]. Therefore, the comparative global warming potential is 25 times greater than CO_2 over a 100 year period [320-336]. To reduce methane emissions, industrial plants and waste management sites have introduced methane capture technologies [35, 320-336].

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. Additionally, it is crucial to ensure the provision of vital nutrients to maximize output and productivity [340-346]. The fundamental factors which affect a plant's growth include pH, temperature, CO_2, and EC of the water in the hydroponic system. Four primary sensors control the environment in hydroponics system [35, 346]. They are DHT11 (temperature and humidity), ultrasonic sensors (water flows), EC sensors (nutrient dissolvability), and pH sensors (acidity of nutrient solution). For these factors, Sangeetha T, Periyathambi (2024) [346] used an Arduino UNO to communicate and monitor whether or not the readings are in the given threshold range[35, 346].

Nature uses carbon to store energy[35, 320-336]. In the air, carbon exists mostly as carbon dioxide (CO_2). Carbon dioxide (CO_2) is a colorless, odourless gas that is found in small quantities in the air, and is essential for plant life, without CO_2 plants could not survive [320-336]. Carbon dioxide is absorbed by the plants during photosynthesis and the CO_2 is split into two basic elements, carbon and oxygen [320-336]. Small amounts of oxygen are used by the plant but most of the oxygen are released back into the atmosphere[320-336]. The carbon is combined with water (H_2O) in the presence of light to form a sugar molecule. The plants then convert the sugar into carbohydrates [320-336]. When the plant absorbs nutrients (primarily nitrogen from the roots) they are combined with the carbohydrates to form new plant tissue [320-336]. This process is called photosynthesis[320-336]. Through photosynthesis, green plants invest the sun's energy in this CO_2, building from it first sugars and then other energy-rich forms[320-336]. Plant materials are then eaten by other organisms-microbes, cows, and humans, among others-who, in effect, burn the material back to CO_2, using the solar energy it contains to live and grow[320-336]. Some of the energy-rich carbon materials can be stored for thousands or millions of years before being converted back to CO_2 [320-336]. For example, soils contain vast amounts of carbon held in organic matter (humus), and the carbon in fossil fuels such as coal, oil and natural gas, which is solar energy trapped by plants long back ago[320-336]. The other ecosystems can be likened to batteries; building carbon stocks is like charging the battery and losing carbon like discharging[320-336]. If the rate of carbon input exceeds the rate of loss, carbon accumulates [320-336]. This is called a carbon sink. If the rate of carbon added is less than the rate of the loss, carbon is depleted [320-336]. This is called a carbon source. Carbon can be removed through sequestration. This is a process whereby biological matter, such as soils and trees, absorb CO_2 as part of their natural carbon cycle[320-336].

If any of the required ingredients (light, CO_2, water and nutrients) are at a level below that which the plant can use for maximum efficiency, the plant will not perform at it's full potential [320-336]. In other words, if CO_2 injected into a system that is not receiving enough light or nutrients the results will be disappointing [8, 320-336]. Therefore, CO_2 injection should only be done by experienced gardeners with a good working knowledge of their gardening system [320-336]. Once a gardener is comfortable with the workings of their system and plant growth, CO_2 can be a great benefit [320-336]. However, there are a lot of variables involved with using CO_2 and beginners can really have their hands full, increasing the likelihood of a disaster (like total death of the entire crop) [320-336]. There are several conditions that must be met for the plants to be able to use the increased CO_2 levels properly [320-336]. The most important is lighting. Light levels must be very high (more than 20 watts per square foot) or there will be little or no increase in plant growth rates [320-336]. The plants will like slightly higher temperatures than normal (approx. 3 to 5 degrees higher) [320-336]. The plants will also metabolize water and nutrients faster. Therefore, reservoirs may need a little more attention [320-336].

Plants can absorb and process very large amounts of CO_2. There is usually about 300 to 600 ppm. (parts per million) of CO_2 in the atmosphere[320-336]. Most plants can use 1500 ppm in optimum growing conditions [320-336-347]. When using elevated levels of CO_2, the growth rate can be increased by as much as 100% to 200% [320-336]. Most studies reported increases in the 40% to 50% range[320-336]. When CO_2 levels approach 2000 ppm, most plants will die [320-336]. High levels of CO_2 are also toxic to humans, primarily due to oxygen deficiency [320-336]. Before injecting CO_2, the room should be vented to remove excess CO_2 that might be left over from the previous injection. This prevents the build up of CO_2 that could harm the plants [320-336-347].

There are several ways to get extra CO_2, the two most common are using bottled CO_2 and using CO_2 generators[320-336]. These are the automated ways to add CO_2 to the growing environment[320-336]. Getting precise control of the CO_2 levels in growing environment can be rather expensive, CO_2 monitors are the best method, these monitors keep a constant reading of the C levels and automatically adds gas when needed [320-336]. These monitors are fairly expensive so most people opt for a more inexpensive method (like timers) [320-336].

The greenhouse farming experts are of the opinion that there are several gases that need to keep in mind when producing hydroponic crops in controlled environments, including carbon dioxide (CO_2), oxygen (O_2) and water (H_2O) [320-347]. Carbon dioxide is the precursor to the carbohydrates that are fixed through photosynthesis [320-347]. When CO_2 concentrations in the growing environment decrease, the growth and productivity of hydroponic crops diminish[320-340]. The less carbon that is available from CO_2, the less there is that can be converted to carbohydrates, which ultimately are used for growth or stored [320-336]. 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 [320-336]. 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 [320-347]. However, CO_2 concentrations can decrease to concentrations below 400 ppm when the greenhouse is not being ventilated [320-336]. This occurs mostly in the winter when cooling is not required to maintain the desired air temperatures in the greenhouse [320-336]. When light levels are strong, CO_2 concentrations can decline quickly if plants are actively growing in the greenhouse, since uptake is increased [320-336].

The greenhouse farming experts are of the opinion that there are two methods of injecting CO_2 into a greenhouse: 1) burners or 2) liquid. Each of these methods has advantages and disadvantages. Burners can be simple to install and use[320-336]. However, it is extremely important to monitor their function to avoid undesirable gases for both plant growth (ethylene) and human safety (carbon monoxide) [320-336]. Liquid CO_2 can also be used, and it is expensive too [320-336]. As previously mentioned, CO_2 can be limited when greenhouses are venting less from the later fall, through winter, into early spring for many locations [320-336]. The use of CO_2 should only occur when vents are closed. Otherwise, the CO_2 introduced into the greenhouse can be lost [320-336]. Once the venting season has begun for cooling, then reduce or discontinue the use of supplemental CO_2, as the costs increase when it is more challenging to contain the CO_2 in the greenhouse [320-336].

The greenhouse farming experts are of the opinion that the concentration of CO_2 accessible to the plant should be based on the plant's requirements, because amounts of CO_2 concentration that are too high or too low reduce the plant's yield and make photosynthesis difficult [338-340]. The method of CO_2 enrichment is found to increase the productivity of plants gown in greenhouses [338-340]. By increasing the amount of CO_2 from 340 to 1000 ppm (parts per million), most plants perform successful photosynthesis [338-340]. 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. Hence, CO_2 enrichment is essential [338-340]. In the study of Hans Peter Kläring [338, 339, 340], it was shown that providing CO_2 for plant photosynthesis in the greenhouse increased the yield by 35% compared to greenhouses where this was not conducted[338, 339, 340], Also, 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 [338, 339, 340].

The greenhouse farming experts are of the opinion that to improve the growth and productivity of crops, CO_2 can be added inside the greenhouse [320-338]. When increasing CO_2 concentrations, it is common to not simply increase concentrations to the point of ambient (~400 ppm), but to increase the concentrations to 800 to 1,000 ppm [320-336, 338]. Therefore, CO_2 acts as a fertilizer in hydroponic system [320-336]. Hence observation should be made on hydroponic plants on a regular basis, and CO_2 levels should also be recorded [320-340]. The lower concentrations of CO_2 levels can slow the plant growth. Therefore, concentrations of $C0_2$ is increased to improve plant growth [320-336].

Measuring the levels of CO_2 in hydroponics is an important step in ensuring garden is functioning at its optimal levels [320-340]. To measure the levels of CO_2 in hydroponics, the more intermediate to advanced grower can use a CO_2 monitoring system[320-340]. These units measure the amount of CO_2 in ppm (parts per million) which is the unit of measurement for carbon dioxide [320-336]. CO_2 controllers and monitors can be purchased at local hydroponics or indoor gardening supply store [320-336]. They can also order them online from www. ehydroponics.com [320-336]. The average or recommended levels of CO_2 in hydroponics systems should be between 1,000 and 2,000 ppm [320-336]. There are CO_2 monitoring systems available which will automatically boost CO_2 levels if they fall below a certain ppm level [320-336]. 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 [320-336, 338].

The greenhouse farming experts are of the opinion that another important gas is oxygen. For traditional greenhouse crop production, there is little or no concern about oxygen concentrations during production[8, 320-340]. While the same is true for hydroponic production atmospheres, it is important for nutrient solutions in nutrient-film (NFT) and deep-flow technique (DFT) systems [320-340]. Adequate oxygen concentrations need to be maintained in these systems where roots are partially or completely submerged in nutrient solution[320-340]. A few different factors affect dissolved oxygen concentrations[320-340]. First, the production system that used affects O_2 concentrations [320-340]. NFT systems will contain higher concentrations of dissolved oxygen because the nutrient solution is aerated as it is passed through channels, drained into the nutrient reservoir and recirculated [320-336]. Alternatively, O_2 concentrations in nutrient solutions for DFT systems can diminish more quickly, since there is no agitation of the nutrient solution to incorporate O_2 [8, 320-336]. In addition to production systems, the temperature of the nutrient solution affects dissolved O_2 concentrations [320-336]. The solubility of O_2 in water decreases as water temperature increases [320-336]. This is especially important for DFT systems in the summer, as they have a larger volume of water or nutrient solution per plant [320-336]. This increases the capacity of the system to hold heat [320-340]. Another factor that can affect dissolved O_2 concentrations is the size of the bubble used for aeration [320-336]. The smaller the bubble that is introduced into nutrient solution, the higher the O_2 concentrations [320-336]. This is due to the fact that, with smaller bubbles, the amount of surface area relative to the volume of gas is high compared to larger bubbles, and more surface area increases the solubility in solution [320-336].

The final gas need to consider is water vapor. The amount of water vapor is measured as relative humidity or vapor pressure deficit [320-336-340]. Water vapor or humidity can impact the growth and development of plants as well as pathogens. When humidity is high, plants diminish their transpiration [320-336]. The greenhouse farming experts are of the opinion that one of the biggest problems associated with low transpiration is tip burn on lettuce. Since calcium is taken up passively when plants take up water, less water uptake also causes less calcium uptake [320-336]. This is why air movement, which reduces humidity around shoot tips, is used to reduce tip burn of lettuce[320-340]. In addition to water use and nutrient uptake, humid environments can favor the development of pathogens[320-336]. On the basis of literature survey, it is confirmed that powdery mildew and botrytis are two pathogens that can thrive in humid environments [320-340]. 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[320-336].

There are two primary greenhouse cultivation systems: conventional and hydroponic methods [8, 338]. Each system has distinct similarities and differences regarding energy consumption, crop production per unit area, and environmental impacts [338]. The use of renewable energy in these two methods of greenhouse cultivation can reduce the emissions by up to 9% in hydroponics and 2% in conventional cultivation [338]. Life cycle analysis (LCA) is a detailed approach to examining all the inputs, outputs, and total environmental effects in the production life cycle of a product and is very useful for different systems [338]. This method is very effective in solving problems such as the limitation of natural resources and the disadvantages of excessive use of energy resources [338]. There are two main methods for LCA, namely Attributional life cycle assessment (ALCA) and Consequential life cycle analysis (CLCA) [338].

The results of one of the study by **Farvardin et al.** (2024) [338] demonstrated that LCA in hydroponic cultivation after normalization and weighting determined that the most environmental emissions belong to a set of ecosystem damages [338]. Also, the results of LCA in conventional greenhouse cultivation showed that the main environmental effects of direct emission were caused by input consumption (air: carbon dioxide (CO_2) and nitrogen oxides (NOx); soil: mercury (Hg), copper (Cu) and lead (Pb) and indirect emissions from the production of chemical fertilizers, greenhouse structures and chemical pesticide [338]. Overall, the hydroponic cultivation system, with its precise environmental control, results in better quality, higher yields, and optimal use of water and fertilizer [338]. While the initial investment cost for hydroponic cultivation is higher in comparison to conventional methods, it significantly reduces energy losses [8, 338].

The research study by Farvardin et al. (2024) [338] concluded that in order to fully optimize hydroponic cultivation, experts and farmers in this field are advised to expand their practices based on geographical location, available resources, and initial capital investment [338]. While the initial capital investment for hydroponics may be higher, it can be mitigated by selecting an appropriate greenhouse location and utilizing renewable energy sources [338]. However, conventional greenhouse cultivation requires less investment, it is less energy efficient compared to hydroponic methods [338]. Therefore, Farvardin et al. (2024) [338] is of the opinion that adopting hydroponic cultivation in greenhouse settings ensures sustainable and efficient production, optimized energy consumption, and efficient resource utilization [338].

The findings of Farvardin et al. (2024) [338] also indicated that hydroponic systems, with advanced IOT technology and formulated growth mediums, create optimal conditions for plant growth [338]. Also, hydroponics offered 11 ± 1.7 times higher yields but required 82 ± 11 times more energy compared to those conventionally produced in some plant productions [338]. Moreover, specific energy consumption increased by 17% compared to conventional cultivation for some vegetables [338].

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. Hydroponics culture highly depends on human attention to supply the suitable parameters for the quality growth of plants[346].

32. Conclusion

Greenhouses are built with transparent materials in which the climatic controlled conditions are adopted to enhance plant growth, productivity and ensure all-year-round production. This controlled system which encourages the cultivation of crops in a hi-tech facilities with enclosed structures, away from extreme weather conditions, pests and diseases, and other unfavorable factors. On the basis of literature survey it is found that there are many reasons why greenhouse farming is adopted due to increasing world populations, there might be a shortage of water, food and agricultural land. One of the biggest challenges will be meeting the demand for food, as farmland is being lost due to climate change, water scarcity, soil pollution, and other factors. Among the main factors increasing urban population growth, migration from rural to urban locations, and reclassification. Hydroponics, offers some benefits and addresses serious problems with traditional agricultural methods. A major advantage of greenhouse production is its year-round productive capacity and smaller exposure to environmental risks, as it reduces the dependency on, and disruptions by, natural factors and cycles, such as temperature and light, water and rain, pests and diseases. Hydroponic technology has been able to meet the challenges related to greenhouse farming and ensuring agriculture sustainability. The hydroponic system provides better yield and crop productivity by saving water, energy, and space. Therefore, this modern sustainable agriculture holds promises for future food security particularly for urban region. Agriculture Experts believed that hydroponics also saves 90% less water consumption, than conventional farming methods. Hydroponics, with formulated nutrient solutions, may produce far greater quantities of greens than conventional soil gardening. Hydroponics also allows for greater crop output per unit area because of its vertical farming methodology, which makes the most efficient use of available space. Finally, hydroponics allows for continuous production throughout the year independent of external weather conditions, guaranteeing a steady supply of fresh vegetables.

The factors governing hydroponic farming are pH, electrical conductivity (EC), water, light, temperature, humidity, and carbon di-oxide levels. Furthermore, various Internet of Things (IOT) technologies communication protocols, sensors, devices, and technologies are introduced for the automatic controlling of the greenhouse farming. However, there are some disadvantages of hydroponic system is that initial investment is very high, energy cost is high, and price of the end product that is produce is also very high. Hydroponic system also needs basic maintenances, training, and high tech computer system which is not possible in the developing countries. In India, the hydroponic system of producing vegetable is still not yet developed. There are many reasons for this. In India, 99% of the agriculture is open land agriculture which is the backbone of the country. Therefore, it is very difficult to convinces farmers with this hi-tech system of agriculture. Second is public, and farmers are confused as organic/ or non-organic food production. In India many of the opinion that, hydroponically grown food is not as tasty as open land agriculture and found very expensive. Only rich people can afford to have this food in urban areas but not poor people can not afford. Therefore, corporate, and rich people in India are developing greenhouse farming, hydroponic and vertical farming in metros in India. It will take some more time for the public awareness and development of greenhouse farming technology in India. Hydroponic, vertical farming, aeroponics and aquaponics has been used as the modern urban farming for the production of leafy vegetables, and other plants. The three main greenhouse gases (GHGs) emissions in greenhouse agriculture are nitrous oxide, methane and carbon dioxide (CO_2). Co_2 controllers and monitors can be installed at hydroponics or indoor gardening for the maintenance of carbon dioxide levels in the greenhouse farming. This will help to monitor the carbon foot print of the hydroponic system. Another disadvantage of hydroponic urban agriculture is the high carbon foot print.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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