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ADVANCING SUSTAINABLE AGRICULTURE: INTEGRATING VERTICAL FARMING WITH HYDROPONIC SYSTEMS

Akanksha Sant*, Shilpa Kaushal, Subhrajit Ojha, Shubham Seth and Preeti Parihar

University Institute of Agricultural Sciences, Chandigarh University, Gharuan, Mohali - 140 413, Punjab, India.
*Corresponding author E-mail : akankshasant84@gmail.com; ORCID ID: 0000-0001-9510-7000
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ABSTRACT

The World's expanding need for fruits, vegetables and optimum crop production can be accomplished by integrating the revolutionary agricultural technologies of hydroponics and vertical farming as they offer effective ecological and sustainable farming solutions to countrymen. Therefore, the present review explores the ideas and issues related to lesser crop production of field and vegetable crop and aims to identify the various measures to address these issues. Monitoring and optimizing the correct amount of water and fertilizer consumption, such techniques reduce compliance with arable and conventional farming methods by growing crops in controlled environmental conditions. Various obstacles have been discussed in this review which includes energy consumption, costs, maintenance and knowledge required. This paper also discusses the integration of vertical farming with hydroponics explaining various types of hydroponics for specific plant types. Along with explaining the potential and sustainable prospects of vertical farming and hydroponics techniques, which would broaden the concept and visualization of techniques for present-day and future needs. By 2050, vertical farming will anticipate a cutting-edge method for completing the needs for feeding, satisfying the population and agriculture needs by producing disease-free, organic and affordable crops. A significant contribution to 21st century food sustainability is made possible by smart farming as plant growth is directly impacted by environmental management.

Key words : Hydroponics, Crop production, Sustainable agriculture, Vertical farming.

Introduction

Growing crops in layers stacked vertically or integrated into other structures like a high-rise tower or building is known as vertical farming using no soil and less water. Due to elevating issues and current trends, increasing farming and crop growth with minimal land utilization is important (Despommier, 1999; Billah *et al*., 2021). Complications like climate change, water scarcity, land degradation, land shortages, etc can be covered by lowering the environmental effect of conventional agriculture by utilizing vertical space and diminishing brilliantly using advanced technology of 'Vertical Farming' (Despommier *et al*., 1999). The corresponding rise in demand, a certain amount of resource depletion, and population growth in the past couple of years due to the steady growth of towns imposed limitations on food industries and related sectors, making it even more difficult to use technology like vertical farming (Foley *et al*., 2011; Sahoo *et al*., 2023). Combining agricultural design and building results and integration into a single tall structure of agro-industrial unit which turns out to be a method of vertical farming. Modern vertical farming concepts use controlled environment agriculture (CEA) technology and indoor farming methods, which allow for the artificial control of all environmental parameters, including temperature, humidity, and light. This includes biofortification, which involves breeding crops to have more nutritional content. By artificially stacking them vertically above one another, animals, fungi, and other living forms are farmed for food, fuel, fiber (Savvas and Gruda, 2018). Nowadays, many nations employ vertical farms. These farms currently produce a variety of crops and are mostly located inside cities (Raviv *et al*., 2019). Another technique used in the present-day is hydroponics used as the CEA (Controlled environment agriculture) technique. Hydroponics is a technique and a future trend to sustain agriculture by soilless growing crops in nutrient-rich water that enhances ideal plant development. Areas with scarcity of water can grow an ample amount of crops according to per square feet density. Such methods produce higher plant density than traditional farming. Additionally, since not all crops may be well suited to the circumstances of a controlled environment, a lack of crop diversity can be problematic. However, further development of CEA technologies like hydroponics and vertical farming can assist in fulfilling the growing need for food sustainably while lowering the environmental effect of agriculture, provided that cost, energy consumption and crop diversity are carefully considered. Growing crops in layers stacked vertically or integrated into other structures like a high rise tower or building is known as vertical farming using no soil and less water (Schwarz *et al*., 2008). Due to elevating issues and current trends, increasing farming and crop growth with minimal land utilization is important. Complications like climate change, water scarcity, land degradation, land shortages etc can be covered by lowering the environmental effect of conventional agriculture by utilizing vertical space and diminishing brilliantly using advanced technology of 'Vertical Farming'. The corresponding rise in demand, a certain amount of resource depletion, and population growth in the past couple of years due to the steady growth of towns imposed limitations on food industries and related sectors, making it even more difficult to use technology like vertical farming. Combining agricultural design and building results and integration into a single tall structure of an agro-industrial unit which turns out to be a method of vertical farming (Santosh and Gaikwad, 2022). Modern vertical farming concepts use controlled environment agriculture (CEA) technology and indoor farming methods, which allow for the artificial control of all environmental parameters, including temperature, humidity and light. This includes bio-fortification, which involves breeding crops to have more nutritional content. By artificially stacking them vertically above one another, animals, fungi, and other living forms are farmed for food, fuel and fiber (Love *et al*., 2015). Nowadays, many nations employ vertical farms. These farms currently produce a variety of crops and are mostly located inside cities (Sousa *et al.*, 2024). Another technique used in the present day is CEA (Controlled Environment Agriculture) technique known as hydroponics.

History and evolution of vertical farming and hydroponics

The earliest known technique for growing plants vertically is the hanging garden of Babylon. The American geologist Gilbert in 1915 employed the idea of tall, multi-story structures for indoor farming. Dickson Despommier, an Emeritus Professor of Microbiology at Columbia University, created the idea of vertical farming in 1999. Dr. Dickson Despommier phrased the term "vertical farming" in 1999 followed by the idea of tall buildings covered with layers of crops (Pivoto *et al*., 2018). Researchers have improved the concept of growing crops under controlled environmental conditions to use the fewest resources and obtain maximum yield. The idea has been more globally recognized after the first vertical farm in Singapore in 2012, growing leafy greens on revolving vertical shelves. Since then more and more ideas for vertical farms and hydroponics have come up with the latest technology trends. Vertical farms including hydroponics, aeroponics and aquaponics have been found in major cities (Pomoni *et al*., 2023). Following the medieval era in the 19th century, Gericke first phrased the word hydroponics in the 1930's. The development of hydroponics and vertical farming systems has been extensively developed by technological advancements, especially in areas of LED lighting, automation and sensors which effectively contribute to real-time crop monitoring and accurate control over growth conditions (Wolfert *et al*., 2017). To deal with agriculture field-related problems vertical farming systems have been proven to be a potential and promising way to address problems, including space constraints, water scarcity and climate change. Nutritional solutions and "hydroponics" were developed to help plants flourish without soil. Hydroponic methods were further refined in the ensuing decades, and advancements in materials science and lighting technology enabled more cost-effective and efficient systems (Frasetya *et al*., 2021).

Pre-requisites for vertical farming

The unethical use of limited resources such as soil, water, fossil fuels, etc has elevated the need for vertical farming. One of the biggest problems is the increased demand for food brought on by population growth and the rapidly declining amount of arable land. For present-day generations and future generations needs concerning metropolitan areas, vertical farming provides an alternative source of sustainable food production units. Limiting agriculture only to the source of soil and land would restrict it to a certain limit and it would not be able to grow globally and sustainably. The practice of growing crops indoors in a structure in a city or urban area, where floors are made to accommodate certain crops.

Vertical farming technology

The base of the vertical farming system is made up of hydroponic techniques like aeroponics, deep water culture (DWC) and nutrient film technique (NFT). A deliberate attempt has been made to utilize space efficiency and resource material with a variety of cutting-edge agricultural techniques. Such techniques necessitate supplying roots with vital nutrients through nutrient-rich water solutions.

Hydroponic systems

A method and farming system which doesn't utilize soil is 'hydroponic'. An aquatic solution made of a full nutrient-rich solution in which the roots of plants are been dipped. The roots have taken nutrients and such processes are utilized in sophisticated greenhouses globally. Compared to outdoor farming systems a lot of water resources, land, soil, etc are been saved with such critical farming systems. By least human interventions, crops grown would have no wastewater contamination biohazard contamination, fecal pollution, etc. Plant roots more readily absorb nutrient-rich solutions that completely substitute soil. Apart from nutrient-rich solutions and perlite, gravel have also been used which is used as a supporting medium for plant growth. This approach is proven to use fertilizer or nutrient growth solutions for growing plants rather than soil for cultivation. In return, this technique provides a lot of benefits as hydroponics provides a physical support and is followed by providing a mineral storage system as soon as soil is dissolved in water. There are 6 types of hydroponic systems i) Aeroponic system ii) Ebb and flow (Flood and drain) iii) Water culture iv) NFT (Nutrient film technique) v) Drip feed system vi) Aeroponic system.

Bio-stimulants as a source in hydroponics

A basic definition of bio-stimulant is an organic substance supporting plant nutrition, as defined by the European Bio-stimulant Industry Council (Pomoni *et al.*, 2023). Natural organic materials like plant extracts, microbial metabolites and amino acids. In previous or traditional hydroponic systems, chemical fertilizers or adulterated solutions may have downside consequences causing resource depletion and eutrophication in the environment. Creating sustainable substitutes is paramount to regenerating the traditional hydroponic system because bio-stimulants provide an environmentally sustainable method of crop management, nutrient uptake, stress tolerance, drought tolerance, etc (Fig. 2). In agriculture, cyanobacteria and microalgae have shown promising results as renewable bioactive resources for the creation of creating plant bio-stimulants. Although, seaweed extracts constitute an important microbial category as compared to microalgae. Microalgae come under the category of organisms that can survive in marine eater and freshwater known as photosynthetic phyto-planktonic organisms. For bio-stimulant qualities of microalgae biomass amino acids, phytohormones, phenolics, osmolytes and sulphated polysaccharides are responsible. All of these metabolites have been determined to enhance crop performance, impart resistance against abiotic stresses, induce plant defence response against pathogens and infections, and improve essential nutrient uptake, including nitrogen (N), phosphorus (P), potassium (K) and other minerals

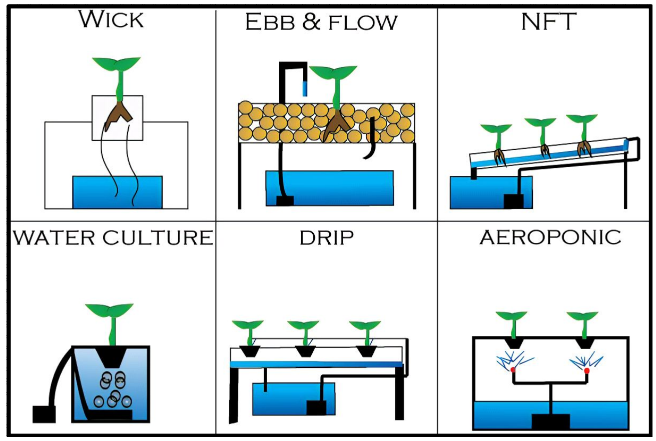

Fig. 1 : Schematic representation of types of hydroponic system.

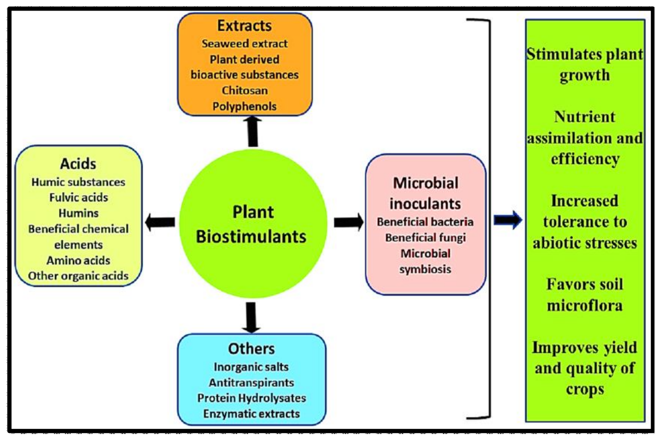

Fig. 2 : Schematic representation of Bio-stimulants as a source in hydroponics.

Potentials and pitfalls of hydroponics

Potentials of hydroponics

- Number of important elements maximizes the productivity of crops and plant growth resulting in higher yield which is a major advantage in hydroponics. Yields from hydroponics are much higher than those of conventional soil-based farming (Lal, 2001).

Table 1 : Types of hydroponic systems and specific plants.

S. no.	Hydroponic system	Characteristics	Specific plants	References
1)	**Deep water culture (DWC)**	In this process, the nutritional solution is constantly oxygenated by an air pumpin which there is a continuous suspension of the air pump. More nutrients and oxygen are been transported to those plants whose roots are deeply submerged in nutrient-rich medium. The Dutch bucket system is one of the famous bucket systems that allows easy access of nutrients to plant roots as buckets are filled with inert matter like coconut coir or perlite (Fig. 1).	Lettuce, Spinach and Cucumber	Ferrarezi and Testezlaf (2014), Thangaiah *et al.* (2022), Elkazzaz (2017)
2)	**Nutrient Film Technique (NFT)**	A thin layer of nutrient-richwater is been used to absorb nutrients by roots as a plant's roots are continuously covered in a thin layer of nutrient-rich water and the left of the solution is been recycled.	Kale, Mustard Greens and Strawberry	Sharma *et al.* (2019), Singh *et al.* (2019)
3)	**Ebb and Flow (Flood and Drain)**	This hydroponic is quite divergent in correlation with the above two hydroponic systems. In this system, a reservoir is been utilized after periodically immersing plants into a nutritional solution as draining plants back requires a reservoir.	Tomato and cucumbers	Somerville and Townsend (2014), Wongkiew *et al.* (2017)
4)	**Drip system**	Nutrient distribution in carried out by drip systems as drips are extensively used to directly used to distribute nutrients to plant zones. Solutions are directly dripped on growing material like coco coir , perlite etc.	Fruits, vegetables and herbs	Dubey and Nain (2020)
5)	**Krakty method**	A kind of static, suspended pot method is very effective. This system is price-efficient and significantly improved compared to other hydroponic systems. It requires only initial applications of water and nutrients.	Spinach, lettuce and herbs	Bhargava (2022)
6)	**Wick system**	As the name suggests, a wick or a cotton rope is used to transfer nutrient solutions from the reservoir to the upward zone while plants are placed in a nutrient-forming medium.	Low nutrient plant demands, small plants	Rajaseger *et al.* (2023)
7)	**Aeroponics**	Include mist or spray to the roots while plant roots are suspended in the air. (Fig. 1).	Herbs, leafy greens, strawberries	Santosh and Gaikwad (2023)

- Hydroponics techniques are extremely accessible and useful in urban areas with limited land as they would not hamper plant growth but enhance the amount of produce grown per square foot. The integration of vertical farming with hydroponics is another element boosting technology for producing higher yields. Hydroponics techniques most often produce higher yields than by traditional farming methods. Traditional soil farming requires larger space for better sunlight absorption rather hydroponics allows it to grow within minimum space and guarantee better yield and sunlight absorption. More compact farming systems are possible with hydroponics systems, particularly with vertical farming (Wijerathnayapa and Pathirana, 2022).
- Hydroponic system initially benefits from the effective use of resources, especially in terms of space and water and due to this farmers are more interested and work and invest in hydroponic technologies which results in better yield, crop production and economic values (Hussain *et al.*, 2014).
- Growing crops in a controlled environment is yet another important feature and advantage of hydroponics techniques. To increase output it's important to grow crops in controlled environmental conditions. Various problems have been associated

with the traditional farming method such as soil types, pests and weather conditions which could hamper yield and hurt growth. A steady and regulated environment can be provided for crops. A hydroponic system grows crops in controlled environmental conditions by providing constant humidity and temperature (Resh, 2022).

- It also provides an edge in integrated pest management and disease control compared to traditional farming.Avoiding harsh weather and seasonal variations allows plants to grow more consistently and reliably. This regularity results in several cropping cycles in a year, raising overall production even more (Abegunde *et al*., 2019).
- Avoiding harsh weather and seasonal variations allows plants to grow more consistently and reliably. This regularity results in several cropping cycles in a year, raising overall production even more (Jones, 2014; Shubham *et al*., 2024).

Pitfalls of hydroponics

Costs and maintenance : Annually ongoing maintenance includes filter replacements, pump, growing trays as well as building a controlled environment in greenhouses. Small-scale systems cost between Rs.480 to Rs. 720 per square foot as compared to commercial systems which cost quite high due to larger facilities required such as Ph monitoring, fertilization,and environment control of systems. Initial set up costsaccount for 6%-9% as guaranteed results and production have been guaranteed by such investments, Maintaining the environment, cost and technology for the long run can be a pitfall in hydroponic systems (Barbosa *et al*., 2015).

Monetization and knowledge requirement : In addition, an effective and advanced hydroponic farming system requires proper knowledge and skills to monetize automated controls and sensors to regulate environmental factors such as electrical conductivity (EC), temperature and pH (Ampim *et al.*, 2022). An understanding of the nutrient uptake process and plant physiology for the successful operation of hydroponic systems is primarily required as hydroponics uses precise nutrient solutionsfor serving plants with essential minerals, unlike traditional soil-based agriculture farming practices (Kumar *et al*., 2024). As per the requirement of knowledge, it's essential to ascertain signs of nutrient deficiencies or toxicities along with the management of macronutrients and micronutrients to resist plant diseases such as root rot, stunted growth, stunted growth, wilting of leaves, drooping down (Barbosa *et al*., 2015). Hydroponic farming requires advanced data-driven modifications to achieve optimum output which could prove as a hurdle for farmers going with traditional farming practices. Monetization and knowledge are required at a great extent which may not cope up with farmers' traditional cultivation knowledge. While automation helps manage these parameters, growers still need to understand the underlying principles to troubleshoot issues and optimize system performance. Continuous monitoring and data-driven adjustments are essential to successful hydroponic farming (Velazquez-Gonzalez *et al*., 2022). Thus, proficiency in both plant nutrition and system management is akey to achieving high productivity in hydroponics.

Limitation of crop variety : Some crops might be more suited for hydroponic cultivation than others. Although hydroponic systems can be used to cultivate a variety of leafy greens, herbs and some fruiting plants, the method might not be suitable for all crops. Certain hydroponic environments, such as potatoes or carrots, may present challenges for root crops with extensive root systems.

Energy consumption : As heating, ventilation and air conditioning require a lot of energy is been utilized to maintain ideal environmental conditions including humidity, ventilation, and temperature. According to recent reports around 59-61% of the system's overall energy is used in artificial illumination (Ikeda *et al*., 2002). Energy consumption has an important significance in the sustainability and viability of hydroponic farming systems when it comes to climate control, artificial lightning, lamp running and other required inputs. For indoor or low-light plant growth, artificial lightning is necessary which is one of the hydroponic most intensive features. To supply the required light spectrum and intensity, high-intensity discharge (HID) lamps, light-emitting diodes (LED's), and fluorescent lights are frequently utilized; however, these systems can use significant quantities of electricity, raising operating costs and hurting the environment.

Sustainability and future prospects

Challenges and problems faced challenges and problems faced by traditional farming systems can be assisted by modern-day hydroponic techniques (Neev Fund, 2023). Hydroponic has a great market potential that is projected to grow crops by 27% yearly and reach 20,000 metric tonnes by mid of 2025. This proves that hydroponics, which deals with soilless farming technologies and uses water to provide nutrients is expected to beneficially impact sustainable agriculture (Zhang *et al*., 2020).

Food security and urban agriculture : Hydroponic systems can enhance food security by minimizing crop

Comparison between hydroponics and conventional soil farming

Sector	Hydroponics	Conventional soil farming
Skills and knowledge	Intellectual knowledge and training	Frequently enough
Cost	Costs requirement is high in setting up	Relatively low
Climate	Year-round cultivation is possible	Only in fixed seasons
Water uptake	Primarily, 90% less	More is required, due to soil & evaporation
Soil	Irrespective of soil type	Majorly dependent on soil type
Insecticide usage	Less requirement, as production is in a controlled environment	Usage is more
Location	Can be set up anywhere	Requirement of a large tract of land
Space utility	Less space is sufficient as can be applied in vertical form too	Requires larger space
Sustainable future	More and better scope	Less sustainable due to soil and water
Crop yield	Better crop production	Less crop output

losses and providing urban people with pesticide-free, enriched nutrient-quality food. By lowering food distancing and resulting in 100% year-round production, hydroponic techniques provide a practical answer for modern agriculture by giving plausible ways to cultivate crops in limited space areas for instance rooftops, indoor facilities, and vertical farms (Romeo *et al*., 2018).

Efficiency of resources : There is a need to efficiently optimize resources as optimal utilization of nutrients decreases the use of fertilizers, pesticides as well as water need. Hydroponic systems are incredibly efficient as they consume less water. Concerning traditional farming or conventional farming practices, hydroponic systems use 85%-90% less water, which simply manages water efficiency and contributes to sustainable agriculture (Salis *et al*., 2020).

Climate adaptability : A more robust food supply can be achieved through hydroponic farming as this quality of climate adaptation will allow to grow more crops and adapt to various climatic conditions. Such techniques would help to adjust to shifting climatic circumstances. Hydroponic systems guarantee consistent crop yields by lowering obstacles like climate, and disruption of the food chain. Hydroponic systems provide regulated and according to crop type environment for optimum crop results (Taylor *et al*.,2012; Salma *et al*., 2024).

Development of technology : There will be a huge development in technology as advances in hydroponics will increase the cost of systems concerning conventional farming practices. There is continuous emerging development in sectors related to agricultural sciences, artificial lightning, variety developments, agriculture polymers, etc. Such techniques increase crop yields, encouraging industry expansion and best development technical uptake (Duangpakdee *et al*., 2024).

Collaboration of geothermal energy with hydroponic system : By combining renewable energy sources geothermal, wind and solar energy can be used to power hydroponic systems, cutting greenhouse gas emissions and reliance on fossil fuels. This integration lessens the negative effects of food production on the environment and advances sustainable farming methods (Ampim *et al.*, 2022; Sharma *et al*., 2023).

Assistance by government : Government agencies assist such sustainable technologies and offer hydroponics subsidies or assistance. As such assistance can encourage the broader adoption of hydroponics techniques to overcome high setup costs. The hydroponic system is an asset of Indian farming technology to make good food production in harsh conditions (Chin and Audah, 2017; Choorappulakkal *et al*., 2024).

Conclusion

Hydroponic farming systems can be used in a variety of climates or environments including populated urban areas by giving controlled environment conditions to crops to grow. Hydroponics techniques offer a plethora of potential as compared to traditional soil farming practices. Hydroponic techniques have been advantageous lately offering reduced water usage, resource management, efficient utilization of land, better productivity, excellent growth outputs, etc. Unquestionably certain challenges and pitfalls can be assessed such as high initial costs for setting up, management of nutrients, complexities due to technicality, and many more. Hydroponics can overcome problems such as stable crop yield, urbanization and frequent changes in climate along with reducing reliance on fossil fuels. Hydroponics will contribute to the future of agriculture and future research should be continued to bring such advanced technologies to manage nutrient supply and cost budgeting technologies. There are some challenges and major obstacles related to vertical farming and hydroponics as lack of experience and knowledge, high initial setup costand the need for controlled environmental conditions. However due to sustainability for food vertical farming has been proven to be an excellent source, so it's gaining attention to sustain food quality and continue the food chain. Additionally, it is anticipated that urban agriculture and vertical farming will maximize product quality to create new capacities in the horticultural and agricultural farms.

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References

Abegunde, V.O. *et al.* (2019). *Climate*, **7**, 132. doi: 10.3390/cli7110132. [DOI] [Google Scholar]

Ampim, P.A., Obeng E. and Olvera-Gonzalez E. (2022). Indoor vegetable production: An alternative approach to increasing cultivation. *Plants*, **11(21)**, 2843.

Avgoustaki, D.D. and Xydis G. (2020). How energy innovation in indoor vertical farming can improve food security, sustainability and food safety. *Advances in Food Security and Sustainability*. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7516583/pdf/main.pdf

Barbosa, G., Gadelha F., Kublik N., Proctor A., Reichelm L., Weissinger E., Wohlleb G. and Halden R. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown using Hydroponic vs. Conventional Agricultural Methods. *Int. J. Environ. Res. Publ. Hlth.*, **12**, 6879–6891. https://doi.org/10.3390/ijerph120606879

Billah, M., Aktar S., Brestic M., Zivcak M., Khaldun A.B.M., Uddin M.S., Bagum S.A., Yang X., Skalicky M., Mehari T.G., Maitra S. and Hossain A. (2021). Progressive genomic approaches to explore drought-and salt-induced oxidative stress responses in plants under changing climate. *Plants*, **10(9)**, 1910.

Chin, Y. and Audah L. (2017). Vertical farming monitoring system using the internet of things (IoT). In: *AIP ConferenceProceedings*, 1883. https://doi.org/10.1063/1.5002039

Choorappulakkal, J., Jaglan P., Shubham and Kaushal S. (2024). Optimizing Hydroponics Farming: A Comprehensive Review of AI and IoT Integration for enhanced Efficiency and Sustainability. *Arch. Curr. Res. Int.*, **24(11)**, 366-374.

Despommier, D. (1999). The Vertical Farm: Feeding the World in the 21st **1(1)**, 1-33.

Duangpakdee, K. and Sukpancharoen S. (2024). Vertical Smart Farm System for off Season Crop Production using Hydroponics and IoT-based Environmental Control. In: *2024 International Conference on Advanced Robotics and Mechatronics* (ICARM) 284-289.

Dubey, N. and Nain V. (2020). Hydroponic- The Future of Farming. *Int. J. Biotechnol. Environ. Agricult.* https://doi.org/10.22161/ijeab.54.2

Ferrarezi, R. and Testezlaf R. (2014). Performance of Wick Irrigation System using Self-Compensating Troughs with Substrates for Lettuce Production. *J. Plant Nutr.* https://doi.org/10.1080/01904167.2014.983127

Frasetya, B., Harisman K. and Ramdaniah N.A.H. (2021). The effect of hydroponics systems on the growth of lettuce. *IOP Conf. Ser.: Mat. Sci. Engg*., **1098 (4)**, 042115. https://doi.org/10.1088/1757-899X/1098/4/042115.

Hussain, A. (2014). *Int. J. Agricult. Sci*., **7**, 833 [Google Scholar]

Ikeda, H., Koohakan P. and Jaenaksorn T. (2002). Problems and countermeasures in the re-use of the nutrient solution in soilless production. *Acta Horticulturae* **578**. https://doi.org/10.17660/ActaHortic.2002.578.26

Jones, Jr J.B. (2014). A complete guide for growing plants hydroponically. Boca Raton, Florida, USA: CRC Press.

Kumar, A., Mehta A., Yadav A. and Kumari K. (2024). Advanced Horticultural Techniques: Hydroponics, Aquaponics and Aeroponics for Optimal Crop

Production. *Int. J. Plant Soil Sci.*, **36(8)**, 884-892.

Lal, RL. (2001). *Land Degradation & Development*, **12**, 519. doi:10.1002/ldr.472.

Love, D.C., Fry J.P., Genello L., Hill E.S., Frederick J.A., Li X. and Semmens K. (2014). An International Survey of Aquaponics Practitioners. *PloS One*, **9(7)**, e102662.

Pivoto, D., Waquil P.D., Talamini E., Finocchio C.P.S, Dalla Corte V.F. and de Vargas Mores G. (2018). Scientific development of smart farming technologies and their application in Brazil. *Information Processing in Agriculture*, **5**, 21–32 https://doi.org/10.1016/ j.inpa.2017.12.00(1).

Pomoni, D., Koukou M., Vrachopoulos M. and Vasiliadis L. (2023). A Review of Hydroponics and Conventional Agriculture based on Energy and Water Consumption, Environmental Impact and Land Use. *Energies*, **16**, 1690. https://doi.org/10.3390/en16041690

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

Resh, H.M. (2022). Hydroponic food production, A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. USA: CRC press.

Romeo, D., Blikra Vea E. and Thomsen M. (2018). Environmental Impacts of Urban Hydroponics in Europe: A Case study in Lyon. *Procedia CIRP*, 6 https://doi.org/10.1016/ j.procir.2017.11.048.

Rufí-Salís, M., Petit-Boix A., Villalba G., Sanjuan-Delmás D., Parada F., Ercilla Montserrat M. and Gabarrell X. (2020). Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency. *J. Cleaner Product.*, **261**, 121-213.

Salma, S.B., Shubham and Kaushal S. (2024). Aeroponics: An emerging food growing system in sustainable agriculture for food security. *Int. J. Res. Agron.*, **7(11)**, 93-97. DOI: https://doi.org/10.33545/2618060X.2024.v7.i11b.1947

Savvas, D. and Gruda N. (2018). Application of soilless culture technologies in the modern greenhouse industry—A review. *Europ. J. Horticult. Sci.*, **83(5)**, 280-293.

Schwarz, D., Franken P., Krumbein A., Klaring H.P. and Bar-Yosef B. (2008). Nutrient management in soilless culture in the conflict of plant, microorganism, consumer and environmental demands. *Int. Symposium on Soilless Culture and Hydroponics* **843**, 27-34.

Sharma, S., Lishika B., Shahi A., Shubham and Kaushal S. (2023). Hydroponics: The Potential to Enhance Sustainable Food Production in Non-Arable Areas. *Curr. J. Appl. Sci. Technol.*, **42(39)**, 13-23. DOI: 10.9734/CJAST/ 2023/v42i39107843

Shubham, Rao A. and Kaushal S. (2024). The Multifaceted Soils of Himachal Pradesh, India: Types and Characteristics. *Arch. Curr. Res. Int.*, **24 (11)**, 145-160. https://doi.org/10.9734/acri/2024/v24i11956.

Somerville, M. and Townsend J. (2014). A student-centered approach to designing teaming experiences. *IEEE Frontiers in Education Conference (FIE) Proceedings*. https://doi.org/10.1109/FIE.2014.7044403.

Sousa, R.D., Braganca L., da Silva M.V. and Oliveira R.S. (2024). Challenges and solutions for sustainable food systems: The potential of home hydroponics. *Sustainability*, **16(2)**, 817.

Taylor, R., Carandang J.S., Alexander C. and Calleja J.S. (2012). Making global cities sustainable: Urban rooftop hydroponics for diversified agriculture in emerging economies. *OIDA Int. J. Sustainable Development*, 11-28.

Wijerathna-Yapa, A. and Pathirana R. (2022). *Agriculture*, **12**, 1554. doi: 10.3390/agriculture12101554.

Wolfert, S., Ge L., Verdouw C. and Bogaardt M.J. (2017). Big Data in Smart Farming – A review. *Agricult. Syst.*, **153**, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023.