International Journal of Advanced Biochemistry Research 2025; SP-9(9): 1309-1314

International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(9): 1309-1314
www.biochemjournal.com
Received: 13-06-2025
Accepted: 18-07-2025

Shruti S Sarode
PG Scholar, Department of Horticulture, Dr. SPCOA, Baramati, Maharashtra, India

Gayatri S Waghmare
PG Scholar, Department of Horticulture, Dr. SPCOA, Baramati, Maharashtra, India

Kalyan N Borde
PG Scholar, Department of Agricultural Extension Education, College of Agriculture, Parbhani, VNMKV, Parbhani

Machhindra G Agale
Assistant Professor, Department of Horticulture, Dr. SPCOA, Baramati, Maharashtra, India

Ganesh S Shinde
Assistant Professor, Department of Horticulture, Dr. SPCOA, Baramati, Maharashtra, India

Sneha K Kshirsagar
Assistant Professor, Department of Horticulture, Dr. SPCOA, Baramati, Maharashtra, India

Shivkumar S. Gholave
PG Scholar, Department of Horticulture, MPKV, Rahuri, Maharashtra, India

Chandan Kumar
Founder & CEO (Farmingwave Agri Solutions Pvt Ltd.)
Bihar, India

Corresponding Author:
Shruti S Sarode
PG Scholar, Department of Horticulture, Dr. SPCOA, Baramati, Maharashtra, India

Hydroponics: A sustainable pathway for future farming

Shruti S Sarode, Gayatri S Waghmare, Kalyan N Borde, Machhindra G Agale, Ganesh S Shinde, Sneha K Kshirsagar, Shivkumar S Gholave and Chandan Kumar

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i9Sq.5689

Abstract
Hydroponics, a modern approach to soilless cultivation, offers an efficient and sustainable alternative to traditional farming by directly supplying plants with nutrient-enriched water solutions. This system supports year-round cultivation, higher yields and faster growth cycles while conserving up to 90% more water than conventional methods. Hydroponics employs diverse growing systems such as nutrient film technique (NFT), deep water culture (DWC), ebb and flow, drip irrigation, wick systems, floating rafts and aeroponics, each suited for specific crops and scales of production. Substrate culture, using inert or organic media like cocopeat, perlite, or rockwool, further enhances root aeration and nutrient uptake while minimizing soil-borne pathogens. Integration with vertical farming and energy-efficient LED lighting enables intensive urban food production and reduces dependence on arable land. Aeroponics has shown exceptional promise in seed potato production, yielding significantly more disease-free minitubers compared to soil-based methods. By combining precision resource management, space optimization and climate resilience, hydroponics emerges as a key innovation for ensuring sustainable and secure food systems for growing populations worldwide.

Keywords: Hydroponics, organic media, vertical farming, aeroponics and space optimization

Introduction

Hydroponics is a method of cultivating plants in nutrient solutions, which are water-based solutions containing fertilizers. This technique may utilize inert media such as sand, gravel, vermiculite, rock wool, perlite, peat moss, coco peat, or pebbles to provide mechanical support (Swain *et al.*, 2021) [46]. According to hydroponics users, continuous year-round production is achievable only with hydroponic systems. These systems enable shorter growing periods, require less space and allow cultivation in small areas with a controlled environment. Hydroponics users often state that this method consistently provides higher productivity and yields, without being limited by climate, weather conditions, or many common plant diseases (Mohite and Pathade, 2023) [27]. A wide variety of commercial and specialty crops can be cultivated using hydroponics, including leafy greens, spinach, broccoli, tomatoes, cucumbers, peppers, strawberries, watermelons, ornamental flowers and many others. As the population grows and cities and industries expand, the amount of land available for farming is steadily decreasing. Traditional farming methods are also struggling with unusual climate patterns. Because of these challenges, we need to develop new and modern ways to produce enough food for the world's increasing population in a sustainable way (Mohite and Pathade, 2023) [27]. The essential need for water conservation in agriculture, particularly in drought-prone areas, is addressed by hydroponic systems, which use up to 90% less water than conventional soil-based farming. (Rajaseger *et al.*, 2023) [32]. Because of the decrease in soil fertility and the reduction in acreage due to urbanization, hydroponics enables growing in places that are inappropriate for traditional agriculture, such as indoor and urban regions.

Hydroponic farms reduce the need for toxic fertilizers and pesticides, which results in better food and less environmental damage such chemical runoff and soil erosion. Urban planners and building managers are increasingly installing hydroponic systems in offices and urban spaces to support localized food production, enhance air quality and promote employee well-being. Hydroponic systems enable crops to grow 25 to 50 percent faster and achieve higher yields per unit area compared to soil-based agriculture (Rajaseger *et al.*, 2023) [32]. This increased efficiency addresses the challenge of supporting a growing population with limited available land. It enables year-round and off-season vegetable production with better quality and price stability (Khapte *et al.*, 2022) [23]. High plant density and vertical farming allow more crops to be grown in less area, supporting urban food systems and reducing transportation costs. Including hydroponic systems in infrastructure and buildings offers a sustainable food source and lessens the environmental effect of food transportation as cities grow. With advanced hydroponic solutions, food systems become more resilient in adapting quickly to changing environmental, economic, or health challenges (Anusree *et al.*, 2024) [2].

Soilless Cultivation Systems for Sustainable Crop Production: Soilless cultivation denotes the technique of growing plants without using natural soil opting instead for substrates or soluble nutrient solutions to fulfil the functions of soil (Gruda, 2009) [15]. This approach offers enhanced precision in controlling nutrient delivery, water use and disease management, making it ideal for modern, intensive horticulture especially where soil quality or availability is problematic (Roy, 2022) [35].

Substrate culture is a prominent branch of soilless cultivation where plants are anchored in a solid medium rather than soil, while nutrient solutions are delivered externally. This method enhances root-zone aeration, minimizes soil-borne pathogen pressure and allows for precise control over nutrient and water supply. As per shown in figure 1, substrate culture is generally classified into inert substrates such as rockwool, perlite, vermiculite, expanded clay aggregate (LECA), sand, pumice and gravel and natural organic substrates including cocopeat, peat moss, rice husk, sawdust, bark, compost and organic waste-based media (Raviv and Lieth, 2008) [34]. Inert substrates are chemically stable and supply no nutrients, making them ideal for standardized fertigation control, while organic substrates contribute varying levels of nutrients and organic matter, often improving water retention capacity (Schmilewski, 2009) [40]. The selection of substrate is based on factors such as water-holding characteristics, porosity, cost and local availability, with materials like cocopeat and rockwool being widely adopted in commercial horticulture for crops including tomato, cucumber and ornamentals.

Hydroponics, recognized as a modern form of agriculture, offers diverse systems designed to deliver nutrients directly to plant roots without soil (Nguyen *et al.*, 2016) [30]. Among the most prominent are the nutrient film technique (NFT), where a thin, flowing layer of nutrient solution passes over roots; deep water culture (DWC), in which roots hang submerged in aerated nutrient solution; ebb and flow (flood and drain), where growing trays are periodically flooded and drained; drip systems, delivering controlled nutrient drips to individual plants; aeroponics, suspending roots in air and applying nutrient mist; floating raft systems, which support plants on rafts floating a top nutrient solutions, this all are examples of passive system of hydroponics and wick systems, using capillary action to draw nutrients from a reservoir (Atherton and Li, 2023) [3]. Wick system is the example of passive system of hydroponics (George and George, 2016) [14]. The various types of hydroponic systems are illustrated in Figure 2. Each system highlights a unique approach to efficient plant growth without soil.

Different systems of hydroponic cultivation

1. Nutrient Film Technique (NFT)

The Nutrient Film Technique or NFT, involves delivering a very shallow stream of nutrient-rich water that constantly flows over a slight slope, bathing plant roots in a thin film of solution. This ensures roots can absorb nutrients while still getting ample oxygen. NFT is renowned for its efficient water and nutrient use, suitability for high-density setups (like leafy greens) and ability to provide a controlled environment for precision farming (Somerville and Townsend, 2014) [43]. Downsides include reliance on pumps and electricity, susceptibility to nutrient imbalances or root drying if flow is interrupted and a higher learning curve. Monitoring systems or backup pumps are often recommended to mitigate these risks (Wongkiew *et al.*, 2017) [48].

2. Deep Water Culture

Deep Water Culture suspends plant roots directly in a reservoir of oxygenated, nutrient-rich water typically using air stones or diffusers to supply oxygen. This system is simple to build, promotes rapid plant growth and is beginner-friendly due to its minimal components. It's particularly effective for leafy greens and herbs. However, maintaining proper temperature and oxygen levels is key, as warmer water holds less oxygen and root diseases can take hold without good aeration (Hamza *et al.*, 2022) [17].

3. Ebb and flow system

In the Ebb and Flow (also called Flood and Drain) system, trays containing plants and growing medium are periodically flooded with nutrient solution and then drained back into a reservoir. This alternation delivers nutrients and oxygen to the roots passively, making it flexible for different crop sizes, including fruiting plants. It’s DIY-friendly and doesn’t require complex aeration equipment. The potential drawbacks include complexity in setup (requiring pumps, timers and overflow safeguards) and higher space requirements. Users report that it's forgiving during power outages and works well with media like clay pellets (Rajaseger *et al.*, 2023) [32].

4. Drip System

Drip systems distribute nutrient solution drop by drop to each plant, either through media-based setups or net pots. This method is highly customizable and scalable making it popular for crops such as tomatoes and peppers. Efficient use of nutrients and water is a major advantage, especially with recirculating systems. However, emitters can become clogged, media can accumulate salts over time and spread mechanics call for regular maintenance (Sharma *et al.*, 2018) [41].

5. Aeroponics

Aeroponics grows plants with their roots suspended in air, which are periodically misted with nutrient solution. This method maximizes root oxygen access, enabling extraordinarily fast growth, reduced water usage and improved nutrient uptake. It's highly space-efficient (often used in vertical setups) and suspicious of soil-borne diseases. On the flip side, aeroponics demands fine nozzle misting control, clean conditions and electrical reliability equipment failures can quickly stress plants (Santosh and Gaikwad, 2023) [39].

6. Wick System
The Wick System is a passive, no-pump hydroponic setup where wicks draw nutrient solution from a reservoir into a growing medium by capillary action. It's ideal for beginners simple, inexpensive and low-maintenance. But growth rates tend to be slower, nutrient delivery is less precise, wicks can clog and it's not well-suited for high-demand crops or large-scale systems (Mugundhan *et al.*, 2011) [28].

7. Floating Raft Method
In the Floating Raft (or DWC-raft) method, plants are placed into foam rafts that float atop a nutrient solution reservoir, allowing roots to hang into the solution below. This design ensures excellent oxygenation, easy harvesting and high plant density especially for leafy greens and herbs. It's commonly used in commercial greenhouses. Maintenance includes temperature control of the nutrient tank and preventing algae growth around raft gaps (Mullins *et al.*, 2023) [29].

Advancing Agricultural Productivity through Hydroponics: Hydroponic farming is recognized as an efficient and sustainable cultivation technique that provides higher yields than conventional soil-based systems (Table 1). Through precise control of environmental conditions and direct nutrient delivery, it overcomes the constraints associated with soil fertility and heterogeneity. Studies have demonstrated that hydroponics enhances plant growth, optimizes resource utilization and ensures uniformity and superior quality of produce (Khatri *et al.*, 2024) [24]. These advantages position hydroponics as a key strategy to address the increasing global demand for food in a sustainable way.

Table 1: yield comparison: hydroponics vs soil

Crop	Hydroponics yield	Soil yield	Hydroponic system	Reference
Lettuce	5.8 kg m^{-2}	3.9 kg m^{-2}	NFT	Dutta *et al.* (2023) [12]
Tomato	50-60 kg m^{-2}	3-8 kg m^{-2}	Substrate drip	D´Andrea (2017) [10]
Cherry tomato	3.5-4.3 kg $plant^{-1}$	1.4-1.8 kg $plant^{-1}$	Dutch bucket	Hartz and Miyao (1993) [18]
Capsicum	15.7-19.0 kg m^{-2}	3-6 kg m^{-2}	Substrate drip	Ko *et al.* (2013) [25]
Cucumber	15.4 kg m^{-2}	2.5-3.5 kg m^{-2}	NFT	Samba *et al.* (2023) [38]
Spinach	3.43 kg m^{-2}	1.20 kg m^{-2}	NFT	Jalal *et al.* (2022) [20]
Basil	1.8 kg m^{-2}	0.6 kg m^{-2}	DWC/Raft	Saha (2016) [37]
Zucchini	1.6 kg $plant^{-1}$	16.7-38.9 t ha^{-1}	Substrate drip	Suvo (2016) [45]

Potential of Aeroponics Systems in Producing High-Quality Potato Seed: Aeroponics offers a highly effective approach for producing quality seed potatoes (*Solanum tuberosum* L.), especially in developing regions where conventional multiplication systems are hindered by soil-borne diseases, limited arable land and high production expenses. In this soilless technique, potato roots are suspended in air and periodically misted with nutrient solutions, eliminating soil-related pathogen risks and promoting healthier growth while accelerating tuber initiation and development, allowing multiple harvests annually (Otazu, 2010; Rykaczewska, 2016) [31, 36]. In Table 2, studies have shown that aeroponic cultivation can yield up to ten times more minitubers per unit area compared to traditional field methods, all while preserving phytosanitary quality (Chiipanthenga *et al.*, 2012) [9]. Additionally, the system's closed-loop nutrient recycling conserves water and fertilizers, making it an environmentally sustainable solution for resource-constrained areas (Mateus-Rodriguez *et al.*, 2013) [26]. Incorporating aeroponics into national seed programs can lessen reliance on imported seed, improve access to disease-free planting material and boost productivity throughout the potato production chain.

Table 2: Aeroponics vs. Conventional Potato Minituber Production

Aspect	Aeroponics	Conventional field- based/ soil production	References
Minitubers per plant	Approximately 50-100, with some reports up to 250-300	Around 5-10 per plant	Chiipanthenga *et al.*, 2012; Mateus-Rodriguez *et al.*, 2013) [9, 26]
Minituber yield per m²	Generally, > 900 minitubers/m²	Approximately 300 minitubers/m²	Mateus-Rodriguez *et al.* (2013) [26]
Field performance traits	Cultivar Ametyst yielded 42.6 t/ha, 644 tubers/ha >3 cm; cv. Tajfun: 37.3 t/ha, 438 tubers/ha >3 cm	Lower yield and fewer tubers across same conditions	Rykaczewska (2016), [36] field trials of aeroponic minitubers for *Solanum tuberosum* L. (Potato)
Multiplication rate	2-3 times higher minituber production compared to traditional methods	Baseline conventional rate	Rykaczewska (2016) [36]
Advantages	Pathogen-free seeds; no acclimatization needed; fast cycles; high yield and uniform quality	Simple, low tech, minimal upfront cost	Chiipanthenga *et al.* (2012); Mateus-Rodriguez *et al.* (2013) [9, 26]

Vertical Farming: Systems and Lighting Strategies
Vertical farming is a modern agricultural approach that cultivates crops in vertically stacked layers or integrated structures, allowing for intensive production in controlled environments. It maximizes space utilization, minimizes land requirements and provides the ability to regulate

environmental parameters such as temperature, humidity, CO_2 concentration and light, thereby ensuring consistent crop yield and quality (Bhargava, 2022) [6]. This farming method can be implemented in urban buildings, greenhouses, or dedicated plant factories, making it an important innovation for addressing global food demands while conserving natural resources (Benke and Tomkins, 2017) [5].

Different approaches to vertical farming

Vertical farming can be classified based on the arrangement and technology used for plant growth. Tower systems involve cylindrical or vertical columns with plants growing along the structure, allowing efficient nutrient and water delivery. Rack systems use multi-tier shelving units equipped with lighting and irrigation, enabling high-density production within limited spaces (Hogewoning *et al.*, 2010) [19]. A-frame systems are triangular structures that maximize light interception and airflow, suitable for compact farming setups. Wall-mounted systems, or living walls, attach plants to vertical surfaces, offering both aesthetic and functional benefits for small-scale or urban farming. Hybrid systems integrate more than one vertical farming method to accommodate different crops, optimize resource use and improve efficiency (Tabibi, 2024) [47].

Artificial lighting is a critical component of vertical farming, compensating for the lack of natural sunlight in enclosed or urban environments. Light-emitting diodes (LEDs) are the most widely used due to their energy efficiency, spectral tunability and low heat emission, allowing close placement to plants without causing thermal stress (Singh *et al.*, 2015) [42]. Red and blue LED combinations are highly efficient for photosynthesis red light (600-700 nm) supports flowering and biomass accumulation, while blue light (400-500 nm) promotes vegetative growth and leaf morphology. Full-spectrum white LEDs simulate natural sunlight, enhancing plant colour rendering and allowing growers to better monitor plant health. Supplemental spectra, such as green light for deeper canopy penetration, far-red light for flowering induction and morphological control and UV-B light for stimulating secondary metabolite production, are increasingly used to optimize growth and crop quality. Dynamic spectrum control systems allow growers to adjust light wavelengths according to the crop's developmental stage, further improving productivity and energy savings (Gupta and Jatothu, 2013) [16].

Advantages of Hydroponics: Hydroponic farming provides multiple advantages over traditional soil-based agriculture. One of the most significant benefits is the efficient utilization of water, as closed-loop systems recycle nutrient solutions and reduce overall consumption compared to field cultivation (De and Maggio, 2004) [11]. Hydroponics also ensures higher crop productivity due to precise nutrient delivery, optimized growing conditions and reduced exposure to soil-borne pathogens (Barbosa *et al.*, 2015) [4]. In addition, the system eliminates the need for chemical pesticides to a large extent, thereby producing healthier and pesticide-free food (Fernandez *et al.*, 2018) [13].

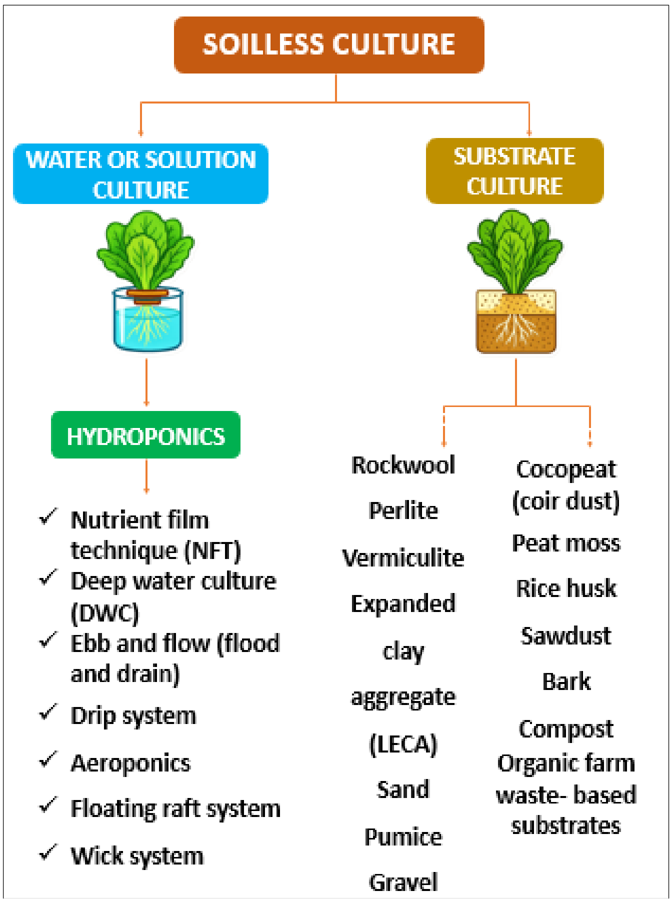
Another major advantage is its adaptability to non-arable areas, including urban rooftops, vertical farms and regions with poor soil quality, where hydroponics enables year-round production of fresh vegetables (Bhargava, 2022) [6]. Nutrient management is more accurate and ontrolled,resulting in faster growth rates and higher yields compared to conventional systems (Bugbee, 2004) [7]. Furthermore, hydroponics can integrate with renewable energy technologies such as solar and wind, thereby reducing greenhouse gas emissions and enhancing sustainability (Califano *et al.*, 2024) [8]. With urbanization and climate change placing increasing pressure on food security, these advantages make hydroponics a viable and resilient farming alternative for the future.

Future Prospects and Limitations of Hydroponics

Hydroponics represents one of the most promising sustainable farming methods, with the potential to address pressing agricultural challenges linked to climate change, water scarcity and land degradation. By creating controlled environments, it allows stable yields even under erratic rainfall and extreme weather conditions. Hydroponics maximizes water and nutrient use efficiency, which is particularly crucial in regions facing resource limitations (Sharma *et al.*, 2018) [41]. Furthermore, its integration into urban agriculture such as rooftop and vertical farms can significantly contribute to local food security and reduce the carbon footprint associated with food transport (Jensen and Malter, 1995) [21].

Future growth of hydroponics will likely be driven by technological advancements, including automated fertigation, climate control and smart monitoring systems, which will make cultivation more precise and cost-effective. The use of renewable energy sources such as solar panels in hydroponic systems can further minimize greenhouse gas emissions, enhancing their sustainability (Rakocy *et al.*, 2016) [33]. Moreover, supportive policies, research investments and farmer training programs will be vital in scaling up adoption and ensuring that hydroponics contributes meaningfully to global food security (Kalantari *et al.*, 2017) [22].

However, hydroponics is not without its limitations. High initial setup costs pose a significant challenge, particularly for smallholder farmers in developing countries. In addition, hydroponic systems require skilled management of nutrient solutions and continuous energy supply; power failures or system breakdowns can result in rapid crop losses (AlShrouf, 2017) [1]. Disposal of nutrient-rich effluents, if not properly managed, may also lead to environmental concerns. Large-scale adoption further depends on infrastructure development, reliable markets and consumer acceptance of hydroponically grown produce. Addressing these limitations through cost reduction, renewable energy integration and training initiatives will be essential for unlocking the full potential of hydroponics (Sonneveld and Voogt, 2009) [44].



Conclusions

Hydroponics presents a transformative pathway for sustainable agriculture by ensuring efficient resource use, higher productivity and resilience against climate and urbanization pressures. Its ability to provide year-round, pesticide-free produce makes it a strong candidate for addressing global food security challenges. However, high establishment costs, technical requirements and environmental management of nutrient solutions remain significant hurdles. Future strategies should focus on technological innovations, integration with renewable energy, government support and capacity building to overcome these barriers. With the right interventions, hydroponics can evolve into a cornerstone of future farming systems, balancing productivity with sustainability.

References

1. AlShrouf A. Hydroponics, aeroponic and aquaponic as compared with conventional farming. American Scientific Research Journal for Engineering, Technology and Sciences. 2017;27(1):247-255.
2. Anusree G, Sajitha Rani T, Shalini Pillai P. Exploring the potential of soil-less farming through hydroponics in India: a review. Journal of Experimental Agriculture International. 2024;46(12):902-922.
3. Atherton M, Li Y. Hydroponic cultivation of medicinal plants—Plant organs and hydroponic systems: techniques and trends. Horticulturae. 2023;9(3):1-26.
4. Barbosa G, Gadelha F, Kubik N, Proctor A, Reischel L, Weissinger E, *et al.* Comparison of land, water and energy requirements of lettuce grown using hydroponic vs conventional agricultural methods. International Journal of Environmental Research and Public Health. 2015;12(6):6879-6891.
5. Benke K, Tomkins B. Future food-production systems: vertical farming and controlled-environment agriculture. Sustainability: Science, Practice and Policy. 2017;13(1):13-26.
6. Bhargava G. Future prospects of vertical and hydroponic farming. Humanities, Policy, and Applied Research Review. 2022. https://doi.org/10.47611/hparr.226
7. Bugbee B. Nutrient management in recirculating hydroponic culture. Acta Horticulturae. 2004;648:99-112.
8. Califano G, Crichton-Fock A, Spence C. Consumer perceptions and preferences for urban farming, hydroponics and robotic cultivation: a case study on parsley. Future Foods. 2024;9:100353.
9. Chiipanthenga M, Maliro M, Demo P, Njoloma J. Potential of aeroponics system in the production of quality potato (*Solanum tuberosum* L.) seed in developing countries. African Journal of Biotechnology. 2012;11(17):3993-3999.
10. D'Andrea SAG. Hydroponic systems and vegetable yield performance in controlled environments. Acta Horticulturae. 2017;1176:23-30.
11. De Pascale S, Maggio A. Sustainable protected cultivation at a Mediterranean climate: perspectives and challenges. Acta Horticulturae. 2004;691:29-42.
12. Dutta S, Sahu R, Sahu N, Behera TK. Hydroponics in vegetable crops: a review. Agricultural Reviews. 2023;44(3):234-242.
13. Fernandez JA, Orsini F, Baeza E, Oztekin GB, Muñoz P, Contreras J, *et al.* Current trends in protected cultivation in Mediterranean climates. European Journal of Horticultural Science. 2018;83(5):294-305.

14. George P, George N. Hydroponics Soilless cultivation of plants for biodiversity conservation. 2016.
15. Gruda N. Do soilless culture systems have an influence on product quality of vegetables? Journal of Applied Botany and Food Quality. 2009;82(2):141-147.
16. Gupta SD, Jatothu B. Fundamentals and applications of light-emitting diodes (LEDs) in *in vitro* plant growth and morphogenesis. Plant Biotechnology Reports. 2013;7(3):211-220.
17. Hamza A, Abdelraouf RE, Helmy YI, El Sawy SM. Using deep water culture as one of the important hydroponic systems for saving water, mineral fertilizers and improving the productivity of lettuce crop. International Journal of Health Sciences. 2022;6(S9):2311-2331.
18. Hartz TK, Miyao G. Production practices and yield of cherry tomato under greenhouse and field conditions. HortScience. 1993;28(9):901-904.
19. Hogewoning SW, Trouwborst G, Maljaars H, Poorter H, van Ieperen W, Harbinson J. Blue light dose-responses of leaf photosynthesis, morphology and chemical composition of *Cucumis sativus* grown under different combinations of red and blue light. Journal of Experimental Botany. 2010;61(11):3107-3117.
20. Jalal A, Rahman M, Karim M. Comparative performance of spinach (*Spinacia oleracea* L.) under hydroponic and soil culture. International Journal of Agronomy. 2022;2022:1-9.
21. Jensen MH, Malter AJ. Protected agriculture: a global review. World Bank Technical Paper No. 253. Washington, DC: World Bank; 1995. p. 1-157.
22. Kalantari F, Mohd Tahir O, Joni RA, Fatemi E. Opportunities and challenges in sustainability of vertical farming: a review. Journal of Landscape Ecology. 2018;11(1):35-60.
23. Khapte P, Kumar P, Singh A, Wakchaure G, Saxena A, Sabatino L. Integrative effect of protective structures and irrigation levels on tomato performance in Indian hot-arid region. Plants. 2022;11(20):2743.
24. Khatri L, Kunwar A, Bist DR. Hydroponics: advantages and challenges in soilless farming. Big Data in Agriculture. 2024;6(2):81-88.
25. Ko K, Cho M, Lee J, Kim H. Growth and fruit yield of sweet pepper in different soilless culture systems. Protected Horticulture and Plant Factory. 2013;22(3):207-214.
26. Mateus-Rodriguez JR, de Haan S, Andrade-Piedra J, Maldonado L, Hareau G, Barker I, *et al.* Technical and economic analysis of aeroponics and other systems for potato mini-tuber production in Latin America. American Journal of Potato Research. 2013;90(4):357-368.
27. Mohite AD, Pathade GR. Hydroponics: a review. Economic, Environmental and Conservation Sciences. 2024;30:S314-S324.
28. Mugundhan RM, Soundaria M, Maheswari V, Santhakumari P, Gopal V. Hydroponics a novel alternative for geoponic cultivation of medicinal plants and food crops. International Journal of Pharma and Bio Sciences. 2011;2(2):296.
29. Mullins C, Vallotton A, Latimer J, Sperry T, Scoggins H. Hydroponic production of edible crops: deep water culture (DWC). Virginia Cooperative Extension. 2023;SPES-464NP.
30. Nguyen NT, McInturf SA, Mendoza-Cózatl DG. Hydroponics: a versatile system to study nutrient allocation and plant responses to nutrient availability and exposure to toxic elements. Journal of Visualized Experiments. 2016;(113):e54317.
31. Otazu V. Manual on quality seed potato production using aeroponics. Lima: International Potato Center (CIP); 2010.
32. Rajaseger G, Chan KL, Yee Tan K, Ramasamy S, Khin MC, Amaladoss A, *et al.* Hydroponics: current trends in sustainable crop production. Bioinformation. 2023;19(9):925-938.
33. Rakocy JE, Bailey DS, Shultz RC, Thoman ES. Update on tilapia and vegetable production in the UVI aquaponic system. Proceedings of the 8th International Symposium on Tilapia in Aquaculture. 2016;1-15.
34. Raviv M, Lieth JH. Soilless culture: theory and practice. Amsterdam: Elsevier; 2008. p. 101-120.
35. Roy D. Hydroponics: soil-less farming technique. AgriCos e-Newsletter. 2022;3(7):214-218.
36. Rykaczewska K. Field performance of potato minitubers produced in aeroponic culture. Plant Soil and Environment. 2016;62(11):522-526.
37. Saha S. Hydroponics and soilless cultivation systems for sustainable agriculture. International Journal of Agricultural Science and Research. 2016;6(2):235-246.
38. Samba N, Patil RS, Rane J. Evaluation of training methods for cucumber under NFT hydroponic system. Horticulturae. 2023;9(7):785.
39. Santosh DT, Gaikwad D. Advances in hydroponic systems: types and management. 2023. p. 16-28.
40. Schmilewski G. Growing medium constituents used in the EU. Acta Horticulturae. 2009;819:33-46.
41. Sharma N, Acharya S, Kumar K, Singh N, Chaurasia OP. Hydroponics as an advanced technique for vegetable production: an overview. Journal of Soil and Water Conservation. 2018;17(4):364-371.
42. Singh D, Basu C, Meinhardt-Wollweber M, Roth B. LEDs for energy efficient greenhouse lighting. Renewable and Sustainable Energy Reviews. 2015;49:139-147.
43. Somerville M, Townsend J. A student-centered approach to designing teaming experiences. 2014 IEEE Frontiers in Education Conference (FIE) Proceedings. 2014;1-2.
44. Sonneveld C, Voogt W. Plant nutrition of greenhouse crops. Dordrecht: Springer; 2009. p. 1-431.
45. Suvo D. Hydroponics as an advanced technique for vegetable production: an overview. Journal of Plant Science. 2016;4(3):56-64.
46. Swain A, Chatterjee S, Vishwanath M. Hydroponics in vegetable crops: a review. The Pharma Innovation Journal. 2021;10(6):629-634.
47. Tabibi A. Types of vertical farming systems. Green.org. 2024. Available from: https://green.org
48. Wongkiew S, Hu Z, Chandran K, Lee JW, Khanal SK. Nitrogen transformations in aquaponic systems: a review. Aquacultural Engineering. 2017;76:9-19.