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Advancing Agriculture: Exploring the Potential of Aeroponic Systems for Vegetable Cultivation: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Aeroponic systems offer an efficient and sustainable approach to vegetable cutivation, highlighting advantages such as water and resource efficiency, year-round production and high quality crops. The review explores the principles of aeroponic cultivation, key factors like nutrient delivery, root oxygenation, and space optimization. It also examines the advantages and limitations of aeroponics compared to traditional soil-based methods. It also discusses recent advancements in technology and research and the future prospects for the continued development and adoption of aeroponic vegetable cultivation. Overall, this review underscores the potential of aeroponics to revolutionize vegetable farming practices to offer a promising solution for today's agricultural farming problems viz., shrinking land, scarcity of water, declined productivity etc. and contribute to global food security in the coming years.

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1. INTRODUCTION

"Soil fertility is increasingly compromised by chemical usage, natural disasters, and global warming, leading to a significant decline in arable land and productivity. By 2050, with the global population is projected to reach 8.9 billion, food production needs to increase by 50%, yet available fertile land is insufficient". (FAO, 2020).

"Traditional soil-based agriculture faces serious threats from these challenges, making food production a real challenge today. Soil-based farming practices need to be supplemented by more efficient and environmentally friendly forms of modern farming. Land degradation poses a significant threat to traditional farming, with soil erosion, nutrient depletion and loss of arable land becoming critical challenges. Apart from the previously mentioned issue, inadequate planning also leads to the critical problem of insufficient human nutrition, primarily caused by the increasing population. To solve the problems mentioned, new farming methods have been searched, one of them being aeroponics. This method involves holding the plants in place with specific structures so that the roots are kept up in the air" [1].

"Farming in the sky aeroponics is modeled after naturally occurring plants, such as the "air plant" called Tillandsia, which features bare roots that take moisture directly from humid air. Aeroponic means "growing in air." Aeroponics is soilless cultivation and it is a process of growing crops suspended in the air or a mist without using soil. The word 'Aeroponic' is derived from the Greek words *aer* (air) and *ponos* (labour)" [2]. Aeroponics, a soil-less cultivation method where plants are suspended in air and roots are exposed to a nutrient-rich mist, emerges as a revolutionary approach. It maximizes resource use, reduces water consumption, and minimizes soil degradation impacts, offering a flexible solution suitable for urban areas, arid regions, and even space agriculture.

1.1 Why do we need aeroponics?

- To end hunger and poverty
- The population is expected to reach 8.9 billion in 2050 and the world has to produce 50% more food
- Soil degradation
- Climate changes
- Rapid urbanization
- Industrialization
- Water scarcity

1.2 Advantages

- **Water Efficiency**: Minimize water usage through targeted misting.
- **Nutrient Absorption**: Provides direct access to nutrients, promoting faster growth
- **Oxygenation:** Enhance oxygen availability for vigorous root development
- **Space Efficiency:** Maximize vertical space utilization for high density planting
- **YearRound Cultivation**: Enables consistent production regardless of external condition
- **Pest and Disease Control:** Reduce soil born pests and diseases, promoting healthier plants
- **Resource Efficiency:** Require fewer resources such as fertilizers and pesticide
- **High Yield and Quality:** Produce premium quality crops with higher yield.

Table 1. Comparison between aeroponics and hydroponics [3-5]

Aeroponics	Hydroponics
✓ Roots misted with nutrient solution	✓ Roots submerged in nutrient solution
✓ Solution: Sprayed in the form of fine mist of mineral nutrients	✓ Solution: Dissolved in the medium
✓ Exposure to CO_2: Greater and Larger exposure	✓ Exposure to CO_2: Smaller and Less exposure
✓ Spread of diseases: Reduced	✓ Spread of diseases: Possible
✓ Water: Required in minimal amount	✓ Water: Required twice the amount of water by aeroponics

Table 2. Comparison of farming in soil vs aeroponics

	Aeroponics	Soil
Set up	Once	After every harvest
Water usage	96 % less	high
Insecticide, herbicide	None	High
Fertilizer	Very low	high
Weather and soil	Not dependent	Dependent

1.3 Disadvantages

- **Initial Cost:** Higher setup costs compared to traditional methods.
- **Complexity:** Requires technical knowledge and maintenance.
- **Risk of System Failure:** Vulnerable to power outages or equipment malfunctions.
- **Root Sensitivity:** Roots may be sensitive to drying out if the misting system fails.
- **Dependency on Supplies:** Relies on consistent access to water, nutrients, and electricity.
- **Potential for Contamination:** Mist can spread pathogens if not properly managed.
- **Limited Crop Options:** Not all crops may thrive in aeroponic environments.
- **Skill Requirement:** Requires skill and experience to optimize system performance.

1.4 Vegetable Crops Suitable for Aeroponics Systems

- Tomato, Potato, Bean, Watermelon, Lettuce, Yam, Carrot, Cucumber, Leafy vegetables, Squash, Kale, Bell pepper, *etc*.

2. COMPONENTS

Nutrient Solution Tank: This is where the nutrient solution is stored. Usually, it is a mixture of water and particular nutrients needed for plant growth. A pump could be included in the reservoir to circulate the solution to maintain the nutrient levels consistent.

Nutrient Pump: A pump is used to transfer the nutrient solution from the reservoir to the sprayers or misters in systems where the solution needs to be circulated. This ensures that nutrients reach the roots of the plants continuously.

Growing Chamber or Tower: This is where the plants are housed. It can take various forms such as horizontal trays, vertical towers, or enclosed chambers. The design allows the roots to hang freely in the air, allowing for maximum oxygenation and nutrient absorption.

Sprayers or Misters: These components are in charge of delivering the nutrient solution to the roots of the plants. Usually placed either above or below the roots, they periodically release a fine mist or spray. The mist covers the roots, giving them nutrition and moisture while maintaining an adequate amount of oxygen.

Timer or Controller: The misting cycles are frequently automated with the use of a timer or controller. It optimizes growing conditions and resource utilization by controlling the frequency and duration of nutrient delivery to the plants.

pH and EC (Electrical Conductivity) Monitor: By monitoring the nutrient solution's pH and EC, these instruments make sure it remains within the optimum range for plant growth. While EC indicates the concentration of dissolved salts in the solution, pH levels affect nutrient availability.

Table 3. pH and EC requirement for some vegetable crops in aeroponics [6,7,2,8]

Crops	pH	EC
Cucumber	5.8-6.0	1.7-2.2
Carrot	5.8-6.4	1.6-2.0
Lettuce	5.5-6.5	0.8-1.2
Tomato	5.5-6.5	2.0-5.0
Potato	5.0-6.0	2.0-2.5

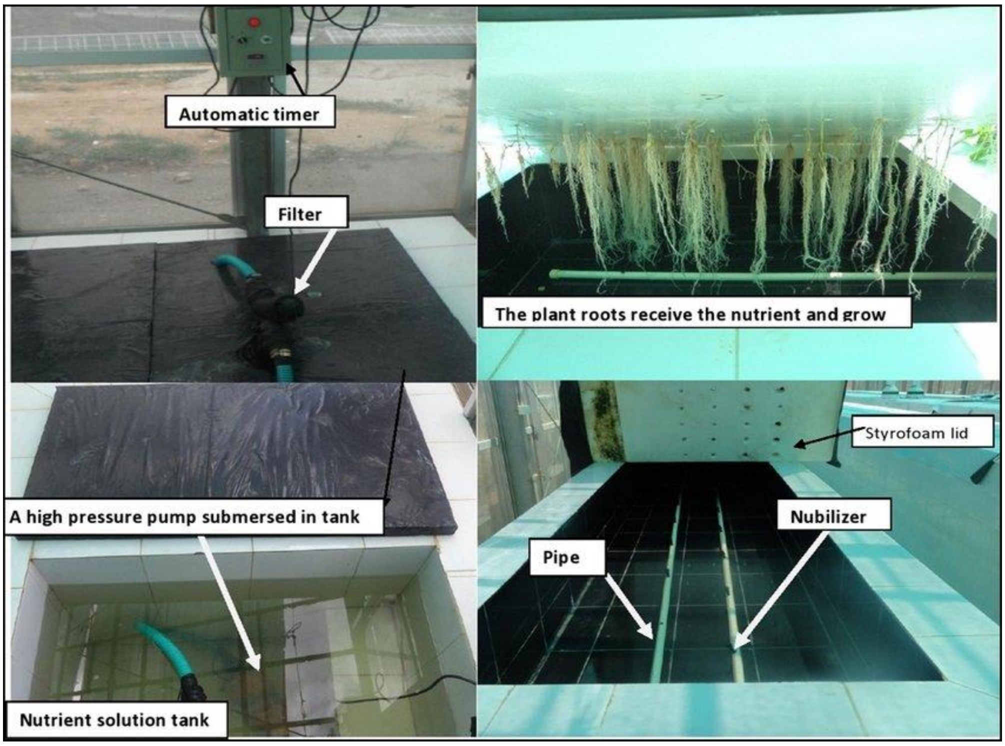

Fig. 1. Different components of aeroponics system

2.1 How does Aeroponics work?

Seeds, cuttings, or young plants are first planted in a specific growing space in aeroponics. This area can be enclosed chambers, horizontal trays, or vertical towers. The plants are firmly planted with their roots hanging in midair. A nutrient solution is prepared and kept in a reservoir. It is composed of water enriched with essential nutrients for plant growth. The macro and micronutrients required by the plants are all provided by this solution. A misting system is installed within the growing area. Typically, this system consists of strategically placed nozzles or misters that distribute the nutrient solution evenly. A pump attached to these misters pulls the solution from the reservoir. Spray droplets of less than 30 microns tend to remain in the air as a 'fog' and are not readily absorbed by the roots, while any droplets over 100 microns tend to fall out of the air before containing any roots. As a general rule, a misting cycle of 1 -2 minutes of misting followed by 5 minutes off will ensure the root system does not dry out under most conditions. The plant roots immediately take up moisture and nutrients from the surrounding air as the mist settles upon their suspended roots. Aeroponics offers a very effective way to deliver nutrients, in contrast to conventional soil-based cultivation techniques where roots must look for nutrients in the soil. By providing a steady supply of oxygen to the roots, the misting procedure promotes healthy growth and nutrient absorption. Regular monitoring of pH and EC levels in the nutrient solution is essential to maintain optimal growing conditions. Depending on the plant species and desired yield, harvesting can occur once the plants reach maturity. Compared to conventional techniques, aeroponic systems frequently encourage faster growth rates, leading to shorter growing cycles and earlier harvests.

2.2 Factors Affecting Aeroponics

1. **pH and EC:** The ideal pH and EC range for each plant depend on available environmental conditions [9]. In an aeroponics system, the optimum EC value for a nutrient solution is 1.5 to 2.5 ds m^1 and the pH values of nutrient solution 5.5 to 6.5 [10].
2. **Temperature:** In the aeroponics system, both air and nutrient solution temperature should be controlled for quick plant maturation. The optimum temperature range for all plants is 15–25 °C. The temperature of the growth chamber should be not higher than 30°C and less than 4°C. This condition can be maintained by air conditioning and exhaust fan ventilation.

3. **Light:** Replacement for sunlight is very essential. It can be replaced by fluorescent tubes of the required intensity. To adjust the various light environments, recently a Light Emitting Diode (LED) has spread as a new light source in the aeroponics system.
4. **Nutrient reservoir:** The pH and EC of nutrient solution should be monitored regularly. These will change as the nutrient solution is being used. So, check the nutrients weekly and make changes for the type of plant growing in your aeroponic system.
5. **Humidity and dissolved oxygen concentration:** Humidity is the amount of available water in the growth chamber as water vapor content. It is the main component required for plant growth and development and it is significantly affected by increases and decreases in relative humidity. It is important to regularly maintain and control the required humidity concentration of the growth chamber based on plant needs. When there isn't enough oxygen, root cells can't burn as much sugar, and they can't absorb as much water and nutrients. Low oxygen concentrations can also reduce the uptake of water and nutrients through soil respiration, which can hinder transpiration and plant growth.

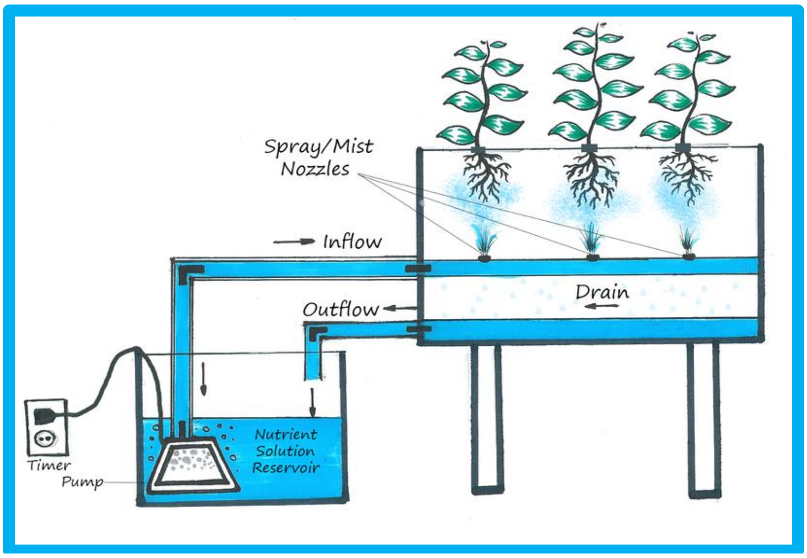

Fig. 2. Schematic representation of aeroponics system

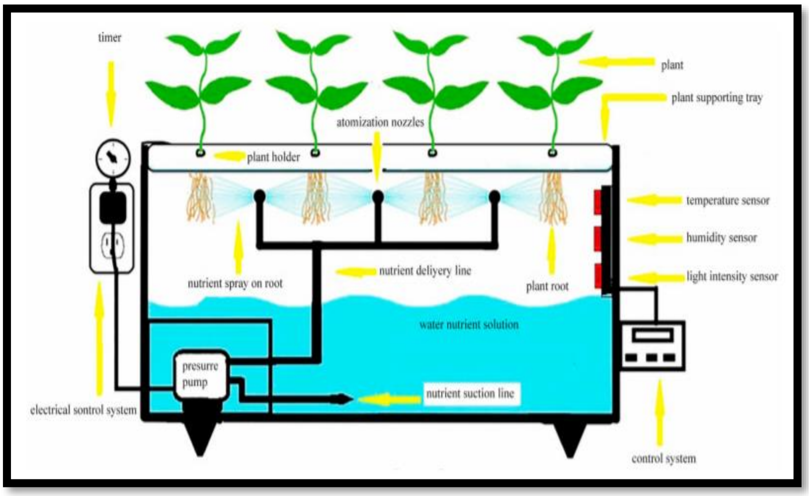

Fig. 3. Aeroponics plant growing system with computer controlled techniques

Table 4. Essential mineral elements concentration used in aeroponics system [11]

	Steiner (1984)	Cooper (1988)	Hewitt (1966)	Hoagland and Arnon (1938)
Nutrient	**mg L^{-1}**			
N	168	200-236	168	210
P	31	60	41	31
K	273	300	156	234
Ca	180	170-185	160	160
Mg	48	50	36	34
S	336	68	48	64
Fe	2-4	12	2.8	2.5
Cu	0.02	0.1	0.064	0.02
Zn	0.11	0.1	0.065	0.05
Mn	0.62	2.0	0.54	0.5
B	0.44	0.3	0.54	0.5
Mo	Not considered	0.2	0.04	0.01

2.3 Types of Aeroponics System

1) **Low Pressure Units:** It is simpler and costs less. The plants are suspended in the air the nutrient based water below it. Then, a lowpressure pump sprays the plants roots. The nutrients then drip back down into the nutrient based water below and are used repeatedly. This system does not remove any unwanted materials and does not purify the nutrient solution
2) **High Pressure Units:** In this system, the mist is generated by high pressure pump. It has the same concept as low pressure units, but instead uses a high pressure pump. These units are usually used for high valued crops. unlike low pressure units, this system has a purifying system for nutrient sterilization and a pressurized nutrient delivery system.
3) **Commercial Systems:** This system is very much like high pressure units but has more beneficial and convenient features. Some features include: disease prevention, precision timing, temperature sensors and many more. Like high pressure systems, commercial systems are used for high valued crops.

2.4 Research Work in Vegetable Crops

2.4.1 Potato

Ritter et al., [5] "compared hydroponics and aeroponics cultivation systems to produce potato mini tubers and revealed that the aeroponic system produced the maximum average number of tuber/plant (12.4) and yield/plant (109.9 g) compared to the hydroponic system. It might be due to root damage due to replanting and lifting is avoided". Farran and Mingo., [2] carried out "research on plant density and harvesting interval on potato mini tuber production in an aeroponics system and they found the highest number of tubers/plant (13.4) and yield (118.61 g/plant) with 7 days harvesting interval, while maximum mean tuber weight (9.44 g) found with 10 day harvesting interval in lower plant density (60 plant/m^2). It might be due to a decrease in minituber yield and no.of mini tuber per plant with an increase in plant density with repetitive harvesting". Mateus et al., [12] "experimented on the comparison of yield parameters of potato cultivars grown under an aeroponics system (winter 2008 - summer 2009) and noticed the highest number of tubers/plant (71.7), yield (860.2 g/plant) and mean tuber weight (12.1 g) in variety Chucmarina. It might be due to a lack of mechanical resistance for root growth and delay in tuberization of potato plants grown aeroponically which favor the growth of new and secondary stolon". Tierno et al., [13] compared "the production of three potato cultivars under aeroponics and greenhouse beds and they noticed the highest yield/plant (88.6 g/plant) from cv". Monalisa. Bag et al., [7] "compared the yield performance of potato mini tubers of three varieties under the aeroponics system for two years (2013 and 2014). They found that Kufri Megha showed better performance concerning days to tuberization (32.67 and 30.00), number of mini tubers/plant (42.68 and 38.11), the yield of mini tubers/plant (118.54 and 108.94 g) and average mini-tuber weight (2.91 g and 2.96 g), while Kufri Himalini found better in day to senescence (127.00) in 2013 and yield of mini tuber/ plant (161.80) in 2014". Tessema et al., [14] found that "the application of 59 g $CaNO_3$, 126 g KNO_3, 68 g KH_2PO_4 and 100 g $MgSO_4$ nutrient solution produced maximum number of tuber/plants with potato cv. Belete. It might be due to the use of lesser nitrate fertilizer because as the concentration of nitrate increases it increases vegetative growth and decreases yield". Brocic et al., [15] studied "the influence of the potato cultivar on the number and mass of potato mini tubers in the aeroponics system and it was evident that the highest number of mini-tubers/m^2 (373.26) and average number of mini tubers/plant (15.55) were recorded from the cv. Desiree, while maximum yield of mini tuber/m^2 (2304 g/m^2) and average mass of a mini-tuber (8.97 g) were obtained from cv. Agria".

2.4.2 Yam

Otengo-Darko et al., [1] revealed that "the power dependent aeroponics unit produced maximum mean yield/cutting (3.67 g), multiplication ratio/explant (477.10) and seed yam/explant (1393) from cv. Mankrong Pona of white yam. Maroya et al., [16-18] found that in aeroponics the establishment of rooting is higher near about 95% as compared to 70% obtained by using carbonized rice husk and it also takes less time for rooting".

2.4.3 Lettuce

Ali et al., [19-21] compared "aeroponics and hydroponics systems and found the highest fresh mass (290.84 g/plant) and dry mass (39.41 g/plant) of the shoot with aeroponics system at 0.5 L/h flow rate". Lakhiar et al., [11] studied "the effect of different aeroponic atomizers (A1 = air-based, A2 = airless atomizer and A3 = ultrasonic fogger) on growth parameters of lettuce and reported maximum leaf area, stem diameter, number of leaves/plant, shoot length, root length, shoot wet weight, root wet weight, shoot dry weight and root dry weight with A2 as compared to A1 and A3". El-Helaly and Darwish [22-25] studied "the effect of different culture systems on the growth parameter of lettuce at harvest (6 weeks of transplanting) and revealed that the aeroponic plants recorded raises in shoots dry weight (4.49g), roots fresh weight (15.99g), roots dry weight (0.85g), root length (58.73cm) than the hydroponic and sandy substrate plants. It might be due to in aeroponics, the root system is totally suspended in air, giving the plant stem and root system access to 100% of the available oxygen at the air and hence enhancing plant growth".

2.4.4 Leafy vegetables and fruit vegetable crops

"Several leafy vegetables/herbs (basil, chard, parsley, and red kale) and fruit crops (bell pepper, cherry tomatoes, cucumber, and squash) grown in aeroponic growing systems and in the field were compared in terms of product yield, total phenolics, total flavonoids and antioxidant qualities. An average increase of around 19%, 8%, 65%, 21%, 53%, 35%,7% and 50% in yield was recorded for basil, chard, red kale, parsley, bell pepper, cherry tomatoes, cucumber and squash, respectively, when grown in the aeroponic system as compared to grown in the soil. In general, the study shows that the plants grown in the aeroponic system had a higher yield and comparable phenolics, flavonoids, and antioxidant properties as compared to those grown in the soil" [24-26]. Osvald et al., [27-28] studied "the yield of tomato cv. 'Arletta' grown in aeroponics with different plant densities viz., 24, 32, 40 and 48 plants/m^2. They recorded a maximum average yield/plant (526 g) with lower plant density (24 plant/m^2) while, a maximum average yield/m^2 (21.2 kg) with higher plant density (48 plant/m^2). It might be due to increasing plant density formation of fruit is also increased and proper and regular supply of nutrient solution towards plant roots which increases quality as well as quantity of fruit".

3. CONCLUSION

In conclusion, aeroponic systems present a novel and highly effective way to cultivate vegetables. With benefits like year-round production with better crop quality, minimum usage of resources with maximum water use efficiency thus, aeroponics offers a promising solution to today's agricultural problems. Aeroponics has the potential to completely transform vegetable farming, despite certain inherent complexities and challenges that are being overcome by continuous research and technological advancements. Aeroponic vegetable farming is becoming more and more important as we work toward resilient and sustainable agricultural methods that will meet the world's food needs with having the least negative environmental effects.

4. FUTURE PROSPECTS

Looking ahead, the future of vegetable cultivation in aeroponics holds significant promise. Continued research and innovation are expected to further enhance the efficiency, sustainability, and scalability of aeroponic systems. Advancements in technology, such as precision agriculture techniques and automation, are poised to streamline operations and optimize resource utilization. Moreover, ongoing efforts to expand crop diversity and adapt aeroponic methods to new environments hold the potential to revolutionize global food production. As we embrace the potential of aeroponics, it is clear that this innovative approach will play a pivotal role in addressing future challenges in vegetable cultivation, ensuring food security and fostering sustainable agricultural practices.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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