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Ponical Farming: Exploring Hydroponics and Aeroponics Farming Techniques

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Abstract

To meet the increasing global food needs, traditional farming systems are currently challenged to keep up due to urbanization, decreasing crop land, and even environmental issues such as soil erosion, climate change, and deforestation. The innovation of soilless farming techniques gives us the opportunity to use hydroponics and aeroponics to resolve such issues sustainably. Aeroponics uses a high-pressure system to spray nutrient-rich mist onto roots that accelerates plant growth while hydroponics helps facilitate plant growth by delivering essential nutrients through water-based solutions. With the use of these innovative techniques, plant growth is 10x more efficient, lower water is required, and diseases from soil are eliminated.

These methods have gained popularity because of recent advancements in technology like IoT, automation, and LED lighting, making it more cost-effective and efficient for large scale businesses. This paper analyses the advanced nutrient requirements as well as the distinguishing aspects of hydroponic and aeroponic systems.

Through the analysis of strengths and weaknesses in ponical systems, this paper seeks to address how they have transformed agriculture, encouraged sustainable practices, and fostered effective resource management. The results point out the gaps and investment, policy as well as research directions that are necessary to make such systems more mainstream and integrated

into food production. Nonetheless, we have already established, with no regard to the global advancement, that soilless cultivation technology is a feasible way out of food insecurity in the future.

Keywords: Hydroponics, Aeroponics, Water Efficient Technology, Smart-Farming Agriculture, Food security, Soil free Cultivation.

Introduction

The astonishing growth in urbanization and industrial development leads to the aggressive invasion of cultivable areas which casts a shadow on food security. This problem is further exacerbated by environmental pressures like soil erosion, drought, and global warming, which undermine the efficiency of conventional agricultural practices. The world population continues to increase and is expected to reach 9.6 billion by the year 2050. This increases the demand of food, creating immense strain on conventional farming techniques (FAO, 2017). Although farming methods have always held importance, they have their fair share of challenges, including dependency on fertile land, reliance on erratic climatic conditions, over exploitation of freshwater, and fragility to pathogens and pests residing in soil (Basu et al, 2021). This highlights the ever in demand necessity for novel approaches towards agriculture, allowing for high yield crops with efficient resource management.

To counter these obstacles, advanced alternatives such as hydroponics and aeroponics are winning methods for food production. The term hydroponics comes from the Greek word "hydro" meaning water and "ponos" meaning labor. It refers to systems whereby plants are grown without soil while all the necessary nutrients are provided in the form of a water solution. Hydroponics enables nutrient delivery to be precisely controlled, improves water use efficiency, and mitigates the risk of pathogens that stem from soil (Barbosa et al. 2015). Aeroponics, on the other hand, is a productive cultivation approach that comprises a set of techniques allowing for the suspension of plant roots in air, and delivery of nutrient mist at regular intervals. This allows for rapid growth and the effective use of water (Otto et al., 2019). Hydroponics and aeroponics farming systems support growing crops in a controlled environment throughout the year making them ideal for urban agriculture, greenhouse farming, and vertical farming (Despommier 2010, Al-Kodmany 2018).

The improvement of controlled environment agriculture (CEA) is making hydroponics and aeroponics operationally and economically efficient. New technologies such as IoT, automation, AI, and LED lighting have transformed these methods to be more economical and resource saving (Kalantari et al., 2017; Kozai et al., 2021). Smart sensors allow for nutrient concentration, pH, and humidity, including other important parameters, to be monitored in real time and maintained to ensure plants grow optimally (Turner et al., 2020). In addition to these benefits, automated irrigation and climate control systems make it possible to reduce labour interventions while increasing the accuracy of nutrient application (Nandhini et al., 2019; Basu et al., 2021). Such inventions have made hydroponics and aeroponics adaptable systems capable of mitigating food insecurity challenges while minimizing the ecological footprint of the system and promoting sustainable agriculture.

Both hydroponic and aeroponic systems are highly effective in increasing the productivity of crops with maximum efficiency, especially for leafy greens, various herbs, root vegetables, and fruiting plants like tomatoes and peppers (Barbosa et al., 2015; Banerjee & Adenauer, 2014). According to Studies the nutrients that are delivered in the right amount and the conditions like temperature, humidity, and light are well controlled, that help in making farming easier. With the right ways, crops grown in greenhouses can yield 30-50% more than traditional farming methods. Similarly, the process of aeroponic cultivation further improves plant development because the oxygen increased in the root system region which allows effective nutrient absorption and increases the plant's immunity to pathogens (Otto et al., 2019; Patil & Singh, 2016). Compared to normal farming, these strategies consume substantially less water; hydroponics and aeroponics use 90% and 95% less water, respectively (Jones, 2016).

Even though hydroponic and aeroponic systems offer many benefits, they face obstacles to widespread use. These include high costs to set up reliance on steady power sources, and the need for know-how to manage the systems (Turner et al. 2020; Kozai et al. 2021). What's more, rules for soilless farming differ from place to place. Some organic certifiers haven't yet accepted these growing methods (FAO, 2017). To bring hydroponic and aeroponic systems into mainstream farming, we need to tackle these issues. This means putting money into research, backing policies, and teaching farmers (Tiwari et al. 2021).

This study attempts to analyze the development in technology and techniques for growing plants using hydroponics and aeroponics, its impacts on contemporary agriculture, and the problems that still exist. This study seeks to examine the soilless farming phenomena's 'pros' and 'cons' to hopefully contribute to the dialogue on sustainable food production and conservation efforts. The specific aim of the research is to analyze the feasibility of inducing conditions that would allow for the enabling of further development of hydroponic and aeroponic farming practices through its scalability, cost effectiveness, and worldwide accessibility to agricultural resources.

The Necessity of Soilless-Farming

The increasing global population rise is projected to increase from 7.2 billion in 2015 to 8.1 billion by 2025, with the further project of 9.6 billion by 2050. This has increased the demand to food and farming land. This challenge places a strain on conventional farming, which is already facing the challenge of insufficient and expensive farmland, soilless farming – especially Ponical-Culture – has provided an answer to these problems and proved to be a major technological change over the traditional methods of farming filed controls. Conventional agriculture has its drawbacks like sufficient labour, farming, which is expensive takes up to 15 hours to complete. The delay of agricultural output increases the time it takes to decompose organic material already created. Soil-borne diseases also occur, and affect not only crops, human beings too. In addition, traditional farming has problems caused by the excessive usage of pesticides that endanger human life and the environment. To overcome these problems, farming methods such as aeroponics which do not use soil farming creates a affordable option, especially in places like India, where things like water, soil, and sunlight are an important factor for economic growth.

A Soil-Less System

Hydroponics:

Hydroponics is the method of growing plants without the use of soil, as it incorporates a liquid nutrient solution instead (Fig. 1). In contrast to traditional farming, this technique allows plants to grow at an accelerated pace and generate greater yields. This is accomplished through ensuring the plants are supplied with the necessary mix of nutrients, water and oxygen. There exists a variety of methods of hydroponics, such as nutrient film technique, deep water culture and This method not only saves water but increases the plants' yield while protecting them from various diseases and pests, thus making hydroponics a sustainable agricultural solution.

Hydroponics makes it feasible to grow crops in regions where there is not only restricted land but is also suited to locations with poor soil, thus becoming an important tool. In metropolitan areas, vertical farming can greatly enhance space utility and make locally grown fresh vegetables available. Moreover, because of using closed systems, which recycle and reuse the water, hydroponic farmers minimize water use in comparison to traditional methods. Hydroponics technology holds huge potential for feeding the future population while addressing climate change, food scarcity, and limited resources in the best possible manner.

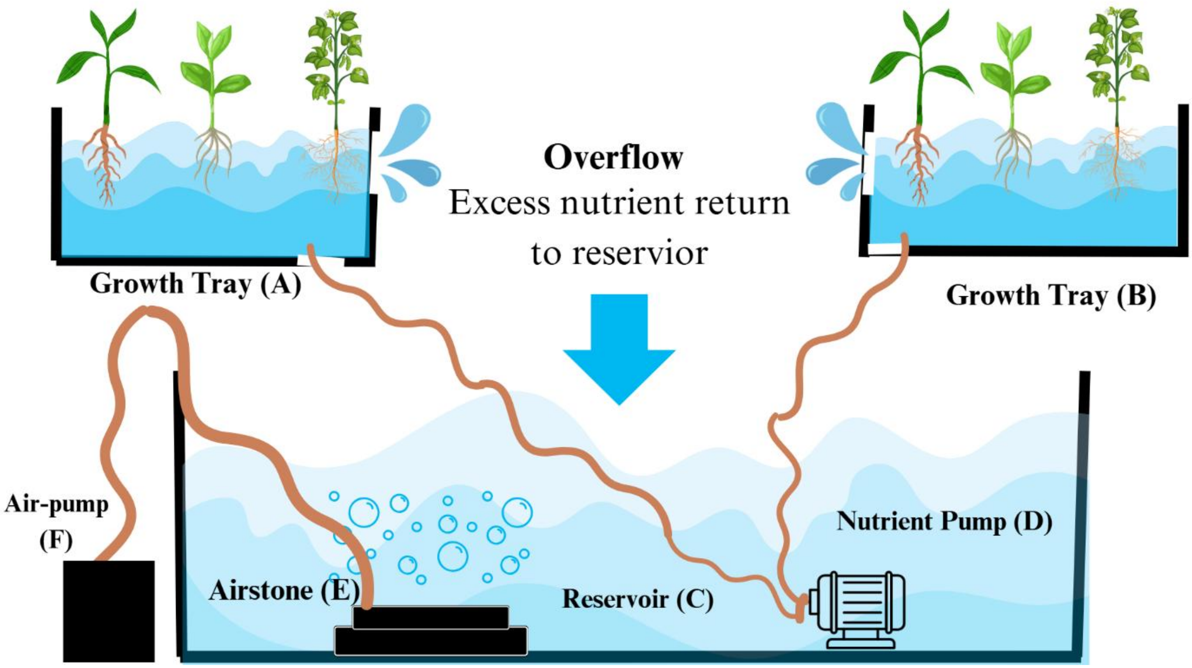

Fig.1 Regulation of general hydroponics system. It consists of a reservoir (C) that holds the nutrient solution, and a nutrient pump (D) that transports the solution to several growth trays (A and B). These trays which have plants growing in them have their nutrition sustaining roots submerged in the nutrient solution, which allows them to easily get the needed nutrients. Any remaining solution that is not used gets drained, and minimal amount is wasted because environmental conditions are controlled. To ensure there is sufficient oxygen in the water, an air pump (F) pushes air into an air stone (E) that releases bubbles into the reservoir, thus avoiding root hypoxia and ensuring healthy plant growth. The solution recirculated through the duct meets the plants requirement of nutrients, oxygen, and moisture. Such means of growing crops in a controlled space is water efficient and nutrient efficient.

Aeroponics:

Aeroponics is an advanced farming method that lets plants grow without soil or regular growing materials. It suspends plants in the air and sprays their roots now and then with a solution full of nutrients. This way gives roots more oxygen while making sure plants get the food and water they need to grow well. People know aeroponics to speed up plant growth and produce more crops, as roots that can get oxygen grow better. What's more, this approach saves a lot of water using up to 90% less than usual farming does. This makes it a green and earth-friendly choice for today's farming world. An aeroponic system is a setup that helps plants grow without soil. These setups have a space where plant roots hang , along with a sprayer that sends a nutrient mix straight to the roots at set times. By making a controlled setting, these systems let growers fine-tune things like moisture, heat, and food levels. This helps plants grow strong and healthy

Types of Ponical System

Deep Water Culture (Fig.2) systems use net pots to suspend plants above a tank filled with nutrient water solutions, immersing the roots directly into the solution, Roots are submersed in water that is constantly aerated by air pumps and air stones, which helps to prevent rot and enables plants to grow quickly. Waster intensive crops like lettuce, spinach, and basil grow particularly well with this approach. Its most important feature is its ease of use, and the fact that it requires little maintenance once set up. More recently, DWC systems have been improved upon. Aeration technologies like fine bubble diffusers and vortex aerators have enhanced oxygen delivery in the nutrient solution, allowing plants to grow even healthier (Marcelino et al., 2023). Furthermore, DWC systems have benefitted from automation in the supervision of oxygen, nutrients and water temperature control, giving ideal conditions without requiring much work. Urban agriculture has led to developments in vertical DWC systems for space constrained cities, increasing crop yield in limited space. One downside to DWC systems is the sensitivity of systems to temperature instability. Aids such lamps can be used but they impact the permanent quantity of oxygen in the water and potentially let the slowdown of development. Addressing these challenges let to improved system designs can further help in enhance the viability and scalability of Deep-Water Culture farming.

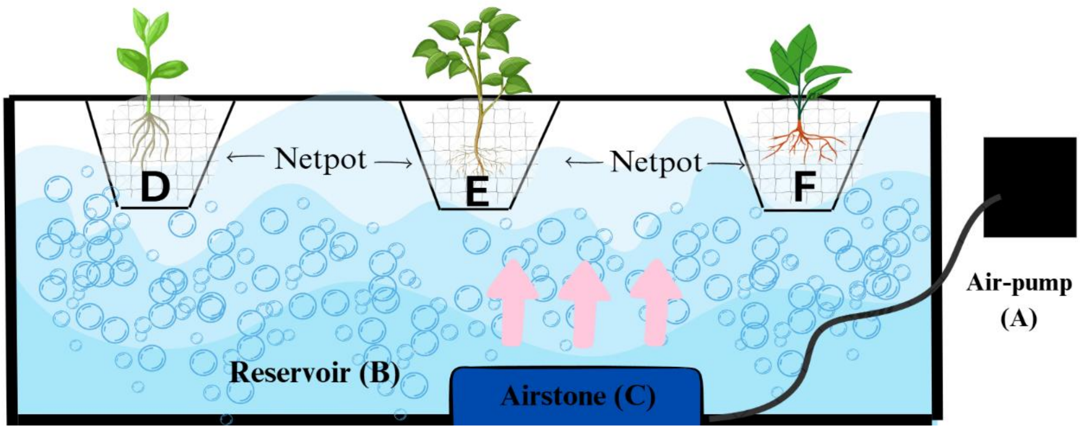

Fig.2 In this system, a plant's root is completely submerged in a reservoir (B) that contains a nutrient solution. The solution's nutrients are readily accessible to the plant. Net pots (D, E, F) act as the plan's support while simultaneously permitting root to the oxygenated solution. An airstone (C) supplies a continuous stream of oxygen bubbles, ensuring roots receive oxygen to prevent suffocation. An air pump (A) ensures that a constant stream of air to the airstone which enables the oxygenation of the solution. The combination of nutrient solution, proper aeration, and immersion of roots within the nutrient solution all enhance the effectiveness of the DWC system making it highly suitable for fast yielding crops such as leafy greens and other herbs.

The Nutrient Film Technique is an effective system of hydroponics growing that provides a continually running film of nutrient solution to the plants within sloped channels. NFT systems are versatile, simple, and highly water efficient because they recycle leftover nutrient solutions by reusing them. In addition, they also capture unused nutrient solutions to minimize waste. Because of this attribute, they are exceptionally well-suited for growing crops like lettuce, kale, and other greens. Innovations in NFT systems have increased their effectiveness and sustainability. Constructing channels using UV resistant food grade plastic has made NFT systems safer and more durable (Sharma et al. 2018). The invention of other advanced monitoring equipment like pH, electrical conductivity (EC) sensors, and flow rate of nutrients enabled managed precision nutrient dosing to achieve optimal plant health and maximum yield (Lakhiar et al. 2018). The modular scalability of NFT systems is another notable advancement, enabling them to be constructed into wicking bed structures for small family farms or large commercial farms. Furthermore, new research is more deviated on improving disease control by increasing levels of cations and solving flow issues that can lead the chances of root saturation and pathogenic growth (Jones, 2016). Despite its numerous profits, NFT does have certain limitations, Firstly in supporting larger plants with extensive root systems, as they require a thicker film of water than the system is designed to provide.

The Ebb and Flow system(fig.3)**,** also known as Flood and Drain system, is a type of Hydroponics that submerges the roots of the plant in a nutrient solution for a certain period, then drains the liquid back into a reservoir. This stepwise process allows the plant to receive nutrients while oxygen is supplied during the drain phase. This enhances the overall health of the root system. The system is adaptable to a variety of crops and can be used to grow leafy greens, strawberries, and tomatoes. One primary benefit is the media flexibility, where expanded clay pellets or coconut coir and even perlite, which help modulate moisture and nutrient retention, can be used. Simulating natural wet and dry cycles helps strengthen roots, which improves the resilience and growth rate of the plant. Newer technologies have perfected the Ebb and Flow System, improving its overall effectiveness and dependability.

The invention of smart controllers with accurate timers and sensors has further improved the accuracy of flood irrigation scheduling, thus saving on water and nutrients (Sharma et al., 2018). In addition, the new materials used in growing media, especially the lightweight and porous types, have further reduced root rot risk by enhancing ventilation and water flow. Another important development is in root zone monitoring sensors, which control moisture levels to ensure proper flooding cycles for optimally healthy plants (Resh, 2013). Nonetheless, there is an existing gap in the system where it is greatly beneficial, but also, if not properly managed, it could be harmful. This gap is when the nutrient solution is allowed to be in excess unchecked because its salinity increases to levels detrimental to crops' growth. Continuing to develop Ebb and Flow systems will undoubtedly further advance technological issues and augment nutrient management approaches. In so doing, the long-term sustainability of the technique will be achieved through considered and controlled hydroponic farming.

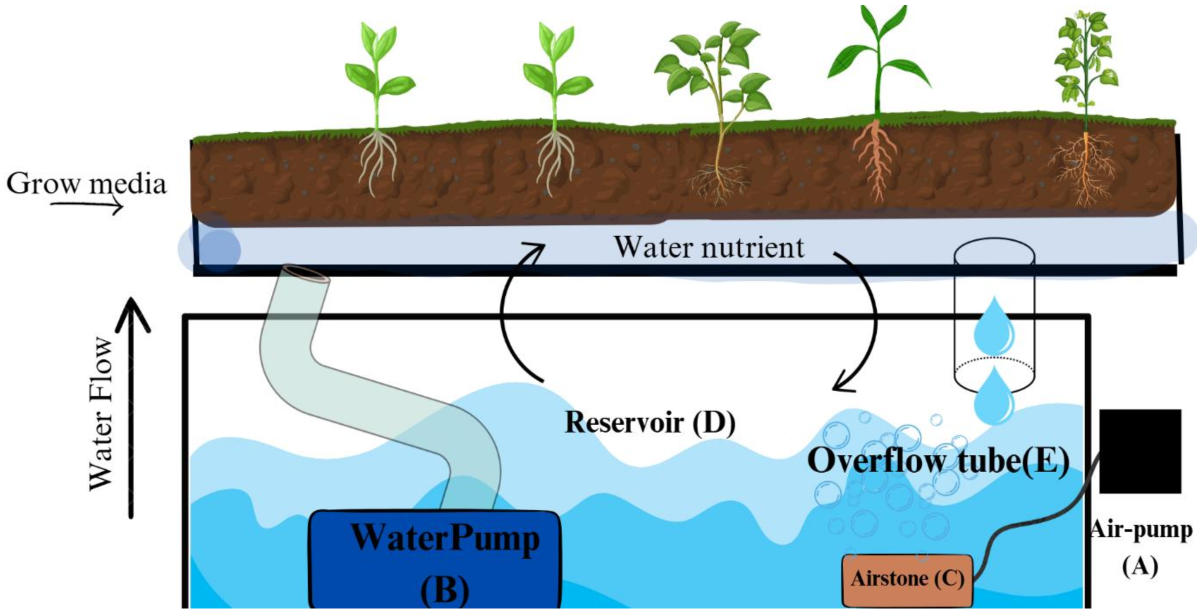

Fig.3 This graphic represented of Ebb and an Flow (also called Flood and Drain) hydroponic method. The plants are cultivated in a grow media and their roots are intermittently flooded with water containing nutrients from the reservoir (D). The water pump (B) moves the solution into the grow tray while air pump (A) provides oxygen to the airstone (C) for increased aeration. The excess water is drained through the overflow tube (E), thus ensuring the plants are well hydrated without the problems of overwatering the plants. In this continuous process healthy plant growth is achieved due to optimal nutrient and oxygen intake.

The Wick System represents (fig.4) a form of passive hydroponics which employs wicks made of nylon or cotton and they function to transport nutritious solution from a reservoir to the growing medium. This method is unique and does not require pumps or electricity, which makes it among the cheapest hydroponic systems. It is best suited for producing decorative herbaceous plants and novelty plants that drink very little water. The system is also quite straightforward to install and works with light growing materials like perlite and vermiculite, which hold water well. Recent advancements have improved Wick Systems by the incorporation of better wicking materials, which makes it possible for plants to receive nutrients consistently (Sharma et al, 2018). In addition to this, ordinary modern hydroponics combine wick systems with other agricultural practices for better efficiency and flexibility (Resh, 2013). Nonetheless, the Wick System is limited when it comes to high yield crops of plants that require much more water than is available passively wicks would provide. Pointing out the constraints through material development and hybrid system collaboration can further let the effectiveness enhancement of this low-maintenance and sustainable hydroponic method.

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            Plant in Growing Media   (Coco Coir, Perlite)

    ┌────────────────────┐
    |                    |
    |      🌱  🌱        |  <- Growing Tray
    |                    |
    └────────────────────┘

              ||
              ||  <- Wicks (Cotton/Nylon Rope)
              ||

    ┌────────────────────┐
    |      Nutrient      |
    |      Solution      |      <- Reservoir
    | (Water +  Nutrients) |
    └────────────────────┘
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Fig.4 Diagrammatic Representation of wick system

Drip Systems presents a leading-edge approach to irrigation that overcomes the need to perform human irrigation by customizing several tubes and emitters to automatically release nutrient solutions at the crop roots. As the system strives for optimal distribution of water and nutrients, it is perfectly suited for long-duration crops such as tomatoes, peppers, and cucumbers. The most significant benefit of the drip systems is its flexibility where crops, requiring different nutrient solutions, can be grown making it possible to tend released nutrient solution to specific plants for maximum output. This technique is also the most effective as it encourages reuse of excess nutrient solutions thus reducing wastage. Quite recently, there have been micro improvements in the automation and efficiency of these systems. One innovation is the automated scheduling integration for drip irrigation which allows for precision in the timing of nutrient dispensing which greatly reduces water consumption. It is now possible to target irrigation to lessen precision nutrient runoff pollution. The growing use of drip irrigation systems in areas with water shortages underscores its potential for efficient resource management coupled with high yields. Still, among the system's benefits, some challenges persist, such as the high price for installation and the potential of emitter clogging if the nutrient solution is inadequately filtered. Investing into advanced filtration systems and affordable technologies that address these issues will increase the effectiveness of Drip Systems in sustainable agriculture.

Aeroponic systems (fig.5), both low-end and high-end, have distinct qualities that enable soilless farming. low-end contain a root chamber with a submerged nutrient solution tank. These units employ pumps or ultrasonic transducers instead of sprinklers to supply nutrients. They work well for tabletop growing and to teach but might lead to dry roots and poor nutrient uptake. In contrast high-end use a high-pressure pump to turn water into mist making them suitable for high-value crops. These systems blend air and water filtering nutrient concentration, and pressurized watering to meet ideal grower needs. Commercial systems that enhance crop growth while cutting down on manual farm tasks combine cutting-edge tech with biological systems. Despite their effectiveness, these methods cost a lot and don't offer value without specific know-how. They also need manual operation. Scientists are working to find better ways to automate, cut energy use, and improve scalability.

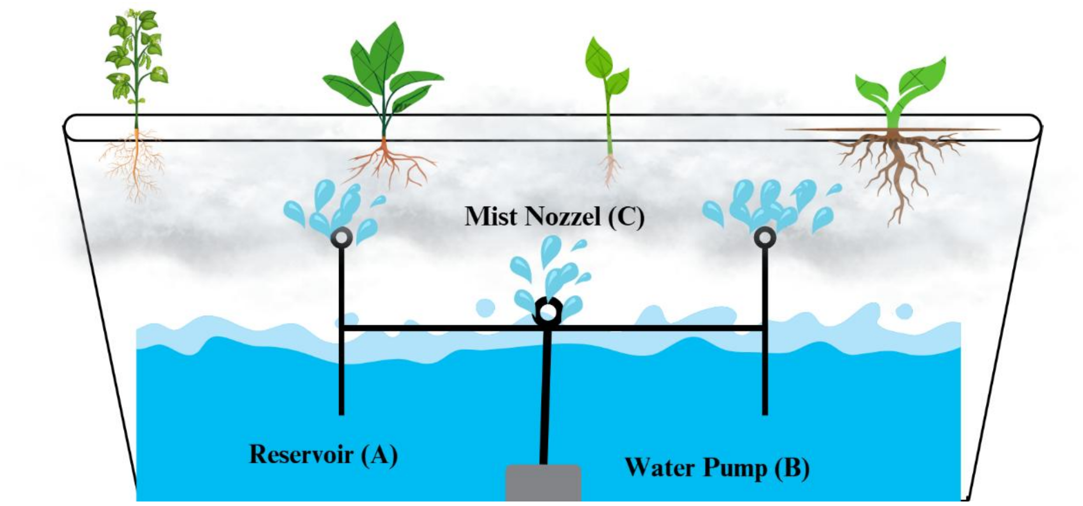

Fig.5 Shows a Aeroponics system that grows plants without soil by hanging roots in the air and spraying them with nutrient-rich water. This setup has a tank (A) to hold the nutrient mix, a pump (B) to move the liquid, and spray nozzles (C) to mist the roots. This method let plants get as much as possible nutrients and also help in grow faster, use low amount of water that make it an effective and eco-friendly way to grow plants. Where High-Pressure system uses special nozzles and highly pressurized pump to create tiny droplets for roots to absorb more oxygen and more relted growth of expensive and bigger crops. In contrast, the low-pressure system makes bigger drops, which makes it easier to set up and cheaper to run.

Nutrient Constituent and Components of System

Aeroponics System

Several parts of the aeroponics system are vital to the healthy growth of plants. The growing chambers is the most important component. Here, the roots dangle in a nutrient-rich mist. To prevent algae growth and regulate humidity and temperature, the compartment remains dark. People often make it from plastic or aluminium, so it lasts longer when wet (Raviteja et al. 2024; Lakhiar et al. 2024). The plant support system holds the plants in place while letting their roots touch the mist. Things like stem foam collars or net pots help support the plants too. These are good because they bend, stay clean, and don't make the plants dirty . The nutrient tank holds and gives out the important nutrient mix. To keep the water good, the EC should be ≤ 1 mS/cm and the pH should be between 5.5 and 6.5. Also, using stuff that doesn't rust will make the system last longer and keep things pure. Nutrients are supplied through specific nozzles including mechanical atomizers and ultrasonic forgers. Ultrasonic forgers are more beneficial since they create finer droplets which improve nutrient absorption. The controller for misting cycles defines misting periods that allow for maximum efficiency and energy conservation. Misting in between intervals (1-2 minutes on and 5 minutes off) saves energy but continuous misting provides better delivery of nutrients even though it is more power intensive. The framework and stand provide balance and support to the system's parts. Because frames made of wood are cheap, they can get damaged easily, but they do provide a water-resistant option. Aluminium and plastic frames are preferred because they are water resistant and durable. Effective filtration measures eliminate the chances of contamination Last but not least, greenhouses as well as plant tissue culture laboratories are also very important in the development of aeroponic agriculture. In vitro plants, tuber sprouts, and rooted cuttings are the best performing materials, provided they go through the required acclimatization procedures prior to placement. The maintenance of a clean greenhouse environment is a prerequisite for infection control and safeguarding the wellbeing of the plants (Raviteja et al., 2024). These factors together help to develop the practicality and phenomenon nature of the aeroponic system of farming.

Hydroponics System

Every hydroponic system has these basic ingredients that provide the ideal conditions for plants to grow and use resources efficiently. The growing space can be as small as all in one room or as large as a commercial greenhouse explicitly used for growing plants. Considerations of the system selected must match with what the plant needs and the available space. Nutrient solution grows the plants within growing trays or channels, and these containers are designed so that the solution flows to the roots as well as allowing for proper drainage. The nutrient solution contains all sustenance required for the plant and by monitoring the concentration levels periodically, the solution can be modified to the optimal ratio (Lakhiar et al., 2020). Effective nutrient delivery is ensured by a water pump that transfers the solution from the reservoir to the plants' roots. Therefore, if the pump is not sized adequately the effectiveness of the system will suffer (Sharat, 2022). Grow lights help with photosynthesis in case there is a deficit of natural light. These lights can be LED, fluorescent or HID lights which all have varying benefits energy wise. Nutrient absorption depends on the acidity and the alkalinity of the solution which is checked by a pH meter. pH meters must be washed, dried and adjusted frequently so that the readings are always correct (Lakhiar et al., 2020). According to a source, water mix enriches oxygen with the help of a pump and air stone, which also aid in the prevention of rot. This is particularly handy for the deep-water culture systems (Raviteja et al., 2024). Rockwool, coco coir, perlite, and clay pellets enhance the hydroponics, helping in the growth of the plants while storing water and nutrients. They serve various purposes, offering structural integrity in the form of a growing medium. The final component of the setup is the control over the environment through a fan, heater, humidifier, and CO2 generator, which enhances plant growth while preventing various ailments (Sharat, 2022). These form the basis of the high-efficiency culture of plants in hydroponics, which ensure control of the growth.

Crops Under both Ponical System

The production of crops through hydroponics and aeroponics have changed dramatically by increasing the control over nutrient intake and the operating environment leading to dramatically improved results compared to traditional farming. Scientists have shown that the growth of some vegetables, like lettuce, is exemplary in a hydroponic setting because the nutrients and growing conditions can be precisely controlled (Chaganti et al., 2021). Further studies regarding lettuce, spinach, and kale cultivated through hydroponics have shown that increasing yields are possible by magnetized water due to more efficient nutrient absorption and plant growth (Castillo et al., 2022). These leafy vegetables need high nitrogen for strong leaf development, moderate phosphorus and potassium, and micronutrients such as calcium, magnesium, iron, and zinc. For best results, electrical conductivity in the range of 1.2-1.8 mS/cm and pH of 5.5-6.5 should be maintained. Aeroponic systems have also great results with growing leafy vegetables and herbs, by using precise control on nutrients their yield and quality is significantly improved (Wright et al., 2020) Hydroponics and aeroponics are also being utilized for carrots, radishes, and beets. New methods, such as the cultivation of radishes using plasma-activated water, have been shown to increase growth rates drastically by enhancing root length and weight. These crops are best suited for regions with a balanced nutrient profile.

The nitrogen levels should be moderate, while adequate phosphorus for root development and potassium for disease resistance enhances the overall quality of the plant. Micronutrients also play a vital role, with boron increasing cell wall strength and calcium aiding in root development. These crops ideally grow with an EC range of 1.0-2.0 mS/cm and a pH of 5.8-6.5. Over the years, it has further been shown that tomatoes, brinjal, and capsicum bear fruits best in hydroponic systems than in soilbased systems, which emphasizes the premise of these studies that hydroponic systems are more efficient than traditional agricultural practices. Ahmed et al., 2019.

The use of aeroponic systems in agriculture has proven beneficial for the cultivation of fruiting vegetables like tomatoes, peppers, and cucumbers, as they can guarantee precise control of the environment that facilitates nutrient absorption, promotes growth, and increases yield (Hort et al., 2021). The crops also have moderate nutrition nitrogen needs, having higher concentration in the vegetation phase and a reduction in flowering phase, and are supplemented with high phosphorus and potassium to encourage flowering and fruiting. Rest of the key micronutrients calcium and magnesium also aid in preventing blossom-end rot, chlorophyll production, and magnesium. The optimal EC range for the fruiting vegetables grown in the aeroponic systems is 2.0-3.5 mS/cm while pH 5.5-6.5 is the optimal range for the healthy growth. In addition, the growing of high value and medicinal plant also benefits from the adoption of aeroponic technology, as it allows easier cultivation under sterile and controlled conditions. This ensures the purity and quality of medicinal crops which pharmaceutical and herbal industries highly need. Hydroponics and aeroponics systems greatly improve resource use efficiency, increasing productivity (Table1) while using more sustainable approaches, and transforming agriculture, more than ever, needing efficiency and sustainability for food production. This also improves the nutrient availability in the crop more efficiently than orthodox farming (Table1).

Table 1: Nutrient requirements with varieties of the crops under hydroponics conditions

Nutrient	**Leafy Greens**	**Fruiting Crops**	**Root Crops**	**Herbs**	**Sources**

Nitrogen (N)	120–180 ppm	100–160 ppm	80–120 ppm	100–140 ppm	Resh (2013); Sonneveld & Straver (1994); Srivastava et al. (2020)
Phosphorus (P)	30–50 ppm	40–60 ppm	50–80 ppm	30–50 ppm	FAO (2017); Srivastava et al. (2023); Kozai et al. (2021)
Potassium (K)	100–180 ppm	200–250 ppm	150–200 ppm	100–160 ppm	Jones (2016); Kalantari et al. (2017); Lakhiar et al. (2020)
Calcium (Ca)	150–200 ppm	150–250 ppm	100–200 ppm	120–180 ppm	Barbosa et al. (2015); Mizushima & Nakamura (2024); Jones & Smith (2022)
Magnesium (Mg)	30–50 ppm	40–60 ppm	30–50 ppm	30–50 ppm	Banerjee & Adenaeuer (2014); Castillo et al. (2022); Chaganti et al. (2021)
Iron (Fe)	2–5 ppm	2–5 ppm	2–4 ppm	2–5 ppm	Tiwari et al. (2021); Kozai et al. (2021); Grand View Research (2024)

Recent Growth in Ponical System

Use of Misting Technology with Sensors and Industry 4.0

The latest development of aeroponic systems incorporated the use of sensors that can monitor and manage temperature, humidity, as well as lighting levels, thus improving the precision of plants growing (Garzón et al., 2023). The application of IoT and data science further transformed aeroponics by making it possible to automate nutrient delivery, constantly check on the plant condition, and reduce the need for human intervention, which increased sustainability and efficiency of resource utilization (Narasegowda & Kumar, 2022). Improvements in plant misting systems have also been important in reforming the nutrient distribution pattern by eliminating oxygen pockets to nutrient assimilation at the root base without water and nutrients plant supplying being compromised (Narasegowda & Kumar, 2022). Also, the evolution of aeroponics technology made it possible to develop multilayered vertical farming, which increases productivity in urban areas that do not have much space available.In addition, Aeroponics are increasingly being adopted within experimental research, helping with the whole plant transpiration analyses, water absorption, and nutrient utilization efficiency which is constantly improving sustainable farming techniques.

Bayesian Network Construction

Ferentinos and Albright conducted research on monitoring key physical parameters in hydroponics, such as pH, water level, and electrical conductivity, for constructing a Bayesian network. This network facilitated system performance assessment and control, providing a graphical user interface (GUI) to display sensor data. The Bayesian Belief Network (BBN) was implemented in a hydroponic system utilizing water reuse, making it a cost-effective approach. This method offers a structured yet comprehensive overview of hydroponics, enhancing efficiency and sustainability (Srivastava et al., 2023).

Artificial Neural Network (ANN)

ANN is a machine learning model that mimics the human brain to process complex data and make intelligent decisions. In soilless farming system, ANN helps in monitoring, predicting, and optimizing plant growth conditions by analysing multiple environmental factors. ANN have proven valuable in predicting key hydroponic parameters such as pH and electrical conductivity. Utilizing input variables like light intensity, plant age, and electrical conductivity, feed-forward neural networks have been developed to generate precise outputs, enabling enhanced automation and efficiency in hydroponic systems (Srivastava et al., 2023). The incorporation of IoT allows hydroponic food production systems to centralize growth and monitoring processes within a secure cloud environment, offering significant advantages. IoT-based cloud monitoring frameworks help reduce maintenance costs, a major challenge in automation. Additionally, supervised machine learning algorithms enhance the performance assessment of smart hydroponic systems for improved management. Further advancements can be achieved by integrating data analytics and machine learning to develop predictive algorithms, deploying additional sensors for enhanced accuracy, and refining AI-driven decision-making processes.

Renewable Energy Utilization:

Integrating the thought of renewable energies like solar and wind into the idea of aeroponic farming systems greatly will help in decreases energy consumption and enhances sustainability. Electricity is must needed energy in conventional farming systems to operate tools like nutrient misters, monitor devices, and climate control systems. Alternative sources will allow farmers moving towards that option will let yo reducing reliance on power grids, which would make farming more self-sufficient and cost-effective. Wind turbines, in addition to solar panels, would provide constant energy during the day and further resources at night. This allows for a constant and reliable energy source to be used for aeroponic systems.

Using cleaner energy sources is not only beneficial economically, but aids in the overall decrease of the environmental impacts that arise from farming. Solar and wind energy is a cleaner alternative to fossil fuels which are commonly burned to generate electricity. By decreasing the reliance on fossil fuels, greenhouse gas emissions become reduced, alongside the overall carbon footprint. This change fosters sustainable agriculture by practicing environmentally friendly techniques while working to combat climate change. In the future, the integration of renewable resources in aeroponic farming is supposed to continue improving the efficacy and environmental friendliness, and as such aiding in faster responsive agriculture (Kumar & Das, 2020).

Closed-Loop Irrigation Systems:

Adoption of closed-loop irrigation technology has enhanced resource use by reducing both the volume and concentration of nutrients needed. This system recycles used nutrient solutions, leading to a reduction in costs and waste (Fernandez et al., 2019).

Modern Aeroponic setups have Controlled Environment Agriculture (CEA) that features proprietary fully controlled environments with precision controls. These include advanced custom lighting arrays, Automated nutrient delivery systems alongside specialized HVAC designs, all contributing to enhanced plant performance (Wang & Zhao, 2022).

Technological Enhancement of LEDs

The use of LEDs has considerably changed the use of lights in hydroponic systems. As compared to other forms of lighting, LEDs have a range of advantages over traditional lights. They are more energy-efficient, last longer, and most importantly are able to emit tailored light specific wavelengths for optimal plant growth (Anderson & Lee, 2008). Recent advancements in the LED technology allow the systems to be programmed with high accuracy, controlling light intensity and the types of light emitted to suit the needs of different crops at various stages of their growth. Increased efficiency of photosynthesis and accelerated growth rates of the plants are achieved when these factors are met (Johnson & Clark, 2015).

Pros of Ponical System

The system combines hydroponics and aeroponics in such a way that water and nutrients are used effectively while helping in the sustainable agriculture. This system uses a self-misting feature to further promote growth of plants owing to the significantly greater availability of oxygen to the roots. The misting increases the oxygen diffusion rate to more than 30% compared to all other methods of farming that utilize soil In addition, the absence of soil permits greater efficiency in space utilization which makes it perfect for gardening in the city, on rooftops, and for vertical farming consequently increasing the output for every unit of land. Another primary benefit water saving. The repetitive use of nutrient solutions manages to save water by over 90% in comparison to ordinary farming techniques, which makes it easy on the environment. Apart from its effectiveness, ponical farming eliminates soil pathogens and pests and consequently comes with the advantage of enhanced crop health. This system is also adaptable to extreme conditions for successful farming in desert, urban areas, and even space research activities that cannot use soil-based agriculture. Furthermore, better regulation of nutrient concentration, pH, temperature and humidity created ideal conditions for growth which helped ensure high plant health and productivity (Trivedi et al., 2024). Large scale ponical farming also incorporates automation which helps reduce manpower needed, thereby cutting costs and increasing efficiency. Moreover, crops derived through hydroponic and aeroponic farming methods are surpassing soil grown crops in nutrient density versus soil grown crops, specifically for vitamins and minerals, which proves that this farming method works best

Cons of Ponical System

Even though the Ponical systems has its merits, it has a few obstacles that can inhibit its further usage. One of the significant drawbacks is the high initial investment that needs to be put down on the specialized equipment like misting systems, sensors, and controlled environments, making it very difficult for a lot of farmers to adapt it. Moreover, reliance in tech alone has its drawbacks since the system is built around electricity, pumps and sensors, which can be turned off during outages or technical problems, deleteriously impacting plant cultivation. Farmers also have problems with supervision and maintenance because misting periods, pH, and electric conductivity (EC) levels along with the oxygen supply have to be constantly managed which is an extremely sophisticated skill set that many traditional farmers simply do not have. Drying root is one example of risky aeroponic systems failure where any breakdown in the misting system would desiccate the plants roots in a matter of minutes leading to a total crop failure in a few hours (Trivedi et al., 2024). In addition, closed-loop nutrient systems are prone to microbial contamination, which, if uncontrolled, permit the development of bacteria, algae, and fungi, endangering the plants if proper procedures are not followed. Ponical farming is best suited for herb and leafy vegetable production as it is highly effective for such crops, but staples like potatoes, carrots, and wheat are more challenging to grow because these crops need some level of modification to succeed. If the solution is not handle carefully that led to imbalance of nutrient, which led to another possibility of either increase toxic amounts or deficient of nutrients being supplied causes negatively impact the quality and yields of the crops Even so, the operational costs remain high because the constant expense of the pumps, lights, climate control systems, and nutrients supplementation is economically burdensome for some growers. An additional constraint is the absence of organic certification as some authorities do not recognize soilless cultivation as organic, which limits market opportunities for produce grown using Ponical practices. Furthermore, moving Ponical farming from a subsistence to a larger scale commercial activity entails a considerable number of resources and infrastructures which some farmers might not afford. These gaps could be resolved through the introduction of new technological tools, accompanied by supportive measures, and training to implement agri policies that enhance the scope of Ponical farming internationally.

The Opportunities and Risks Associated with the Commercialization of Hydroponic and Aeroponic Systems

In 2023, the hydroponics market was estimated to be worth \$5 billion worldwide. As a result, it was predicted to expand from \$5.25 billion to \$6.75 billion, reaching \$10.98 billion by 2030. From 2024 to 2030, this illustrates the 12.4% yearly growth (Patel et al. 2023) Grand View Research. The hydroponics market in the United States was estimated to be worth \$506.25 million in 2023 and is projected to grow by 10.7% year throughout this period, this industry is the result of improved automation, LED lighting, and environmental control techniques. These enhancements help crops grow more and use resources more effectively. Also, more urban and vertical farming has made it possible to grow food all year. This cuts down on transport costs and helps the environment but hydroponic farming still has some problems. It costs a lot to start, needs special know-how, and requires careful management. These issues make it hard for small farmers to get involved (Trivedi et al. 2024). Likewise, the aeroponics market was esteemed at \$1.1 billion of every 2023 and is supposed to develop at a CAGR of more than 15% somewhere in the range of 2024 and 2032 (Gupta and Kumar, 2023; Statistical surveying Future, 2024). In North America, expanding reception of manageable rural practices and high-level cultivating advances has essentially added to showcase development (Ghosh et al., 2020). Aeroponics is especially compelling in preserving assets, utilizing 90% less water than conventional soil-based cultivating (Jones,R. and Smith, 2022). The framework likewise empowers quicker plant development because of improved oxygenation and exact supplement conveyance, prompting better returns (Gupta and Kumar, 2023). Be that as it may, fruitful aeroponic cultivating requires talented administrators for exact control and observing, making it trying for undeveloped clients. Furthermore, the high starting arrangement costs related with trend setting innovation reception stay a huge obstruction contrasted with regular cultivating techniques). Notwithstanding these difficulties, the fast headways in innovation and expanding center around feasible agribusiness are supposed to drive proceeded with development in both aquaculture and aeroponics markets before long.

Conclusion

Soilless farming methods like hydroponics and aeroponics show great potential to tackle the issues and intricacies of today's farming. These approaches work well in city areas, places that need watering, and spots with environmental limits. They lead to bigger harvests better use of resources, and crops that can fight off soil-based illnesses more What's more, these cutting-edge ways of giving plants nutrients would help save water and control how plants grow making our food supply more secure.

More importantly, there is a dire need to reduce the environmental footprint of conventional farming practices. The efficiency, scalability, and commercial adoption of these systems has come a long way with the use of technology focusing on IoT based automation and AI monitoring. The integration of renewable energy sources alongside smart sensors and climate-controlled environments are incredible for boosting performance. That said, there is still an issue of high dependency on technology together with initial high costs and the need for technical skill. Investing in accessible strategies for farmers, in addition to policy support, is a step that needs to be highlighted. To wrap up ponical farming looks like a hopeful answer to future farming needs giving us ways to grow food that last and break new ground compared to old-school methods. These systems can feed more people worldwide and save our planet's resources by using new tech and making current approaches better. To make the most of this idea, we need more studies teamwork between different industries, and new rules to help lots of farmers use it and keep growing food for years to come.

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Declaration

Ethics approval and consent to Participate Before proceeding with the study, necessary clearance was taken from The Head of the Department of Amity Institute of Organic Agriculture to facilitate research concerning the Aeroponic & Hydroponics and their advance technique in the field of agriculture and no licence/permission is required to collect study material for research purposes.

Consent for Publication We hereby declares that this manuscript does not contain any material that has been submitted for the award of any degree or diploma at any university. To the best of our knowledge, the manuscript does not include any content previously published or authored by others, except where proper citation is provided. All authors have given their approval for the submission of this manuscript to the journal.

Conflict of Interest

The authors declare no conflicts of interest relevant to this article.

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