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## Medicinal and aromatic plants under hydroponic systems: A comprehensive review

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### Abstract

Plants used for medicine include Ashwagandha, Basil, and Stevia have a significant part to play within the global health system as well as being a critical part of India's traditional forms of medicine and the growing market for herbal products. Unfortunately, these crops usually require soil-based cultivation traditionally, however, many challenges arise from soil-based production including environmental variability, soil degradation, risk of contamination, and inconsistent composition from a phytochemical perspective which makes them difficult to standardize for pharmaceutical purposes. Hydroponic culture which forms an integral part of controlled environment agriculture offers an attractive alternative due to the ability to precisely manage nutrients, water and a variety of environmental factors. This review evaluates the potential of hydroponic systems for growing these three economically valuable medicinal plants with particular emphasis on production conditions in India. The paper evaluates types of hydroponic systems, growth performance, enhancement of secondary metabolites, nutrient management, control of environmental conditions, sustainability, and the economics of hydroponic production of these three economically valuable crops. Hydroponic production methods can result in increased biomass yields up to 20 to 50%, greater consistency in phytochemical compositions, and reductions of water use of up to 90% when compared with traditional production methods. Advanced technologies, such as Internet of Things (IOT) and Artificial Intelligence (AI), help to improve the efficiency and productivity of an agricultural system as well. Although there are challenges like high initial investment and technical complexities, hydroponics provides excellent opportunities to produce high-value medicinal plants in urban areas and in areas limited by resources due to population density, etc. Hydroponics has the potential to provide a sustainable and climate-resilient solution for meeting the increasing demand for standardized herbal products in both India and worldwide markets.

**Keywords:** Hydroponics, medicinal plants, aromatic plants and secondary metabolites

### 1. Introduction

Medicinal and aromatic plants play a fundamental role in medicine, nutraceuticals, and industries worldwide. They are the foundation of many traditional medicine systems including Ayurveda, Unani, and Siddha. India is known as the "botanical garden of the world" due to the immense diversity of its medicinal plant species that contribute to the global herbal market. While there are many important medicinal plant species, three of the most important medicinal plant species include Ashwagandha, Basil, and Stevia, due to their pharmacological properties and the increased levels of global demand for these species. Ashwagandha is well known as an adaptogen and immunomodulator; Basil is known for its essential oils and antimicrobial properties; Stevia has become a natural, non-caloric sweetener in both food and pharmaceutical industries. The Indian herbal industry is valued at over USD 10 billion and is estimated to grow rapidly due to increased global demand for plant based medicines and wellness products <sup>[1, 2, 25]</sup>. Even though the growing of medicinal plants is very important, conventional soil-grown agricultural systems for the production of these plants face many limitations. The variation in the environment (temperature, amount and timing of rain, and fertility of the soil) causes varying amounts of growth and variability of the amount of bioactive compound(s) produced by medicinal plants from year to year. In addition to the environmental variability, heavy metal contamination of the soil and pesticide residue in the soil creates a serious safety and quality issue for medicinal plant products, especially for export markets where stringent quality assurance

requirements are imposed [3,9]. Furthermore, the degradation of land and declining health of soils across India are significantly impacting sustainable production [25, 30].

Hydroponics refers to the growing of plants using a nutrient-rich medium without using soil (as is traditionally used) and provides an alternative means of addressing the limitations of conventional farming. It provides total control of nutrients (type and amount), pH, temperature, and lighting; thus, it provides uniform growth of plants and produces consistent amounts of phyto-molecules (the plant chemicals produced in the plant tissues) [4, 12]. Given the rapid growth of urban centres in India, the limited availability of water, and increasing effects of climate change on agricultural productivity, hydroponics can be incorporated into urban and peri-urban settings with the ability to grow high-value crops throughout the year in limited areas of land [10, 24].

There is an increase in technological advancements in controlled environmental agriculture (CEA) including but not limited to sensor-based monitoring systems, IoT technologies and Artificial Intelligence. All these advancements have resulted in improvements in efficiency and scalability of hydroponics. These technologies allow for monitoring and optimizing plant growth conditions and therefore result in increased productivity and resource use efficiency in hydroponic systems [8, 14]. For these reasons, hydroponic systems are being recognized more widely as a sustainable, climate resilient option for the cultivation of medicinal plants.

## 2. Hydroponic Systems and Their Applications

Hydroponics is a groundbreaking way to grow crops without soil, relying instead on nutrient-filled water, to help plants develop. Hydroponic systems can be divided in two basic categories: liquid and substrate systems; each of which has many different advantages based on the plant's shape and growth physiology [4, 13]. Hydroponic systems that use liquid solutions work well for plants with shallow and fibrous roots; examples of these types of plants include Basil and Stevia. Two examples of effective liquid hydroponic systems used for such plants are

Nutrient Film Technique (NFT) and Deep Water Culture (DWC). In NFT systems, the plant roots remain in contact with a thin layer of continuously flowing nutrient water, which gives them a consistent supply of water, nutrients, and oxygen, all of which allow, in turn, for rapid plant growth [5, 17].

Deep Water Culture systems use an oxygenated nutrient solution that keeps the roots of the plant submerged to give them consistent food and increased Oxygenation levels. Deep Water Culture is a perfect way to grow Stevia because it gives you consistent leaves and more steviol glycosides (the sweetener in Stevia) accumulates [29]. Growing Ashwagandha is more difficult because its taproot requires structural support and sufficient room for its root system. Therefore, cocopeat, perlite or vermiculite are better ways to grow Ashwagandha since they provide structure and have good aeration and supply of nutrients to Ashwagandha [6, 28].

Aeroponic gardening is a method of growing that uses an advanced form of hydroponic gardening. In aeroponic systems, the roots of plants are suspended in mid-air and a nutrient solution is delivered via a fine mist. As a result, the oxygen supply is maximized, and the plants have the opportunity to absorb more nutrients, thus allowing the roots to develop better and produce more metabolites [17, 21]. While research into aeroponics for ashwagandha is still ongoing, it appears promising for increasing both root biomass and withanolide content.

In India, there has been a rapid increase in the adoption of hydroponic systems because of their ability to overcome the limitations of land and water shortages. Hydroponics is becoming more popular in various Indian states, including Maharashtra, Karnataka and Punjab, partially due to government assistance as well as private investment in the form of capital. One of the main advantages of using closed hydroponic systems, which recycle the nutrient solution, is that they minimize the amount of water used and the amount of nutrient solution wasted, making them an option for sustainable agriculture [4, 10, 24].

**Table 1:** Comparison of Major Hydroponic Systems for MAP Cultivation

| System     | Working Principle                   | Advantages             | Limitations           | Suitable Crops |
|------------|-------------------------------------|------------------------|-----------------------|----------------|
| NFT        | Thin nutrient film flows over roots | Efficient nutrient use | Sensitive to failure  | Basil, Mint    |
| DWC        | Roots submerged in solution         | Simple, rapid growth   | Oxygen control needed | Tulsi          |
| Aeroponics | Nutrient mist applied               | High efficiency        | Expensive             | Stevia         |
| Drip       | Nutrients via drip                  | Scalable               | Substrate needed      | Lavender       |
| Ebb & Flow | Periodic flooding                   | Good aeration          | Complex setup         | Aloe vera      |

## 3. Growth Performance of Medicinal and Aromatic Plants

Due to their ability to precisely control environmental and nutritional variables, Hydroponic Systems significantly increase the growth performance of all types of medicinal plants. For economically important crops such as Basil, Stevia and Ashwagandha, hydroponic systems provide the ideal conditions for the production of greater biomass, enhanced physiological efficiency and increased yield when compared to traditional soil-based production systems [5, 14].

Basil is one of the most responsive crops to hydroponic production systems, with previous research showing that hydroponic basil can produce 40-50 percent more biomass compared to soil-based basil. Factors contributing to the increase in biomass production are improved nutrient absorption and increased photosynthetic efficiency. The controlled environment of a hydroponic system also helps to reduce stress factors such as drought and nutrient deficiencies, resulting in healthy plants

with increased leaf area and increases in essential oil yields [7, 17]. The growth and yield of stevia have also been significantly improved by hydroponic production systems. The highly precise regulation of nutrient compositions and environmental variables result in homogeneous stevia plants and increased amounts of steviol glycosides (which are responsible for the sweetness of stevia) [29].

Even though there hasn't been much research conducted with regard to the hydroponic growing of ashwagandha, the results indicate that hydroponic methods are successful. Since ashwagandha has roots that are very valuable for medicinal purposes, it is essential to optimize root growth. Using either an aeroponic or substrate-based system has increased root biomass and also resulted in better yields of withanolides. Hydroponic methods also avoid the problems that soil can cause (compaction, nutrient imbalance, and pathogens) in reference to the health and productivity of the plants [6, 28].

In addition to producing biomass, hydroponic systems have been shown to positively influence physiologic parameters such as chlorophyll concentration, photosynthetic rate, and water-use efficiency. The improvements result from the ability to control the environmental conditions (light intensity, temperature, humidity) accurately. Because of this, compared to other growing methods, hydroponically produced medicinal plants have better growth performance and consistency of quality, making them better suited for commercial and pharmaceutical uses [8, 14].

**Table 2:** Growth Response of Selected MAPs under Hydroponics

| Plant Species | Parameter Improved | Observed Effect      |
|---------------|--------------------|----------------------|
| Tulsi         | Biomass            | Increased leaf yield |
| Mint          | Oil content        | Higher menthol       |
| Stevia        | Sweet compounds    | More stevioside      |
| Aloe vera     | Gel quality        | Improved purity      |
| Ashwagandha   | Root compounds     | Enhanced metabolites |

#### 4. Secondary Metabolite Production

Secondary metabolites are the primary factors that determine the commercial and medicinal value of plant species. For example, the three most valuable high-value crops are Ashwagandha, Basil, and Stevia. These compounds, primarily made up of secondary metabolites, also include alkaloids, terpenoids, phenolics, and glycosides. They are produced through plant stress responses and are highly sensitive to changes in their environment, as well as physiological conditions. When using conventional agricultural methods, changes in temperature, soil nutrients, or water availability cause metabolite profiles to be inconsistent. This inconsistency will affect the quality and effectiveness of medicinal plant products. A major advantage of hydroponic systems is that the environment in which the plants grow can be controlled and the availability of nutrients can be easily manipulated; this results in consistently high-yielding secondary metabolites.

An example of how hydroponic systems produce promising results for the growth of secondary metabolites is ashwagandha. The primary bioactive secondary metabolites in ashwagandha are withanolides, which are known for their anti-inflammatory properties, stress-relieving properties, and effects on the immune system. Research has demonstrated that growing ashwagandha in a hydroponic system with a controlled amount of nitrogen provides more withanolides than growing ashwagandha in soil [12, 15]. Basil is another excellent example of a secondary metabolite-producing high-value crop. Basil's primary secondary metabolites are its essential oils, which include eugenol, linalool, and methyl chavicol, used in the pharmaceutical, cosmetic, and food industries. Hydroponic methods have been shown to produce up to 25% more of the essential oils found in basil compared to growing basil in soil, which is a trend seen across multiple studies [7, 17].

By producing steviol glycosides, stevia is recognized for its sweetening qualities as an all-natural, non-caloric sweetener; likewise, hydroponically grown stevia will contain a higher concentration of steviol glycosides than traditional (soil) grown stevia, as the amount of steviol glycosides that can be produced from stevia is directly influenced by the availability of nutrients and the environmental conditions under which it was grown. Hydroponic systems allow the grower to control the environment (nutrition, pH, temperature) precisely, resulting in the production of more steviol glycosides and providing greater quality of sweetness [29]. The use of elicitors (salinity stress, UV light, and beneficial microorganisms) to stimulate the production

of additional secondary metabolites in hydroponic systems can also occur [21].

Standardization of metabolite production is another important benefit of hydroponic cultivation and is essential in the pharmaceutical industries. Uniformity in environmental conditions enhances the synthesis of bioactive compounds uniformly, thus reducing variability in the product and enhancing product quality. This is especially important when producing products for export markets where there are strict quality control requirements.

With the rapid growth of the medicinal plant industry in India, an opportunity exists in adopting hydroponic systems for the production of secondary metabolites. Research institutions and universities are focusing their energies on the development of hydroponic protocols to grow those medicinal plants that will exhibit the greatest therapeutic potential. As a result, hydroponics presents a controlled and efficient alternative for the enhancement of secondary metabolite production which translates into increased value for the economic and medicinal properties of ashwagandha, basil, and stevia.

#### 5. Nutrient Management and Environmental Control

Hydroponic systems are fundamentally dependent on nutrient management and environmental controls that will affect plant growth and development, yield, phytochemical composition, etc. Unlike cultivation in soil where the availability of nutrients can vary greatly based upon the soil's physical properties and environmental conditions, hydroponics allows for controlled and precise manipulation of the nutrient's composition, concentration and delivery. This capability of control also provides an advantage to many medicinal crops (e.g., Ashwagandha, Basil, Stevia) due to the specific requirements of these crops to grow optimally and develop metabolites. Nutrient solutions in hydroponics typically include essential macronutrients including nitrogen, phosphorus, potassium, calcium, and magnesium; however, they also include essential micronutrients such as iron, zinc, and manganese. Properly maintaining the nutrient solution pH between 5.5–6.5 and electrical conductivity (EC) between 1.5–2.5 mS/cm is critical to maximizing plant nutrient uptake and avoiding nutrient deficiency or toxicity that can result in reduced plant growth and quality [8, 14].

Temperature, humidity, the amount of light, and CO<sub>2</sub> levels are just a few important environmental factors that can significantly affect the growth of plants in hydroponic farms. For example, basil likes to grow in a medium temperature range (20–30°C) and will do the best in bright light, while stevia performs best in slightly lower temperatures and with controlled amounts of light during the day. Ashwagandha, however, is much hardier and will grow very well in a large variety of different environmental conditions; that being said, it still grows better with some control over temperature, humidity, and light levels and will develop better roots in a controlled environment. The inclusion of sophisticated technology, such as IoT sensors and automated controllers, has greatly improved the efficiency of hydroponic systems. With these technologies, farmers can monitor and change the growing environment in real time to achieve the best growing conditions. The use of smart farming technologies in India is growing rapidly, especially in urban and peri-urban areas, where precision agriculture has become increasingly popular.

In addition, recirculating nutrient systems create less waste and increase resource-use efficiency. Hydroponic systems can achieve reductions in both fertilizer application (up to 50%) and water usage (up to 90%) through recirculation of nutrient

solutions compared to traditional farming methods <sup>[4]</sup> thereby making this technology very sustainable in terms of producing medicinal plants, especially in areas where water is limited.

**Table 3:** Nutrient Solution Composition for MAPs

| Nutrient | Ppm     | Role           |
|----------|---------|----------------|
| N        | 100–200 | Growth         |
| P        | 30–60   | Roots          |
| K        | 150–300 | Metabolites    |
| Ca       | 80–150  | Structure      |
| Mg       | 30–60   | Photosynthesis |

## 6. Quality and Safety Aspects

There are several critical factors in regard to assurance or credibility of acceptance of herbal medicines: As medicinal herbs are used in both pharmaceuticals and nutraceuticals, their quality and safety are of utmost importance. Hydroponically grown plants have a definite superiority due to their growing conditions being free from soil borne contaminants and the ability to control the environment in which the plants grow. The need for maintaining high quality assurance standards in order to sustain both the domestic and export markets for medicinal herbs such as Ashwagandha, Basil and Stevia, is apparent.

A significant problem with conventional farming is the possibility of contamination from heavy metals, pesticides, and pathogens. Hydroponic systems use sterile growing media and controlled nutrient solutions, eliminating any potential for contamination due to improper use of chemicals or microorganisms. Because of this, it becomes possible to produce a cleaner and safer product (especially when used for medicinal purposes <sup>[3, 9]</sup>). Additionally, one of the biggest advantages of hydroponic systems is that the phytochemicals produced by plants grown under controlled environmental conditions are expected to have the same composition on a regular basis. Because of this, bioactive compounds will continue to be produced at the same level and can be used to establish consistency in the production of products used in pharmaceutical industries where active ingredients must have a specific level to maintain both efficacy and safety.

Regulations concerning the production of medicinal plants in India are becoming more stringent especially for products produced for export. Hydroponic systems have the ability to meet the requirements of Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP). This will add to the credibility and marketability of these products.

## 7. Sustainability and Resource Use Efficiency

Hydroponic systems are increasingly recognized as a sustainable alternative to conventional agricultural practices due to their efficient utilization of water, nutrients, and land resources. For high-value medicinal crops such as Ashwagandha, Basil, and Stevia, hydroponics offers a resource-efficient production system that addresses many of the environmental challenges associated with traditional soil-based cultivation. One of the most significant advantages of hydroponics is its ability to drastically reduce water consumption. Unlike conventional farming, where a large portion of irrigation water is lost through evaporation, runoff, and deep percolation, hydroponic systems recirculate nutrient solutions, resulting in water savings of up to 80–90% <sup>[4, 22]</sup>. This feature is particularly important in India, where water scarcity is a growing concern in many agricultural regions.

In addition to water efficiency, hydroponics ensures precise nutrient management, which minimizes fertilizer wastage and

reduces environmental pollution. Nutrients are delivered directly to the plant roots in controlled concentrations, leading to higher nutrient use efficiency and reduced risk of leaching into surrounding ecosystems. This is especially beneficial for medicinal plant cultivation, where maintaining optimal nutrient balance is critical for both yield and phytochemical quality. Furthermore, the elimination of soil in hydroponic systems prevents issues such as soil degradation, erosion, and contamination, thereby contributing to long-term environmental sustainability <sup>[4, 14]</sup>.

Hydroponic systems also reduce the dependency on chemical pesticides and herbicides, as the controlled environment limits the occurrence of pests and diseases. This results in cleaner production and lower chemical residues in the final plant material, which is essential for medicinal applications. Moreover, hydroponics enables cultivation in non-arable and urban areas, including rooftops, greenhouses, and indoor vertical farming units. This adaptability allows for efficient land use and supports agricultural production in densely populated regions where arable land is limited.

Another important aspect of sustainability is the potential integration of renewable energy sources such as solar power into hydroponic systems. In India, where sunlight is abundant, solar-powered hydroponic units are being explored as a means to reduce energy costs and carbon footprint. Additionally, advancements in automation and smart farming technologies further enhance resource efficiency by optimizing water and nutrient delivery based on real-time plant requirements.

Overall, hydroponic cultivation represents a climate-resilient and environmentally sustainable approach for the production of medicinal plants. By improving resource use efficiency and reducing environmental impact, hydroponics aligns well with sustainable agriculture goals and offers a viable pathway for future agricultural development in India and beyond.

## 8. Economic and Commercial Potential

The economic and commercial potential of hydroponic cultivation of medicinal plants in India is substantial, driven by the increasing global demand for herbal products, nutraceuticals, and plant-based pharmaceuticals. Crops such as Ashwagandha, Basil, and Stevia are considered high-value commodities due to their wide range of applications in the pharmaceutical, cosmetic, and food industries. India is one of the leading producers and exporters of medicinal plants, and the sector continues to grow rapidly with the expansion of the Ayurveda and wellness industries <sup>[1, 25]</sup>. In this context, hydroponics presents a modern cultivation approach that can significantly enhance productivity, quality, and profitability.

One of the primary economic advantages of hydroponic systems is their ability to produce higher yields in a relatively smaller area. Compared to conventional soil-based cultivation, hydroponics can increase biomass production by 20–50%, depending on the crop and system design <sup>[5, 10]</sup>. This is particularly beneficial for basil and stevia, which are primarily cultivated for their leaves, as hydroponic systems promote rapid vegetative growth and allow multiple harvest cycles throughout the year. The ability to achieve year-round production ensures a consistent supply of raw material to industries, thereby stabilizing market availability and prices.

For ashwagandha, which is primarily valued for its roots, hydroponic and aeroponic systems offer opportunities for controlled root development and enhanced withanolide content. Although still under research, these systems have shown potential to produce high-quality roots with better uniformity

and reduced contamination, thereby increasing their market value [6, 28]. Additionally, hydroponic cultivation eliminates soil-related risks such as heavy metal contamination and pesticide residues, which enhances the export potential of medicinal plants by meeting international quality standards [9]. Despite the high initial investment required for setting up hydroponic systems, including infrastructure, automation, and energy costs, the long-term economic benefits often outweigh these expenses. Reduced input costs for water, fertilizers, and pesticides, combined with higher productivity and premium product quality, contribute to improved profitability over time. Moreover, the adoption of hydroponics in urban and peri-urban areas reduces transportation costs and post-harvest losses, further enhancing economic returns.

Government support in India, through schemes such as the Mission for Integrated Development of Horticulture (MIDH) and initiatives by the National Medicinal Plants Board, is playing a crucial role in promoting hydroponic cultivation. These programs provide financial assistance, training, and technical support to farmers and entrepreneurs, thereby facilitating the adoption of advanced agricultural technologies. Hydroponic cultivation offers significant economic opportunities for the large-scale production of medicinal plants. With increasing market demand, technological advancements, and policy support, hydroponics has the potential to transform the medicinal plant sector into a more profitable, efficient, and globally competitive industry.

### 9. Challenges and Limitations

Despite its numerous advantages, hydroponic cultivation of medicinal plants such as Ashwagandha, Basil, and Stevia faces several challenges that limit its widespread adoption, particularly in developing countries like India. One of the most significant constraints is the high initial investment required for setting up hydroponic systems. Infrastructure components such as greenhouses, nutrient delivery systems, pumps, sensors, and automation technologies involve substantial capital costs, making it difficult for small and marginal farmers to adopt this technology without financial support [4, 10]. Although long-term returns can be favorable, the initial financial barrier remains a major deterrent.

Another important limitation is the requirement for technical expertise and skilled management. Hydroponic cultivation demands precise control over parameters such as nutrient composition, pH, electrical conductivity (EC), temperature, and humidity. Even minor imbalances can lead to nutrient deficiencies, toxicities, or reduced plant growth. This makes hydroponics a knowledge-intensive system that requires proper training and continuous monitoring, which may not be readily accessible to all farmers [8, 14]. Inadequate technical knowledge can result in system inefficiencies and economic losses.

Energy dependency is another critical issue associated with hydroponic systems. These systems rely heavily on electricity for water circulation, aeration, artificial lighting, and climate control. In regions with unreliable power supply, including many parts of India, interruptions in electricity can lead to rapid crop stress or even complete crop failure. This increases operational risks and necessitates backup power solutions, which further add to the cost of production.

The cultivation of root-based medicinal plants such as Ashwagandha presents additional challenges, as most hydroponic systems are optimized for leafy crops. Achieving proper root development and biomass accumulation requires specialized systems such as aeroponics or modified substrate-

based setups, which are still under research and not widely standardized [6, 28]. This limits the large-scale adoption of hydroponics for certain medicinal crops. Disease management also poses a risk in hydroponic systems, particularly in recirculating setups where pathogens can spread rapidly through the nutrient solution. Once contamination occurs, it can affect the entire crop system, leading to significant losses. Maintaining system hygiene and regular monitoring are therefore essential but can increase operational complexity.

Additionally, regulatory and certification challenges may hinder market acceptance of hydroponically grown medicinal plants. In some cases, the classification of hydroponic produce under organic standards remains unclear, which may affect consumer perception and pricing. Limited awareness, lack of standardized protocols, and insufficient research on specific medicinal plants further restrict the expansion of hydroponic cultivation. Overall, while hydroponics offers promising opportunities, addressing these challenges through technological innovation, capacity building, and policy support is essential for its sustainable adoption and large-scale implementation.

### 10. Future Prospects

The future of hydroponic cultivation of medicinal and aromatic plants (MAPs) is highly promising due to rapid advancements in controlled environment agriculture and digital technologies. The integration of artificial intelligence (AI) and Internet of Things (IoT)-based systems is expected to further enhance precision in nutrient delivery, environmental monitoring, and crop management, leading to improved yield and quality [8]. Emerging approaches such as precision hydroponics and sensor-based automation will allow real-time adjustments based on plant physiological responses, ensuring optimal growth conditions.

Additionally, the application of nanotechnology in nutrient formulation offers new opportunities to improve nutrient use efficiency and targeted delivery, thereby enhancing secondary metabolite production [12]. Hydroponics can also play a crucial role in cultivating MAPs in non-arable regions, including urban areas, deserts, and even controlled environments for space agriculture. This adaptability makes it a climate-resilient solution for ensuring continuous production of high-value medicinal plants under changing environmental conditions [4, 9]. Future research should focus on optimizing hydroponic protocols for root-based medicinal plants and understanding plant-microbe interactions in soilless systems. Standardization of cultivation practices and regulatory frameworks will also be essential to support large-scale commercial adoption. With increasing global demand for plant-based pharmaceuticals and natural products, hydroponics is expected to become a key technology for sustainable and high-quality MAP production [10, 11].

### 11. Conclusion

Hydroponic cultivation represents a transformative and sustainable approach for the production of high-value medicinal plants such as Ashwagandha, Basil, and Stevia, offering significant advantages over conventional soil-based systems. By enabling precise control over nutrient supply and environmental conditions, hydroponics enhances plant growth, yield, and the consistency of bioactive compounds, which is essential for pharmaceutical and nutraceutical applications. In the Indian context, this technology addresses critical challenges such as water scarcity, land degradation, and climate variability while allowing cultivation in non-arable and urban areas with reduced

resource inputs. Additionally, hydroponic systems improve product quality by minimizing contamination risks and ensuring uniform phytochemical profiles, thereby increasing export potential and market value. The integration of advanced technologies such as IoT, automation, and artificial intelligence further improves efficiency and scalability, making hydroponics increasingly suitable for commercial adoption. Although limitations such as high initial investment and technical complexity persist, ongoing innovations and government support are expected to facilitate wider adoption. Overall, hydroponics holds strong potential to revolutionize medicinal plant cultivation by providing a reliable, sustainable, and economically viable production system capable of meeting the growing global demand for standardized and high-quality herbal products.

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