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Hydroponic pharmacopoeia: Optimizing controlled environment agriculture for high-potency therapeutic herbs

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Abstract

For healthcare, the medicinal plant has become a significant global resource. The United Nations Organization considers that almost eighty percent of the global population uses a traditional healthcare system as the primary means of healthcare. Increased demand, over-harvesting from the wild, natural habitat destruction through land development and agriculture have created serious threats to many medicinal plant species. Furthermore, conventional soil production of various medicinal plant species often results in variably concentrated amounts of bioactive compounds within the individual species as well as significant reduction of species growth. Hydroponic cultivation provides a sustainable method to produce medicinal plants which may provide both increased biomass and increased accumulation of secondary metabolites. The aim of this Comprehensive Review is to provide detailed evaluations of current hydroponic systems available for developing and cultivating medicinal plants, with particular emphasis on how to determine which hydroponic system is applicable for each organ of the medicinal plant including: roots, leaves, flowers, fruits, and rhizomes. This article is divided into sections that analyze the Deep Flow Technique (DFT), Nutrient Film Technique (NFT), Floating Technique (FT), Ebb and Flow, and Solid Media cultures in terms of their effective use in producing each type of medicinal plant. Other new methodologies and technologies, such as using the precursors for secondary metabolite accumulation, elicitor treatments (stimulus for secondary metabolite production), and root exudate harvesting are also discussed as they may potentially facilitate new methods of cultivating high-quality medicinal plants. Finally, while hydroponic cultivation has shown considerable potential for producing many high-quality medicinal plants with increased concentrations of bioactive compounds, there has been little research on whether hydroponic cultivate methods are economically feasible; therefore, future studies need to investigate the economic viability of the use of hydroponic systems for growing medicinal plants.

Keywords: Hydroponics, medicinal plants, secondary metabolites, soilless cultivation, bioactive compounds

Introduction

Plants have been important to the health of humans for thousands of years and produce many chemicals throughout their life cycle. For example, secondary metabolites—compounds not involved in the primary metabolic process—have shown to have many therapeutic properties such as anti-inflammatory, antidiabetic, anticancer, and protective effects from cardiovascular disease or infections (Skrovankova *et al.*, 2012). It is estimated that 50% of pharmaceuticals currently in use are derived from plants, and 60% of pharmacological agents can be traced back to natural sources (Kong *et al.*, 2008 [19]; Akinyemi *et al.*, 2018). It has also been estimated that there are about 70,000 plants worldwide that have been used in traditional and modern medicines (Leaman, 2006). In developing countries, 80% of rural populations continue to rely on traditional medicine due to lack of access to modern health systems (Xego *et al.*, 2016) [9]. In China, 40% of health care is based on traditional medicine and in Africa, 80% of health care is based on traditional medicine (Zobayed, 2020). In Traditional Chinese Medicine (TCM), approximately 80% of its products are derived from plants (Zhou and Wu, 2006).While there have been numerous challenges associated with the use medicinal plants, many plants which are considered to have medicinal properties are becoming extinct from wild populations due to overuse and harvesting from these populations (Chen *et al.*2016) [9]. In addition, most commercial plant materials are poorly identified, have varying amounts of secondary metabolites, and contain high levels of contamination by heavy metals (Hsieh and Lin 2019). This has led to serious side effects and fatalities in patients receiving medicinal plants due to substitution of one species for another, misidentification, or contamination (Mankga *et al.* 2013).Cultivation of medicinal plants has greatly increased globally, with China producing approximately 200 different medicinal species over 9.3 million hectares (Li *et al.* 2015) of farmland. However, cultivating plants through field cultivation creates different problems compared to wild populations, which generally have the highest concentrations of secondary metabolites due to the effects of environmental stressors or competition on the development of defensive compounds (Dajic-Stevanovic & Pljevljakusic, 2015; Schippmann *et al.* 2006). Concentrations of hypericin, pseudohypericin, and hyperforin were found to vary widely across various locations where *Hypericum perforatum* L. is cultivated (Bruni and Sacchetti 2009). In another study the yield of salidroside in *Rhodiola sachalinensis* was highly dependent on several soil characteristics (organic matter, nitrogen, phosphorus, potassium, and pH) (Yan *et al.* 2004). The growth and production of phenolic compounds and saponins in several different species of South African medicinal plants were shown to be affected by season (temperature and moisture) (Ncube *et al* 2011).Beyond that, many continuous cropping systems also lead to declining yields from a number of different issues which stem from the accumulation of root exudates in the environment that support soil borne disease (e.g., panic ginseng, see Xiao *et al.*, 2016).Hydroponic cultivation presents potential solutions to these problems by growing plants in liquid nutrient solutions instead of soil (e.g., see Gericke, 1937). The purpose of this review is to thoroughly review the utilization of hydroponic culture systems as a way to cultivate medicinal plants, emphasizing that each hydroponic system must be appropriately optimized based upon the desired plant organ. While there have been prior reviews of non-soil culture for growing medicinal species, to my knowledge there has not been any prior organ-specific reviews of different hydroponic techniques that have been used to produce various medicinal species grown using hydroponic culture systems. This paper compiles existing research about growing each of the above plant organs (e.g., shoots, leaves, stems; flowers; roots and rhizomes; and seeds and fruits) using hydroponic systems and describes the best techniques for achieving success with each type of hydroponic culture system and discusses unique techniques that would suffice as areas needing further investigation.

Hydroponic Systems: Classification and Principles

1. Solution Culture Systems

Circulating Systems: Nutrient solutions are continuously pumped from a reservoir to a culture tank and back to the reservoir. In the Nutrient Film Technique (NFT) sloped troughs are used to provide a thin, continuous nutrient solution that flows over the roots of the plants. This provides both nutrients and oxygen (Sengupta and Banerjee, 2012). Deep Flow Technique (DFT) creates a larger volume of circulating nutrient solution and completely submerges the roots for growing (Fussy and Papenbrock, 2022) [11].

Non-Circulating Systems: In static systems the nutrient solution in the culture tank is replaced when the concentration, pH, or EC becomes unsuitable. The Root Dipping Technique (RDT) suspends the plants with only the root tips submerged, similar to NFT but the plants do not receive circulating water. The plants are grown using the Floating Technique (FT), which places the plants' roots entirely submerged in water like DFT, but no circulation takes place (Hussain *et al*., 2014) [18]. The Capillary Action Technique is used to irrigate the plants using wicks or placing the pots in a shallow container allowing the media to draw moisture from the nutrient solution by capillary action (Sharma *et al*., 2018). The Ebb and Flow Technique floods the culture tray with the nutrient solution and then drains the water; therefore, there are elements of both circulating and static systems (Macwan *et al*., 2020).

2. Solid Media Culture Systems

The meter-long media-filled polyethylene bags are employed in the Hanging Bag Technique, where they are positioned over troughs (Waiba *et al*., 2020). Plant roots in net pots are placed into the openings, and the nutrient solution is pumped into the top of the bag, allowing it to percolate through the media prior to returning to the reservoir.In the Grow Bag Technique, media-filled grow bags are placed on the ground, with seedlings placed through the cut openings of each bag. The seedlings are fertigated through drip line systems (Sengupta and Banerjee, 2012).The Pot Technique consists of planting each plant in an individual container using a mixture of various media, with each container receiving fertigation independently (Hasan *et al*., 2018).The Trench/Trough Technique requires the construction of a trough or trench lined with a waterproof liner and filled with inert media, which is then irrigated through a drip irrigation system (Fussy and Papenbrock, 2022) [11].

3. Comparative Effectiveness

Research comparing hydroponic systems used to cultivate medicinal plants indicates there are significant differences in their respective performance. Hayden's (2006) [13] evaluation studied many species of medicinal plant using multiple systems including NFT, ebb & flow, and aeroponic as the basis for determining how these systems provide advantages and disadvantages in terms of resource allocation by the plants and specifically mentions that no one of these systems was found to be consistently superior to the others for producing rhizomes. When selecting which hydroponic design to use, it is essential to consider the desired type of plant organ because secondary metabolite concentrations frequently occur in specific plant tissues. An excellent example of this is *Glycyrrhiza Uralensis* where contradictory results resulted from the use of different hydroponic cultivation methodologies. Afreen *et al*. (2005) [1] reported G. uralensis to exhibit poor growth using DFT methodology and attributed it to leaching of secondary metabolites into the nutrient solution regarding the efficacy of G. uralensis using DFT hydroponics as opposed to *G. uralensis* grown using NFT and achieving excellent rhizome production with superior quantities of glycyrrhizic acid (Yoshimatsu 2012) [20].

Herbs: Cultivation of Leafy Medicinal Plants

In hydroponics studies, the largest research area for medicinal plants would be the category of medicinal herbs, or plants that have an aerial portion (primarily leaves and stems) used. Examples of how extensively studied hydroponic growth of leafy vegetables such as lettuce (Lactuca sativa) in Deep Flow Technique (DFT) (Ferguson *et al*., 2014), Nutrient Film Technique (NFT) (Li *et al*., 2018), and in pots and spinach (*Spinacia oleracea*) grown using the floating types of systems (Lenzi *et al*., 2011) as well as pak choi (*Brassica rapa*) grown using NFT (Caralde & Salas, 2015) and capillary (Hanafiah *et al*., 2019) systems.

1. Predominant Techniques and Their Applications

Of the various experimental methods available for growing medicinal herbs in hydroponic systems, the Floating Technique (FT) (refer to Table 1) is the most widely used. This is indicative of the predominant use of controlled environmental physiological approaches for experimental rather than commercial (i.e., optimizing production in a commercial environment) purposes. The use of FT allows for the short-term experimentation of plant responses to many different variables, such as: salt stress (Yep *et al*., 2020; Zhang *et al*., 2008), plant elicitors (Bailey, 2019[7]; Zhang *et al*., 2020), endophytes (i.e., fungi that inhabit living plants) (Gong *et al*., 2019), heavy metal (e.g., lead) exposure (Peng *et al*., 2009), macro element omission (e.g., magnesium) (Silva *et al*., 2021), and nitrogen (Li and Liu, 2005) enrichment. There are several reasons FT has become so popular for experimentation in these areas. FT eliminates soil-borne pest and disease problems, removes the need for irrigation, and allows for easy access to the root zone to monitor the effects of environmental variables (Torabi *et al*., 2012). Unlike circulating systems, which circulate a nutrient/solution through a pump, FT systems do not have any type of circulation requirement and therefore are easier and less expensive to set up (Fussy and Papenbrock, 2022) [11]. Studies using FT typically last from a few weeks up to two months, with the increased risk of disease occurring in static systems over extended periods. In comparison, circulating systems may use a number of options to sterilize their nutrient solutions (e.g., ultraviolet radiation, ionization, filtration, ozone treatment, temperature). Static systems are much more difficult to treat, and because of this, the likelihood of pests/disease infecting plants increases (Ikeda *et al*., 2002) [12].

Table 1: Common Hydroponic Systems for Medicinal Herbs (Leaf and Stem Utilization)

Hydroponic System	Representative Species
Deep Flow Technique (DFT)	*Agastache rugosa, Cannabis sativa, Mentha spicata*
Nutrient Film Technique (NFT)	*Atropa belladonna, Ocimum basilicum, Mentha × piperita*
Floating Technique (FT)	*Artemisia vulgaris, Ocimum basilicum, Urtica dioica*
Capillary Action	*Aloe vera, Cannabis sativa*
Ebb and Flow	*Mentha × piperita, Nepeta cataria, Ocimum basilicum*
Grow Bag Technique	*Moringa oleifera, Cannabis sativa*
Pot Technique	*Aloysia citrodora, Ocimum basilicum, Mentha* spp.

2. Long-Term Cultivation in FT Systems

Long-term FT cultivation has shown success, even with potential issues concerning disease. Radman *et al*. (2014) documented their 242-day unheated greenhouse culture of *Urtica dioica* via FT, including 5 separate leaf harvests, even during periods of plant dormancy in the field. Saito *et al*. (2014) [18] grew tea (Camellia sinensis) in FT for 180 days before harvesting roots. Ai *et al*. (2021) produced flowers from Chrysanthemum × morifolium via FT culture over a period of 160 days. Tabatabaei (2008) [19] harvested roots from *Valeriana officinalis* by floating culture after 150 days in FT culture, achieving greater root dry weight and oil content than with either aeroponics or the pot method or soil. Dorais *et al*. (2001) [10] harvested roots from both *Valeriana officinalis* and *Inula helenium* after the 120th day of FT culture, recording yields that were, by weight, more than four times greater than would have been produced in the same time, using field-based (in-soil) methods. Therefore, it can be concluded that FT can be beneficial for both short-term, experimental use, and for longer-term (commercial) production.

3. Cannabis sativa: A Model System

The scientific research performed on C*annabis sativa* because of its value (medically/recreationally), high economic impact, and innovation in the field of cannabis-related commercial production (Kubota, 2020) is vast. Hydroponically produced cannabis has been seeded in most types of hydroponic systems to date; some of these systems commonly used to successfully grow cannabis include Ebb & Flow and Nutrient Film Technique (NFT) (Cervantes, 2006). Research done with regards to growing cannabis also helps to develop successful best-practice models for growing other plants with similar leafy characteristics that are grown for medicinal purposes.

Flowers: Medicinal Blossoms and Inflorescences

Medicinally speaking, the use of flowers as an organ (Shubhashree et.al., 2015) is not very common compared to other plant organs.< Currently, a number of medicinally important flower-producing plants are used to produce essential oils, juices and teas or to be eaten either fresh or dried (Reddy et.al.2015). Most flower-producing plants serve more than one purpose; for example, chrysanthemum × morifolium is used both as an ornamental flower and as a TCM ingredient. Similarly, calendula officinalis is used to treat skin conditions and can also enhance the taste of salads (Sharma et.al. 2011).

1. Hydroponic Systems for Medicinal Flowers

Research into the medicinal uses of flowers also involves FT (see **Table 2**). FT research has used several different types of studies (i.e., salinity [Harathi *et al*., 2012], PGPRs [Rahmoune *et al*. Jousse; *et al*., 2010; Vu *et al*., 2018], heavy metals [Azad and Kafilzadeh; 2012; Gautam *et al*., 2018; Kováčik *et al*., 2022], drought stress [Tian *et al*., 2021; He *et al*., 2021], and plant elicitors [Yan *et al*., 2020; Paponov *et al*., 2021[4]]). The average hydroponic cultivation study was conducted over a period shorter than two months, which indicates that FT is more commonly associated with research use than for commercial production.

Table 2: Common Hydroponic Systems for Medicinal Flowers

Hydroponic System	Representative Species
Deep Flow Technique (DFT)	*Chrysanthemum × morifolium, Taraxacum officinale*
Nutrient Film Technique (NFT)	*Crocus sativus, Hypericum perforatum*
Floating Technique (FT)	*Calendula officinalis, Carthamus tinctorius, Hypericum* spp.
Capillary Action	*Chrysanthemum × morifolium, Pelargonium graveolens*
Ebb and Flow	*Crocus sativus, Hypericum perforatum*
Grow Bag Technique	*Calendula officinalis, Lavandula angustifolia, Thymus vulgaris*
Pot Technique	*Crocus sativus, Datura stramonium*

2. Commercial Flower Production Examples

Although much of the research on using FT was experimental, commercially grown cut-flower production will eventually represent another major area in which FT is used commercially. The following examples of successfully commercially grown flowers provide a glimpse into the future of FT. Dorais *et al*. (2001) [10] cultivated Achillea millefolium, Borago officinalis, Calendula officinalis, Tanacetum parthenium, and Taraxacum officinale in FT with harvestable products produced in less than 4 months.

Ai *et al*. (2021) propagated Chrysanthemum × morifolium using FT in 160 days.

Roots and Rhizomes: Challenges and Innovations

Growing underground plant structures in hydroponics is difficult. Research on root crops such as potatoes, sweet potatoes, and peanuts has developed from space programs (Kitaya *et al*. 2008). Researchers have utilized many different types of hydroponics and media to achieve this including liquid systems (NFT's) (Mackowiak *et al*. 1998; Mortley *et al*. 1991), capillary action systems (Sakamoto and Suzuki, 2018, 2020), and trough systems (Ritter *et al*. 2001). However the systems that are effective for aerial parts of the plants generally do not provide an effective growing medium for root systems, rhizomes, or stolons (Yoshimatsu, 2012) [20].

1. The Waterlogging Challenge

Buried storage organs in the ground have difficulties when completely submerged in nutrient solutions. On the other hand, fibrous roots can endure as long as they receive enough oxygen (Sakamoto and Suzuki 2018). Rhizomes, however, need to be cultivated using water-logging safe techniques (Sakamoto and Suzuki 2020). As a result, both substrate culture (Sakamoto and Suzuki 2018) and liquid culture (Eguchi and Yoshida 2004) have air-gap methods established to assist with cultivation.

2. Rhizome Cultivation: The Persistent Challenge

Rhizomes and bulbs developed under liquid culture conditions usually do not thrive. Hayden (2006) [13] stated that NFT and ebb-flow systems are not compatible with rhizomes, in fact, NFT systems reduced root duration dramatically. According to DFT studies, both Glycyrrhiza glabra (Kakutani) and G. uralensis (Afreen *et al*., 2005) [1] experienced poor root dry weight. Merwilla plumbea in the FT system had large reductions in bulb formation and was not very well formed overall (Lux *et al*., 2011).Most rhizome-producing plants do not have equal success in their development when grown in liquid systems, however some examples do exist. For example, Valerian (Valeriana officinalis) was grown in floating culture and produced more dry root mass compared with either aeroponic or mixed perlite-vermiculite (Tabatabaei, 2008) [19] as well as in a soil substrate (Dorais *et al*., 2001) [10]. Picrorhiza kurroa plants were very productive as well (Thakur *et al*., 2019). Unfortunately, the amounts of rhizome produced by all of these plants were lower than would have been expected based on studies of other plants grown using similar methods and because Dorais *et al*. did not report on development of rhizomes there is evidence that while root systems improved, there remains a negative impact on the production of medicinally important rhizomes.Numerous studies have indicated that FT is superior for the propagation of Coptis chinensis (Huang *et al*., 2018, 2019) [7], G. uralensis (Hou *et al*., 2010; Jiang *et al*., 2019), and Panax notoginseng (Ou *et al*., 2019, 2020) but all of the studies sourced their plant material from wild plants that had pre-existing rhizomes complicating comparisons with studies relying on seedlings.

3. Air-Gap Systems: The Promising Solution

According to Hayden (2006) [13], using perlite air-gap systems that consist of a perlite reservoir and shallow nutrient solution located at the bottom (similar to NFT) provides the best option for growing rhizomes. This method has been shown effective with G. uralensis, C. chinensis and A. belladonna; they produced higher than the Japanese Pharmacopoeia's requirement for secondary metabolites (Yoshimatsu, 2012) [20].Media-free air-gap systems have been developed to overcome the disadvantages of substrate culture for growing underground organs. Sawada *et al*. (2010) designed a cylindrical tube to hold the lower part of the root in nutrient solution, while providing an air gap for rhizome development. Using this method allows for producing extracts of G. uralensis that are equally safe and effective as a commercially available crude drug (Akiyama *et al*., 2017; Nose *et al*., 2019, 2020) [5, 7, 16]. These types of methods will facilitate commercial production of rhizomes for pharmaceutical and traditional medicine purposes.

4. Cannabis sativa: Fruits and Seeds

Cannabis leaves are frequently used for producing medicinal products (Balant *et al*., 2021); however, cannabis fruits and seeds have Traditional Chinese Medicine (TCM) purposes (Chen & Chen, 2004) as well as being used to produce hemp seed oil (Ostapczuk *et al*., 2021) [8]. Drug-type cultivars bred for Δ^9-tetrahydrocannabinolic acid and cannabidiolic acid content (Yep *et al*., 2020) differ from fiber-type cultivars bred for the use of TCM fruits/seeds (Brand & Zhao, 2017) and produced hemp seed oil (Ostapczuk *et al*., 2021).The majority of literature focuses on drug-type cultivars; however, there are studies that use fiber-type varieties in hydroponic systems. Bailey (2019) [7] evaluated the effects of methyl jasmonate and salicylic acid on industrial hemp varities ('Cherry', 'Cherry Blossom', 'Canda') and found that methyl jasmonate was the most effective at stimulating the production of cannabidiolic acid and cannabichromene in the leaves of these industrial varieties. Kalousek *et al*. (2020) assessed the effects of landfill leachate on fiber-type hemp ('Bialobrzeskie', 'Monolica'), measuring reductions in the dry weight of the aerial portion and leaf area. Neither study grew plants in a fruiting stage; there are many opportunities for continued research on the effects of environmental conditions on the medicinal properties of fruits/seeds.

Discussion: Trends, Innovations, and Future Directions

1. Unexploited Medicinal Potential

Traditional medicine generally only uses a limited number of specific plant organs in which phytochemicals are concentrated (Mathe, 2015). However, many of the secondary metabolites in question may also be found in other parts of the plant, and hydroponic growth conditions can provide access to normally challenging-to-harvest parts of a plant.Datura species are an example of this. In addition to having traditional uses based on the different organ types of various species—D. metel flowers are used in TCM (Yang, 2003), D. innoxia roots are used in Chumash tradition (Baker, 1994), and D. stramonium leaves are used in parts of Europe (Soni *et al*., 2012)—all of the plant organs contain tropane alkaloids that can have suitable medicinal qualities (Gaire and Subedi, 2013). In Ayurvedic medicine from India, multiple organ types of Datura can have therapeutic worth (Kadam *et al*., 2018).

In addition to being used for the production of tea leaves (which are used medicinally in TCM), Camellia sinensis is also grown under hydroponic conditions to determine the location of organs with the highest concentration of theanine (an amino acid) found primarily in tea but only in one known inedible mushroom (Saito and Ikeda, 2012). Hydroponically grown C. sinensis had the highest concentration of theanine in the lignified tap root, but high levels were also found in the tips of the root (Saito *et al*., 2014) [18].An additional hydroponic plant example is Hypericum perforatum (St. John's Wort), which produces medicinally beneficial hypericin, pseudohypericin, hyperforin, and hyperoside (Porzel *et al*., 2014). Traditionally, the flowers of H. perforatum have been used in many parts of the world; however, glands containing these phytochemicals are also found in the leaves (Briskin *et al*., 2000), and the concentrations of the compounds present in the leaves come from the same source as those found in the flowers (Zobayed *et al*., 2006). Hydroponic production has led to increased production of glandular tissues per leaf and overall concentrations of leaf secondary metabolites (Zobayed and Saxena, 2004).

2. Nutrient Solution Innovations

Liquid media culture provides novel opportunities for manipulating plant metabolism via the composition of the nutrient solution. While there has been considerable research into optimization of macro- and micronutrients, pH and EC (Torabi *et al*., 2012), innovative approaches to plant nutrient manipulation are emerging.Vimolmangkang *et al*. (2010) looked at how supplementation of sulfur and amino acids affected production of Mentha species grown in deep flow technology (DFT). Results found that Mentha spicata produced the highest yield of volatile oil from sole supplementation of amino acids, while Mentha arvensis var. piperascens showed the best response to a combination of sulfur and amino acids.An alternative approach to with supplementation of precursors is also a possibility. Song *et al*. (2012) used L-proline and L-ornithine (which are precursors to the metabolite stachyridine hydrochloride) in their solution to produce Leonurus japonicus in DFT. Their results indicated that exposure to a 0.5 mM L-proline solution for 96 hours before harvest increased levels of stachyridine hydrochloride by over 50%. Additional investigation into the use of precursors as a possible inexpensive option for use in solutions and translocation from solution to roots for the purpose of metabolite synthesis is warranted.

3. Root Exudate Harvesting and Permeabilization

Harvesting can be avoided completely through liquid culture technique, since many plants will secrete secondary metabolites into their liquid nutrient solution, meaning you can collect them continuously without killing the plant. Paponov *et al*. (2021) [4] studied the application of 10 µM methyl jasmonate to Hypericum perforatum, finding that application of the methyl jasmonate caused an 88% increase in hypericin in root exudates as compared to the control plants.Also, combining the use of precursor supplements with permeabilizing the root tissue of plants has great potential for increasing production. Gontier *et al*. (2002) [12] conducted an experiment where they grew Datura innoxia in a liquid culture media containing phenylalanine and ornithine precursors, while also permeabilizing the roots with Tween20, producing a significant increase in hyoscyamine and scopolamine in root exudates. Root permeabilization may also assist with the movement of precursors into root cells to create the desired substance for subsequent exudation and extraction for use as pharmaceuticals.

Economic Viability

Commercial viability must be established for the cultivation of medicinal plants using hydroponics to replace wild harvesting or field production. Economic assessments of hydroponic farms are still uncommon (Benis and Ferrão, 2018). Papadopoulos *et al*. (2008) evaluated NFT systems in Greece for growing lettuce/tomatoes and HVAC media systems for producing flowering pot plants/tomatoes (4 year). Although NFT systems yielded the most profit, both types of NFT systems were not profitable without EU agriculture subsidies (50% of total cost).Dorais *et al*. (2006) provided annual sales estimates for ten medicinal plants from the FT system, but did not include any type of production costs, thus limiting usability of their results. In a 2014 survey of 165 Japanese PFALs there were 25% operating at a loss and 50% breaching their budget (Kozai and Niu, 2020). However, PFAL-type systems may be more economically feasible for growing medicinal plants than for other crops. Leafy greens must be harvested, transported, and sold within a short time frame to avoid spoilage, while many medicinal plant have a longer shelf-life if they are dried or processed in some way before sale. Bafort *et al*. (2022) [6] assessed the feasibility of growing Euphorbia peplus using DFT systems in shipping containers with LED lighting and evaluated the income levels attained from different processing scenarios. The potential gross margin of making ingenol mebutate as a laboratory produced material is estimated at €5,000–312,000, while pharmaceutical gel made from this same plant had the potential gross margin of generating €160,000–650,000 in revenue. According to Volenzo & Odiyo, 2020, the worldwide medicinal and aromatic plant industry will grow from US$800 million in 2020 to US$50 trillion by 2050. Increasing demand for these plants will result in new opportunities for producing them using hydroponics more profitably than before.

Research Gaps and Future Directions

Several important research gaps have been identified in this review.

Commercial Scale-Up Studies: The majority of research has been limited to small-scale and experimental investigations. This indicates a need for research that specifically addresses the optimization of commercial production.

Economic Analyses: There is a lack of comprehensive cost-benefit analysis of all costs associated with production (rent, labor, packaging, taxes, and electricity, water, and plant materials) and sales price, yield.

Protocols for Long-Term Cultivation: Although FT has shown the possibility of being cultivated over the long term, there is still a need for the development of protocols that minimize disease risk during long-term cultivation.

Species-Specific Optimization: Given the varying response of different species to hydroponic systems (e.g., G. uralensis on the one hand provides negative results and on the other provides positive results), there is a need for the systematic evaluation and optimization of species on an individual basis.

Economic Viability of Precursor and Elicitors: The supplementation of precursors to the addition of elicitor treatments may be viable economically, but further investigation is needed on their effectiveness particularly from an economic point of view.

Continuous Extraction Systems for the Harvesting of Root Exudates: Research on the design and optimization of continuous extraction systems for the recovery of pharmaceutical compounds needs to be undertaken.

Conclusion

Hydroponics is a method of growing plants without soil, and has a lot of potential for making high quality herb-based medicine with a lot of active ingredients. This article reviews some of the most common ways to produce different parts of the herb using hydroponics.The leaves and stems of the herb are produced using liquid systems, such as deep flow technique (DFT), nutrient film technique (NFT), and floating technique (FT), or by using a solid media method when the plant has a woody stem.The flowers of the herb can be produced using both ebb and flow and solid media, but fast-growing flowers should be produced using the FT method prior to developing diseases, while the longer-lived flowers should be grown in pots.Roots can be produced using both solid and liquid systems; however, rhizomes require air-gap methods to prevent waterlogging.Fruits and seeds are most commonly produced by using pots, similar to producing edible fruits.In addition to choosing the system, hydroponics also allows for new production techniques, such as supplementing with precursors, adding elicitors, and harvesting root exudates, that may completely alter how we produce medicinal plants.There are some species of herbs that have valuable active ingredients located in parts of the plant that are not typically used, therefore yielding far more than what has typically been produced.

Nevertheless, there are still major information voids. There have been few studies that have examined the scale-up of commercial production; furthermore, few studies have examined the economic feasibility associated with this activity. With the continued growth in worldwide use of medicinal plant species, addressing these information voids is becoming increasingly important. The direction for future research should be to conduct economic analyses as well as to conduct experimental optimization to ensure that hydroponic methods developed in controlled environments can be translated into commercially viable production systems that will provide increased amounts of safe, effective and sustainable medicinal plant materials to meet the increasing need around the world.

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