Hydroponic Cultivation of Medicinal Herbs

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hydroponics | medicinal and aromatic plants | secondary metabolites

1. Introduction

Plants produce a variety of different chemicals throughout the course of their growth. Some of these compounds, known as secondary metabolites, are beneficial to human health. They have a wide variety of uses, including reducing inflammation, treating diabetes, reducing cancer risk, preventing cardiovascular disease, and some have antimicrobial effects [1]. The production of pharmaceutical drugs relies on many of these chemicals. Up to 60% of anti-infectious or anti-tumour drugs available are sourced from nature [2], and approximately 50% of modern pharmaceuticals overall are natural [3]. Currently, there are around 70,000 different species of plants used by both modern and traditional medicinal systems globally [4]. These plants, known as medicinal plants, have been used for thousands of years to treat health problems. In traditional Chinese medicine (TCM), for example, 80% of medicines are sourced from plants [5]. Traditional medicines are of particular importance in rural areas as up to 90% of the world's rural population use traditional medicine, due to limited access to modern medical facilities [6]. In China, 40% of people rely exclusively on traditional medicines, while in Africa, the proportion is even greater at 80% [7]. Therefore, maintaining the availability of this valuable source of medicinal treatments is of great importance.

However, the increasing interest in medicinal plants also has negative consequences. A number of medicinal plants are listed as endangered species, and the overharvesting of them in the wild puts them at greater threat of extinction [5]. In addition, purveyors of medicinal plants often, intentionally or unintentionally, sell plants that are incorrectly labelled, and samples vary in their secondary metabolite content or are contaminated with heavy metals [8]. The use of incorrect species in herbal medicines could result in an ineffective medicine or even adverse effects. Such instances have occurred where substitution, misidentification, and contamination have resulted in severe side effects and had the potential to cause fatalities [9]. Consequently, it is key that the environmental impact of using medicinal plants is reduced and that the safety and quality of medicinal material is maintained.

To ensure a stable supply of medicinal plants, efforts to cultivate them have been made. In China, around 200 species of medicinal herbs are cultivated on over 9.3 million hectares of land [10]. Similarly, research into the cultivation of Chinese medicinal plants has been conducted in Germany, and a selection of species have reached commercial production [11]. However, there are also disadvantages to cultivating medicinal plants in the field. The

concentrations of secondary metabolites present in wild populations are often higher due to the environmental stresses and competitive pressure of other species, while their slower growth rates also result in the increased accumulation of active ingredients [12][13]. For example, in a review of studies examining the cultivation of *Hypericum perforatum* L., Bruni and Sacchetti [14] observed that cultivation studies conducted in different countries reported hypericin, pseudohypericin, and hyperforin concentrations that varied widely. Similarly, differences in the salidroside yield of *Rhodiola sachalinensis* Boriss. (synonymous of *Rhodiola rosea* L.) roots were observed in response to soil characteristics, such as organic matter, nitrogen, phosphorous, and potassium content, as well as pH [15]. Additionally, seasonal variations in temperature and moisture have also been attributed to differences in the levels of phenolic compounds and saponins in *Tulbaghia violacea* Harv., *Hypoxis hemerocallidea* Fisch. & C.A.Mey., *Drimia robusta* Baker (synonymous of *Drimia elata* Jacq. ex Willd.), and *Merwilla plumbea* (Lindl.) Speta plants [16]. Continuous cropping of some species can also result in declining yields over time. This has been observed in *Panax ginseng* C.A.Mey., whose yields decline due to the proliferation of soilborne disease attributed to the accumulation of root exudates [17]. Hence, reliable methods to improve the secondary metabolite content in cultivated plant material are required.

One potential solution to this is the hydroponic cultivation of medicinal plants. Hydroponics utilises liquid media as the source of micro- and macronutrients that plants require for growth rather than the soil used in traditional systems [18]. There are a number of different systems and techniques used that fall into the category of “hydroponics”. Hydroponic techniques have been divided into two categories: solution culture and media culture, and their differences are outlined as follows.

In solution culture, the roots of plants are placed directly into liquid. Solution culture can be further subdivided into circulating and non-circulating systems. In circulating systems, nutrient solution is pumped from a reservoir into a tank, which then flows back into the reservoir. The nutrient film technique (NFT) utilises a tank on a slope which allows a shallow flow of water over the roots of the plant [19]. Contrastingly, in the deep flow technique (DFT), the tray is filled with solution and the roots are completely submerged [20]. Non-circulating systems are not pumped from a reservoir, and the nutrient solution simply sits within the culture tank and is then replaced when the nutrient concentration is inadequate or the pH or electrical conductivity (EC) are unsuitable. Examples of non-circulating systems include the root dipping technique (RDT), floating technique (FT) and capillary action technique. The root dipping technique uses plants suspended over nutrient solution while only the bottom portion of the roots are within the nutrient solution, while the floating technique sees the roots fully submerged [21], analogous to NFT and DFT, respectively. When the capillary action technique is used, nutrient solution is provided either via placing the pot into a very shallow container, where the solution then makes its way through the media by capillary action, or is transported from a reservoir to the media via wicks [22]. Finally, the ebb and flow technique is similar to DFT, but the nutrient solution is periodically drained from the culture tray and then re-added [23].

Solid media culture differs from solution culture in that plants are fully supported by a solid substrate to which nutrient solution is then applied either by surface or sub-surface fertigation. The hanging bag technique involves the hanging of around one-metre-long, media-filled polythene bags above a trough or channel. Plants in net pots are placed into holes cut into the sides of the bags. Nutrient solution is pumped from a reservoir into the top of the

bags, where it then makes its way through the media, drips into the trough, and is then returned to the reservoir [24]. When the grow bag technique is used, polythene bags containing media are placed on the ground. Small holes are cut into the bag, and seedlings or seeds are then placed inside. Nutrient solution is then fed along pipes to each plant [19]. The pot technique is similar to the grow bag technique, except that plants are placed within individual pots filled with media and individually fertigated [25]. Lastly, in the trench/trough technique, trenches dug into the ground, or troughs created above ground, are lined with a waterproof material and filled with inert media. Plants are then placed in the trough at intervals and are fed nutrient solution via drip irrigation [20]. Sometimes a drainage pipe is placed at the bottom to allow excess solution to drain from the soil.

When compared with soil cultivation, there is contradictory evidence as to whether hydroponic cultivation increases the growth and secondary metabolite concentration of medicinal plants. For example, Yoshimatsu [26] observed an increase in both biomass accumulation and glycyrrhizin content of *Glycyrrhiza uralensis* Fisch. in hydroponics, Surendran et al. [27] recorded that the *Mentha spicata* L. yield, organic acid concentration, and antioxidant content were higher in hydroponically grown plants, and Duan et al. [28] found that *Trichosanthes kirilowii* Maxim. had greater plant height and number of leaves per plant in hydroponics, as well as a 100% seedling survival rate compared with an 87% survival rate in soil. Conversely, Afreen et al. [29] found that hydroponic cultivation resulted in a reduction of root and shoot growth of *G. uralensis*, while Souret and Weathers [30] observed a lower increase in fresh weight in *Crocus sativus* L. when it was grown in hydroponics. Similarly, Maggini et al. [31] found that the echinacoside content of hydroponically grown *Echinacea angustifolia* DC. was below the 1% standard required by the European Pharmacopeia, and Strzemski et al. [32] remarked that cultivation of *Carlina acaulis* L. in hydroponics resulted in lower carlina oxide content than when it was grown in soil. When maximising the yield and medicinal content of hydroponically grown plants is considered, the selection of hydroponic system is an important factor. Hayden [33] compared the cultivation of various medicinal plants in three different systems: NFT, ebb and flow, and aeroponics (where nutrients are provided from an atomised nutrient solution). It was found that the plants responded differently to each system, allocating resources to different parts of the plant, but that no system was specifically suited to cultivating rhizomes. Facilitating the cultivation of different plant organs is important as secondary metabolites are often concentrated within specific tissues of the plant [34]. It is therefore important to select a system suited to cultivating the specific part of the plant that is desired. This is exemplified by Afreen et al. [29], who speculated that *G. uralensis* grew poorly in a DFT system due to leaching of secondary metabolites into the nutrient solution. Oppositely, Yoshimatsu [26] had great success in cultivating the same plant in an NFT system, producing rhizomes with a high content of medicinal compounds. As a consequence, when cultivating medicinal plants, the hydroponic system should be carefully considered in relation to the part of the plant that is desired.

Publications on the topic of hydroponics are widespread. In a review of hydroponic research trends, Erere et al. [35] recorded a total of 2013 scholarly publications on the topic of hydroponics between 2008 and 2018. However, less than 5% (99) of publications were related to the topic of medicine. In addition, of the 207 publications not written in English, 131 (6.5% of the total studies) were written in Chinese, which makes them difficult to access for a large number of researchers. Examination of these studies may reveal insights into hydroponic medicinal plant cultivation that are seldom explored in the wider literature.

2. Hydroponic Cultivation of Medicinal Herbs

Leafy green vegetables are among the most commonly cultivated plants in hydroponic systems. Lettuce (*Lactuca sativa* L.) has been cultivated using DFT [36], NFT [37], and pot technique [37], while spinach (*Spinacia oleracea* L.) has been grown in a floating system [38] but has been said to grow more effectively in solid-substrate systems than liquid culture [39]. Additionally, NFT [40] and capillary technique [41] have been used to cultivate pak choi (*Brassica rapa* subsp. *chinensis* (L.) Hanelt). Production of these leafy vegetables is conducted on a commercial scale in a number of different countries [42], and the techniques used may be applicable to medicinal herbs. Indeed, there is an overlap between herbal plants and food plants, with many of them being used as condiments [20] or as "functional foods" [43]. Most medicinal plants that are cultivated hydroponically are those where the aerial parts of the plants are used, typically the leaves and stems [44]. They are used in a variety of ways: they can be brewed into tea, applied topically, dried and powdered, and eaten fresh or cooked in food. Additionally, pharmaceutical companies may obtain active compounds by extracting and concentrating secondary metabolites directly from the raw plant material [45]. Examples of studies hydroponically cultivating plants where the leaves and stems of plants are used medicinally are shown in **Table 1**.

Table 1. Examples of publications discussing hydroponic cultivation of medicinal plants whose stems or leaves are utilised.

Hydroponic System	Plant Species	References
Liquid Culture Methods		
Deep Flow Technique	*Agastache rugosa* Kuntze	[46][47][48][49][50]
	Cannabis sativa L.	[51]
	Datura stramonium L.	[52]
	Euphorbia peplus L.	[53]
	Mentha spicata L.	[27][54]
Nutrient Film Technique	*Mentha arvensis* var. *piperascens* Malinv. ex Holmes (synonym of *Mentha canadensis* L.)	[54]
	Atropa belladonna L.	[26]
	Cannabis sativa L.	[51]
	Plectranthus amboinicus (Lour.) Spreng.	[55]
	Datura stramonium L.	[52]
	Lepidium sativum L.	[56]

Hydroponic System	Plant Species	References
	Mentha × *piperita* L.	[33]
	Morus alba L. 'Ichinose'	[57]
	Nepeta cataria L.	[33]
	Origanum dictamnus L.	[58][59]
	Ocimum basilicum L.	[56]
	Scutellaria lateriflora L.	[33]
	Urtica dioica L.	[33]
Floating Technique	*Artemisia vulgaris* L.	[60][61]
	Camellia sinensis (L.) Kuntze 'Yabukita'	[62][63]
	Cannabis sativa L.	[51]
	Cannabis sativa L. 'Cherry', 'Cherry Blossom', and 'Canda'	[64]
	Cannabis sativa L. 'Pennywise'	[65]
	Cannabis sativa L. type-II chemovar 'Nordle' and type-I chemovar 'Sensi Star'	[66]
	Camptotheca acuminata Decne.	[67]
	Centella asiatica (L.) Urb.	[68]
	Plectranthus amboinicus (Lour.) Spreng.	[69]
	Coriandrum sativum L.	[70]
	Dendrobium nobile Lindl.	[71]
	Ephedra sinica Stapf	[72]
	Hyssopus officinalis L. 'Lekar'	[73]
	Ilex purpurea Hassk. (synonym of *Ilex chinensis* Sims)	[74]
	Leonurus japonicus Houtt.	[75]
	Lobelia chinensis Lour.	[76]
	Melissa officinalis L.	[77]
	Mentha × *piperita* L.	[78]

Hydroponic System	Plant Species	References
	Ocimum basilicum L.	[31]
	Ocimum basilicum L. 'Genovese'	[78][79]
	Ocimum basilicum L. 'Eleonora', 'Aroma 2′, and 'Italiano Classico'	[80]
	Ocimum basilicum L. 'Superbo' and 'Dark Opal'	[79]
	Platycladus orientalis (L.) Franco	[81][82][83]
	Solanum nigrum Acerbi ex Dunal	[76]
	Stellaria media (L.) Vill.	[60][61]
	Urtica dioica L.	[84][85]
Capillary Action Technique	*Aloe vera* (L.) Burm.f.	[86]
	Cannabis sativa L.	[51]
	Cannabis sativa L.	[51]
Ebb and Flow Technique	*Mentha* × *piperita* L.	[33]
	Moringa oleifera Lam. 'PK1' and Malawi'	[87]
	Nepeta cataria L.	[33]
	Ocimum basilicum L. 'Emily'	[88]
	Scutellaria lateriflora L.	[33]
	Urtica dioica L.	[33]
Solid Culture Methods		
Grow Bag Technique	*Cannabis sativa* L.	[51]
	Mentha × *piperita* L.	[89]
	Moringa oleifera Lam. 'PK1' and Malawi'	[90][91]
Pot Technique	*Aloysia citrodora* Paláu 'Verbena'	[92]
	Cannabis sativa L.	[51][93]
	Cannabis sativa L. 'Bialobrzeskie' and 'Monoica'	[94]
	Cannabis sativa L. 'McLove'	[95]

Hydroponic System	Plant Species	References
	Cannabis sativa L. type-II chemovar 'Nordle'	[96]
	Datura stramonium L.	[97]
	Helichrysum odoratissimum Sweet	[98]
	Mentha arvensis L.	[99]
	Mentha × *piperita* L.	[99]
	Mentha spicata L.	[99]
	Ocimum basilicum L. 'Chádek červená', 'Litra', and 'Mánes'	[99]
	Cannabis sativa L.	[51]
Trough Technique	*Datura stramonium* L.	[100]

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is system
[101] [27][99] *Mentha arvensis* L. [31][88] [99] [46][47][48][49]
[50] [84] *Mentha* × *piperita* L. [99] *vulgaris* L.
[60] when the
Mentha spicata L. [99] a weekly
basis [60][63][70]. The pop *Ocimum basilicum* L. 'Chádek červená', 'Litra', and 'Mánes' [99] ronments
Cannabis sativa L. [51] ed to test
[66][72][74][81] ors [64][72]
[82] [71] *Datura stramonium* L. [67] [100] ssion [77].

Responses to these factors may be observed after only a few weeks of exposure, so cultivating plants to maturity may not be required. This leaves room for studies to examine the hydroponic culture of plants that take longer to grow. This is particularly important for the tree species studied—*Camptotheca acuminata* Decne. [67], *Ilex purpurea* Hassk. (now called *Ilex chinensis* Sims) [74], and *Platycladus orientalis* (L.) Franco [81][82][83]—which may be better cultivated in other hydroponic systems.

While liquid culture appears to be more widely used for small leafy plants, medicinal trees and shrubs used for their leaves are hydroponically cultured using solid media systems. This is because taller plants require a solid substrate to support their weight [21]. Additionally, the basal area of the stem needs to be kept dry to prevent rot [87]. Young *Moringa oleifera* Lam. trees cultivated in grow bags filled with sand and coir at a 3:1 ratio and fertigated with nutrient solution had greater secondary metabolite content when compared with those grown in the field [91]. Likewise, the fresh weight and leaf number of *Aloysia citrodora* Paláu grown in pots containing a 3:1 mixture of perlite and sand supplied with nutrient solution were also greater than those of their soil-grown counterparts [92]. The selection of sand as a significant component of the culture medium for both experiments suggests that adequate drainage is important for larger plants. These systems may be extended for use in cultivating other medicinal trees. In particular, the grow bag system used for the cultivation of *M. oleifera* [90][91] shows promise due to its simple design.

Studies focused on commercial cultivation use a variety of techniques. One particular focus is on the use of plant factories with artificial lighting (PFALs). The aim of PFALs is to optimise environmental conditions to maximise growth and phytonutrient content of high-value plants like vegetables and medicinal plants [102]. A series of studies on the cultivation of *A. rugosa* were conducted with the intention of optimising environmental conditions for commercial production in a PFAL [46][47][48][49][50] using DFT. Similarly, Bafort et al. [53] also used DFT in determining optimum growth conditions and assessing the economic viability of producing *Euphorbia peplus* L. in a modified shipping container analogous to a PFAL. Two different hydroponic techniques—NFT and ebb and flow—were compared by Hayden et al. [33] for the purposes of developing commercial cultivation. They found that *Mentha* ×

piperita L. and *Nepeta cataria* L. grew well in the ebb and flow system, while both systems were less effective than aeroponics for a variety of species. The use of FT has also been proposed for the commercial production of *O. basilicum* [31], as well as *A. vulgaris and S. media* [60], as it has low start-up costs and is cheap to run [45].

Cannabis sativa L. has been extensively studied due to its popularity as a recreational and medicinal drug. In addition, its high economic value means that cannabis cultivation is at the forefront of innovation with regards to the adoption of modern commercial production techniques for plants [103]. It has been cultivated in numerous hydroponic systems, but ebb and flow and NFT are among the most widely used and high-yielding systems [51]. These factors make studies on *C. sativa* cultivation valuable resources for determining the best practices for growing leafy medicinal plants.

References

1. Škrovánková, S.; Mišurcová, L.; Machů, L. Antioxidant Activity and Protecting Health Effects of Common Medicinal Plants. Adv. Food Nutr. Res. 2012, 67, 75–139.
2. Akinyemi, O.; Oyowole, S.O.; Jimoh, K.A. Medicinal Plants and Sustainable Human Health: A Review. Hortic. Int. J. 2018, 2, 194–195.
3. Kong, D.-X.; Li, X.-J.; Tang, G.-Y.; Zhang, H.-Y. How Many Traditional Chinese Medicine Components Have Been Recognized by Modern Western Medicine? A Chemoinformatic Analysis and Implications for Finding Multicomponent Drugs. ChemMedChem 2008, 3, 233–236.
4. Leaman, D.J. Sustainable Wild Collection of Medicinal and Aromatic Plants: Development of an International Standard. In Medicinal and Aromatic Plants; Bogers, R.J., Craker, L.E., Lange, D., Eds.; Springer: Dordrecht, Netherlands, 2006; pp. 97–107.
5. Zhou, L.G.; Wu, J.Y. Development and Application of Medicinal Plant Tissue Cultures for Production of Drugs and Herbal Medicinals in China. Nat. Prod. Rep. 2006, 23, 789–810.
6. Xego, S.; Kambizi, L.; Nchu, F. Threatened Medicinal Plants of South Africa: Case of the Family Hyacinthaceae. Afr. J. Tradit. Complem. 2016, 13, 169–180.
7. Zobayed, S. Medicinal Components. In Plant Factory, 2nd ed.; Kozai, T., Niu, G., Takagaki, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 245–250.
8. Hsieh, H.-J.; Lin, C.-C. Intelligent Medicinal Plant Factory. In Proceedings of the 2019 Prognostics and System Health Management Conference (PHM-Paris), Paris, France, 2–5 May 2019; pp. 239–243.
9. Mankga, L.T.; Yessoufou, K.; Moteetee, A.M.; Daru, B.H.; van der Bank, M. Efficacy of the Core DNA Barcodes in Identifying Processed and Poorly Conserved Plant Materials Commonly used in South African Traditional Medicine. Zookeys 2013, 365, 215–233.

10. Li, X.W.; Chen, Y.N.; Lai, Y.F.; Yang, Q.; Hu, H.; Wang, Y.T. Sustainable Utilization of Traditional Chinese Medicine Resources: Systematic Evaluation on Different Production Modes. Evid.-Based Compl. Alt. 2015, 2015, 218901.
11. Heuberger, H.; Bauer, R.; Friedl, F.; Heubl, G.; Hummelsberger, J.; Nogel, R.; Seidenberger, R.; Torres-Londono, P. Cultivation and Breeding of Chinese Medicinal Plants in Germany. Planta Med. 2010, 76, 1956–1962.
12. Dajic-Stevanovic, Z.; Pljevljakusic, D. Challenges and Decision Making in Cultivation of Medicinal and Aromatic Plants. In Medicinal and Aromatic Plants of the World: Scientific, Production, Commercial and Utilization Aspects; Máthé, A., Ed.; Springer: Dortrecht, The Netherlands, 2015; pp. 145–164.
13. Schippmann, U.; Leaman, D.; Cunningham, A.B. A Comparison of Cultivation and Wild Collection of Medicinal and Aromatic Plants Under Sustainability Aspects. In Medicinal and Aromatic Plants; Bogers, R.J., Craker, L.E., Lange, D., Eds.; Springer: Dortrecht, The Netherlands, 2006; pp. 75–95.
14. Bruni, R.; Sacchetti, G. Factors Affecting Polyphenol Biosynthesis in Wild and Field Grown St. John's Wort (Hypericum perforatum L. Hypericaceae/Guttiferae). Molecules 2009, 14, 682–725.
15. Yan, X.F.; Wu, S.X.; Wang, Y.; Shang, X.H.; Dai, S.J. Soil nutrient factors related to salidroside production of Rhodiola sachalinensis distributed in Chang Bai Mountain. Environ. Exp. Bot. 2004, 52, 267–276.
16. Ncube, B.; Finnie, J.F.; Van Staden, J. Seasonal variation in antimicrobial and phytochemical properties of frequently used medicinal bulbous plants from South Africa. S Afr. J. Bot. 2011, 77, 547.
17. Xiao, C.P.; Yang, L.M.; Zhang, L.X.; Liu, C.J.; Han, M. Effects of cultivation ages and modes on microbial diversity in the rhizosphere soil of Panax ginseng. J. Ginseng. Res. 2016, 40, 28–37.
18. Gericke, W.F. Hydroponics–Crop Production in Liquid Culture Media. Science 1937, 85, 177–178.
19. Sengupta, A.; Banerjee, H. Soil-less Culture in Modern Agriculture. World J. Sci. Technol. 2012, 2, 103–108.
20. Fussy, A.; Papenbrock, J. An Overview of Soil and Soilless Cultivation Techniques-Chances, Challenges and the Neglected Question of Sustainability. Plants 2022, 11, 1153.
21. Hussain, A.; Iqbal, K.; Aziem, S.; Mahato, P.; Negi, A.K. A Review on the Science of Growing Crops Without Soil (Soilless Culture)—A Novel Alternative for Growing Crops. Int. J. Agric. Crop Sci. 2014, 7, 833–842.
22. Sharma, N.; Acharya, S.; Kumar, K.; Singh, N.; Chaurasia, O.P. Hydroponics as an Advanced Technique for Vegetable Production: An Overview. J. Soil Water Conserv. 2018, 17, 364–371.

23. Macwan, J.; Pandya, D.; Pandya, H.; Mankad, A. Review on Soilless Method of Cultivation: Hydroponics. Int. J. Recent Sci. Res. 2020, 11, 37122–37127.
24. Waiba, K.M.; Sharma, P.; Sharma, A.; Chadha, S.; Kaur, M. Soil-less Vegetable Cultivation: A Review. J. Pharmacogn. Phytochem. 2020, 9, 631–636.
25. Hasan, M.; Sabir, N.; Singh, A.K.; Singh, M.C.; Patel, N.; Khanna, M.; Rai, T.; Pragnya, P. Hydroponics Technology for Horticultural Crops; Indian Agricultural Research Institute: Delhi, India, 2018.
26. Yoshimatsu, K. Innovative Cultivation: Hydroponics of Medicinal Plants in the Closed-Type Cultivation Facilities. J. Tradit. Med. 2012, 29, 30–34.
27. Surendran, U.; Chandran, C.; Joseph, E.J. Hydroponic Cultivation of Mentha spicata and Comparison of Biochemical and Antioxidant Activities with Soil-Grown Plants. Acta Physiol. Plant. 2017, 39, 26.
28. Duan, J.-X.; Duan, Q.-X.; Zhang, S.-F.; Cao, Y.-M.; Yang, C.-D.; Cai, X.-D. Morphological, Physiological, Anatomical and Histochemical Responses of Micropropagated Plants of Trichosanthes Kirilowii to Hydroponic and Soil Conditions during Acclimatization. Plant Cell Tissue Organ Cult. 2020, 142, 177–186.
29. Afreen, F.; Zobayed, S.M.A.; Kozai, T. Spectral quality and UV-B stress stimulate glycyrrhizin concentration of Glycyrrhiza uralensis in hydroponic and pot system. Plant Physiol. Bioch. 2005, 43, 1074–1081.
30. Souret, F.F.; Weathers, P.J. The Growth of Saffron (Crocus sativus L.) in Aeroponics and Hydroponics. J. Herbs Spices Med. Plants 2000, 7, 25–35.
31. Maggini, R.K.C.; Guidi, L.; Pardossi, A.; Raffaelli, A. Growing Medicinal Plants in Hydroponic Culture. Acta Hortic. 2012, 952, 697–704.
32. Strzemski, M.; Dresler, S.; Sowa, I.; Czubacka, A.; Agacka-Mołdoch, M.; Płachno, B.J.; Granica, S.; Feldo, M.; Wójciak-Kosior, M. The Impact of Different Cultivation Systems on the Content of Selected Secondary Metabolites and Antioxidant Activity of Carlina acaulis Plant Material. Molecules 2020, 25, 146.
33. Hayden, A.L. Aeroponic and Hydroponic Systems for Medicinal Herb, Rhizome, and Root Crops. Hortscience 2006, 41, 536–538.
34. Máthé, Á. Botanical Aspects of Medicinal and Aromatic Plants. In Medicinal and Aromatic Plants of the World: Scientific, Production, Commercial and Utilization Aspects; Máthé, Á., Ed.; Springer: Dordrecht, Netherlands, 2015; pp. 13–33.
35. Erere, A.; Adeniyi, V.; Adekiya, A.; Abiodun, J.; Abolusoro, S.; Aremu, C.; Olugbenga, O.; Oriade, O.; Olayiwola, I.; Oladokun, A.; et al. Hydroponics Research Trends: A Review and Bibliometric

Analysis (2008–2018). Nat. Volatiles Essent. Oils 2021, 8, 3240–3251.

36. Ferguson, S.D.; Saliga, R.P.; Omaye, S.T. Investigating the Effects of Hydroponic Media on Quality of Greenhouse Grown Leafy Greens. Int. J. Agric. Ext. 2014, 2, 227–234.
37. Li, Q.S.; Li, X.Q.; Tang, B.; Gu, M.M. Growth Responses and Root Characteristics of Lettuce Grown in Aeroponics, Hydroponics, and Substrate Culture. Horticulturae 2018, 4, 35.
38. Lenzi, A.; Baldi, A.; Tesi, R. Growing Spinach in a Floating System with Different Volumes of Aerated or Non Aerated Nutrient Solution. Adv. Hortic. Sci. 2011, 25, 21–25.
39. Parkell, N.B.; Hochmuth, R.C.; Laughlin, W.L. Leafy Greens in Hydroponics and Protected Culture for Florida. EDIS 2016, 2016, 7.
40. Caralde, R.A.; Salas, R.A. Effects of Novel Organic Nutrient Solution on Yield and Quality of Pakchoi under Aggregate Hydroponic System. Acta Hortic. 2015, 1088, 477–480.
41. Hanafiah, N.H.M.; Samsuri, S.; Yusup, S.; Amran, N.A. Effects of Nutrients on the Growth of Pak-Choi (Brassica chinensis L.) Seedlings in a Hydroponic System. Platf. A J. Sci. Technol. 2019, 2, 23–31.
42. Kalantari, F.; Tahir, O.M.; Joni, R.A.; Fatemi, E. Opportunities and Challenges in Sustainability of Vertical Farming: A Review. J. Landsc. Ecol. 2018, 11, 35–60.
43. Sharma, M.; Gupta, A.; Prasad, R. A Review on Herbs, Spices and Functional Food used in Diseases. Int. J. Res. Rev. 2017, 4, 103–108.
44. Hayden, A.; Brigham, L.; Giacomelli, G. Aeroponic Cultivation of Ginger (Zingiber officinale) Rhizomes. Acta Hortic. 2004, 659, 397–402.
45. Maggini, R.; Kiferle, C.; Pardossi, A. Hydroponic Production of Medicinal Plants. In Medicinal Plants: Antioxidant Properties, Traditional Uses and Conservation Strategies; Pereira, D.A.M., Ed.; Nova Science Publishers, Inc.: New York, NY, USA, 2014; pp. 91–116.
46. Kim, S.J.; Bok, K.J.; Lam, V.P.; Park, J.S. Response of Nutrient Solution and Photosynthetic Photon Flux Density for Growth and Accumulation of Antioxidant in Agastache rugosa under hydroponic Culture Systems. Prot. Hortic. Plant Fact. 2017, 26, 249–257.
47. Kim, S.J.; Park, J.E.; Bok, G.J.; Kanth, B.K.; Lam, V.P.; Park, J.S. High Electrical Conductivity of Nutrient Solution and Application of Methyl Jasmonate Promote Phenylpropanoid Production in Hydroponically Grown Agastache rugosa. Hortic. Sci. Technol. 2018, 36, 841–852.
48. Lam, V.P.; Kim, S.J.; Park, J.S. Optimizing the Electrical Conductivity of a Nutrient Solution for Plant Growth and Bioactive Compounds of Agastache rugosa in a Plant Factory. Agronomy 2020, 10, 76.

49. Lam, V.P.; Kim, S.J.; Bok, G.J.; Lee, J.W.; Park, J.S. The Effects of Root Temperature on Growth, Physiology, and Accumulation of Bioactive Compounds of Agastache rugosa. Agriculture 2020, 10, 162.
50. Lam, V.P.; Lee, M.H.; Park, J.S. Optimization of Indole-3-Acetic Acid Concentration in a Nutrient Solution for Increasing Bioactive Compound Accumulation and Production of Agastache rugosa in a Plant Factory. Agriculture 2020, 10, 343.
51. Cervantes, J. Marijuana Horticulture: The Indoor/Outdoor Medical Grower's Bible; Van Patten: Vancouver, Canada, 2006.
52. Rahmoune, B.; Morsli, A.; Khelifi-Slaoui, M.; Khelifi, L.; Strueh, A.; Erban, A.; Kopka, J.; Prell, J.; van Dongen, J.T. Isolation and characterization of three new PGPR and their effects on the growth of Arabidopsis and Datura plants. J. Plant Interact. 2017, 12, 1–6.
53. Bafort, F.; Kohnen, S.; Maron, E.; Bouhadada, A.; Ancion, N.; Crutzen, N.; Jijakli, M.H. The Agro-Economic Feasibility of Growing the Medicinal Plant Euphorbia peplus in a Modified Vertical Hydroponic Shipping Container. Horticulturae 2022, 8, 256.
54. Vimolmangkang, S.; Sitthithaworn, W.; Vannavanich, D.; Keattikunpairoj, S.; Chittasupho, C. Productivity and quality of volatile oil extracted from Mentha spicata and M. arvensis var. piperascens grown by a hydroponic system using the deep flow technique. J. Nat. Med. 2010, 64, 31–35.
55. Ignatius, A.; Arunbabu, V.; Neethu, J.; Ramasamy, E.V. Rhizofiltration of lead using an aromatic medicinal plant Plectranthus amboinicus cultured in a hydroponic nutrient film technique (NFT) system. Environ. Sci. Pollut. R 2014, 21, 13007–13016.
56. Olfati, J.A.; Khasmakhi-Sabet, S.A.; Shabani, H. Nutrient Solutions on Yield and Quality of Basil and Cress. Int. J. Veg. Sci. 2012, 18, 298–304.
57. Sakurai, M.; Sato, S.; Fukushima, T.; Konishi, T. Characteristics of Morus alba L. Cultured by in-Room Hydroponics. Am. J. Plant Sci. 2022, 13, 91–108.
58. Economakis, C.; Skaltsa, H.; Demetzos, C.; Sokovic, M.; Thanos, C.A. Effect of phosphorus concentration of the nutrient solution on the volatile constituents of leaves and bracts of Origanum dictamnus. J. Agric. Food Chem. 2002, 50, 6276–6280.
59. Economaks, C.; Karioti, A.; Skaltsa, H.; Perdetzoglou, D.; Demetzos, C. Effect of solution conductivity on the volatile constituents of Origanum dictamnus L. in nutrient film culture. J. Agric. Food Chem. 2005, 53, 1656–1660.
60. Dorais, M.; Papadopoulos, A.P.; Luo, X.; Leonhart, S.; Gosselin, A.; Pedneault, K.; Angers, P.; Gaudreau, L. Soilless Greenhouse Production of Medicinal Plants in North Eastern Canada. Acta Hortic. 2001, 554, 297–304.

61. Dorais, M.; Ménard, C.; Gosselin, A.; Léonhart, S.; Gaudreau, L.; Desrochers, L.; Martel, M.; Vézina, L.P.; Purcell, M.; Carpentier, E. Influence of Supplemental Lighting on the Production of Medicinal Plants, Spinach and Alfalfa for the Nutraceutical and Pharmaceutical Sectors. Acta Hortic. 2006, 711, 43–50.
62. Saito, K.; Ikeda, M. The Function of Roots of Tea Plant (Camellia sinensis) Cultured by a Novel Form of Hydroponics and Soil Acidification. Am. J. Plant Sci. 2012, 3, 646–648.
63. Saito, K.; Furue, K.; Kametani, H.; Ikeda, M. Roots of Hydroponically Grown Tea (Camellia sinensis) Plants as a Source of a Unique Amino Acid, Theanine. Am. J. Exp. Agric. 2014, 4, 125–129.
64. Bailey, R. The Effect of Elicitor Stimulation on Cannabinoid Production by Industrial Hemp (Cannabis sativa) Varieties in a Hydroponic System; Middle Tennessee State University: Murfreesboro, TN, USA, 2019.
65. Punja, Z.K.; Rodriguez, G. Fusarium and Pythium species infecting roots of hydroponically grown marijuana (Cannabis sativa L.) plants. Can. J. Plant Pathol. 2018, 40, 498–513.
66. Yep, B.; Gale, N.V.; Zheng, Y.B. Aquaponic and Hydroponic Solutions Modulate NaCl-Induced Stress in Drug-Type Cannabis sativa L. Front. Plant Sci. 2020, 11, 1169.
67. Li, Z.H.; Liu, Z.J. Camptothecin production in Camptotheca acuminata cultured hydroponically and with nitrogen enrichments. Can. J. Plant Sci. 2005, 85, 447–452.
68. Prasad, A.; Pragadheesh, V.S.; Mathur, A.; Srivastava, N.K.; Singh, M.; Mathur, A.K. Growth and centelloside production in hydroponically established medicinal plant-Centella asiatica (L.). Ind. Crop Prod. 2012, 35, 309–312.
69. Dass, S.M.; Chai, T.-T.; Wong, F.-C. Investigation on the Effects of Hydroponic-Planting versus Soil-Planting Using Plectranthus amboinicus as a Plant Model. J. Trop. Life Sci. 2022, 12, 53–61.
70. Hazeri, N.; Valizadeh, J.; Shakeri, A.; Rajabpour, M. Evaluation of Essential Oil and Mineral Composition of Coriander (Coriandrum sativum L.) Among Growth Conditions of Hydroponic, Field and Greenhouse. J. Essent. Oil Bear. Plants 2012, 15, 949–954.
71. Gong, J.; Li, F.; Sun, W.; Tang, J.; Yi, Y. Effects of Endophytic Fungi on the Seedling Growth Characteristics of Dendrobium nobile under Nutritional Deficiency. J. Yunnan Agric. Univ. 2019, 34, 110–115.
72. Zhang, Y.; Ji, R.; Li, H.; Liu, J.; Yuan, H. Effects of Exogenous Substances on Root Growth of Ephedra sinica Stapf Seedlings under Salt Stress. For. Ecol. Sci. 2020, 35, 320–324.
73. Skrypnik, L.; Feduraev, P.; Styran, T.; Golovin, A.; Katserov, D.; Nebreeva, S.; Maslennikov, P. Biomass, Phenolic Compounds, Essential Oil Content, and Antioxidant Properties of Hyssop

(Hyssopus officinalis L.) Grown in Hydroponics as Affected by Treatment Type and Selenium Concentration. Horticulturae 2022, 8, 1037.

74. Zhang, L.-J.; Huang, S.-L.; Zhou, J.-M.; Xia, G.-H.; Huang, Y.-J. The Morphological Change of Offorested Trees under Salt Stress and Selection of Salt-Resistant Trees. Acta Agric. Univ. Jianxiensis 2008, 30, 833–838.
75. Song, T.; Peng, F.; Tan, Z.-Y. Effect of Precursors on the Content of Stachydrine Hydrochloride in the Hydroponic Herba Leonuri. Cent. South Pharm. 2012, 10, 814–817.
76. Peng, K.J.; Luo, C.L.; Chen, Y.H.; Wang, G.P.; Li, X.D.; Shen, Z.G. Cadmium and Other Metal Uptake by Lobelia chinensis and Solanum nigrum from Contaminated Soils. B Environ. Contam. Tox 2009, 83, 260–264.
77. Silva, T.C.; Bertolucci, S.K.V.; Carvalho, A.A.; Tostes, W.N.; Alvarenga, I.C.A.; Pacheco, F.V.; de Assis, R.M.A.; Honorato, A.D.; Pinto, J.E.B.P. Macroelement omission in hydroponic systems changes plant growth and chemical composition of Melissa officinalis L. essential oil. J. Appl. Res. Med. Aroma. 2021, 24, 100297.
78. Ronga, D.; Pellati, F.; Brighenti, V.; Laudicella, K.; Laviano, L.; Fedailaine, M.; Benvenuti, S.; Pecchioni, N.; Francia, E. Testing the influence of digestate from biogas on growth and volatile compounds of basil (Ocimum basilicum L.) and peppermint (Mentha x piperita L.) in hydroponics. J. Appl. Res. Med. Aroma. 2018, 11, 18–26.
79. Kiferle, C.; Lucchesini, M.; Mensuali-Sodi, A.; Maggini, R.; Raffaelli, A.; Pardossi, A. Rosmarinic acid content in basil plants grown in vitro and in hydroponics. Cent. Eur. J. Biol. 2011, 6, 946–957.
80. Ciriello, M.; Formisano, L.; El-Nakhel, C.; Corrado, G.; Pannico, A.; De Pascale, S.; Rouphael, Y. Morpho-Physiological Responses and Secondary Metabolites Modulation by Preharvest Factors of Three Hydroponically Grown Genovese Basil Cultivars. Front. Plant Sci. 2021, 12, 671026.
81. Yao, X.; Ji, J.; Yue, J.; Xie, T.; Deng, N.; Shi, S.; Jiang, Z.; Chang, E. Reactive Oxygen Metabolism and Related Gene Expression in Platycladus orientalis under Salt Stress. Acta Bot. Boreali Occident. Sin. 2017, 37, 105–114.
82. Yao, X.-M.; Chang, E.-M.; Ji, J.; Yue, J.-Y.; Xie, T.-T.; Deng, N.; Shi, S.-Q.; Jiang, Z.-P. Reactive Oxygen Metabolism and Its Related Gene Expression in Platycladus orientalis under H2O2 Stress and Regulated by ABA. For. Res. 2017, 30, 624–632.
83. Yang, G.; Liu, W.; Fan, B.; Pei, B.; Yang, X. Effects of Root-Cutting on Antioxidant Enzyme System and Osmotic Adjustment Substances of Platycladus orientalis. J. Henan Agric. Sci. 2017, 46, 92–96.
84. Radman, S.; Fabek, S.; Žutić, I.; Benko, B.; Toth, N. Stinging Nettle Cultivation in Floating Hydropon. Contemp. Agric. 2014, 63, 624–632.

85. Radman, S.; Javornik, M.; Žutić, I.; Opačić, N.; Benko, B. Impact of different nutrient solution composition on stinging nettle growth and mineral content. In Proceedings of the VIII South-Eastern Europe Symposium on Vegetables and Potatoes 1320, Ohrid, North Macedonia, 24–26 September 2021; pp. 157–166.
86. Bhattacharya, N. Hydroponics: Producing Plants In-Vitro on Artificial Support Medium. Int. J. Sci. Eng. Res. 2017, 8, 224–229.
87. Crosby, G.W.; Craker, L.E. Development of Soilless Culture Methods for Production of Moringa (Moringa oleifera Lam.) Root and Leaf Biomass. Acta Hortic. 2007, 756, 139–146.
88. Hosseini, H.; Mozafari, V.; Roosta, H.R.; Shirani, H.; van de Vlasakker, P.C.H.; Farhangi, M. Nutrient Use in Vertical Farming: Optimal Electrical Conductivity of Nutrient Solution for Growth of Lettuce and Basil in Hydroponic Cultivation. Horticulturae 2021, 7, 283.
89. Mollafilabi, A.; Hassan, Z.R.K.; Aroiee, H.; Sadrabadi, H.R.; Jahedi, P.S.; Taghi, E.M. Effect of Optimizing Nitrogen and Potassium Application in Johnson Nutrient Solution on Essential Oil Content of Peppermint in Hydroponics Culture. Acta Hortic. 2010, 853, 157–160.
90. Managa, L.R.; du Toit, E.S.; Prinsloo, G. Variations in the Leaf Metabolite Profile between Hydroponic and Field Grown Moringa oleifera Lam. Genotypes. Biochem. Syst. Ecol. 2021, 97, 104302.
91. Managa, L.R.; du Toit, E.S.; Prinsloo, G. NMR-Based Metabolomic Analyses to Identify the Effect of Harvesting Frequencies on the Leaf Metabolite Profile of a Moringa oleifera Cultivar Grown in an Open Hydroponic System. Molecules 2021, 26, 2298.
92. Aliniaeifard, S.; Rezaei-Nejad, A.H.; Seifi-Kalhor, M.; Sahhlaei, A.; Aliniaeifard, A. Comparison of Soil and Perlite (with Nutrient Solution Supply) Growing Media for Cultivation of Lemon Verbena (Lippia citriodora var. ‘verbena’). Med. Aromat. Plant Sci. Biotechnol. 2011, 5, 30–33.
93. Chandra, S.; Lata, H.; Khan, I.A.; ElSohly, M.A. Propagation of Elite Cannabis sativa L. for the Production of Δ9-Tetrahydrocannabinol (THC) using Biotechnological Tools. In Medicinal Plant Biotechnology; Arora, R., Ed.; C.A.B.I.: Cambridge, MA, USA, 2011; pp. 98–114.
94. Kalousek, P.; Schreiber, P.; Vyhnanek, T.; Trojan, V.; Adamcova, D.; Vaverkova, M.D. Effect of Landfill Leachate on the Growth Parameters in Two Selected Varieties of Fiber Hemp. Int. J. Environ. Res. 2020, 14, 155–163.
95. Malik, M.; Velechovsky, J.; Praus, L.; Janatova, A.; Kahankova, Z.; Kloucek, P.; Tlustos, P. Amino Acid Supplementation as a Biostimulant in Medical Cannabis (Cannabis sativa L.) Plant Nutrition. Front. Plant Sci. 2022, 13, 868350.
96. Yep, B.; Gale, N.V.; Zheng, Y.B. Comparing hydroponic and aquaponic rootzones on the growth of two drug-type Cannabis sativa L. cultivars during the flowering stage. Ind. Crop. Prod. 2020, 157, 112881.

97. Vaillant, N.; Monnet, F.; Hitmi, A.; Sallanon, H.; Coudret, A. Comparative study of responses in four Datura species to a zinc stress. Chemosphere 2005, 59, 1005–1013.
98. Zantanta, N.; Kambizi, L.; Etsassala, N.G.E.R.; Nchu, F. Comparing Crop Yield, Secondary Metabolite Contents, and Antifungal Activity of Extracts of Helichrysum odoratissimum Cultivated in Aquaponic, Hydroponic, and Field Systems. Plants 2022, 11, 2696.
99. Zeljkovic, S.C.; Aucique-Perez, C.E.; Štefelová, N.; De Diego, N. Optimizing growing conditions for hydroponic farming of selected medicinal and aromatic plants. Food Chem 2022, 375, 131845.
100. Sellar, A.D.W. Effects of Gibberellic Acid on Datura Species. Datura stramonium var. tatula (L.) Torr; University of Glasgow: Glasgow, UK, 1964.
101. Resh, H.M. Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower, 7th ed.; CRC Press: Boca Raton, FL, USA, 2013.
102. Kozai, T.; Niu, G. Role of the Plant Factory with Artificial Lighting (PFAL) in Urban Areas. In Plant Factory, 2nd ed.; Kozai, T., Niu, G., Takagi, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 7–34.
103. Kubota, C. North America. In Plant Factory, 2nd ed.; Kozai, T., Niu, G., Takagi, M., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 69–73.