Aeroponic and Hydroponic Systems for Medicinal Herb, Rhizome, and Root Crops

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***Summary*. Hydroponic and aeroponic production of medicinal crops in controlled environments provides opportunities for improving quality, purity, consistency, bioactivity, and biomass production on a commercial scale. Ideally, the goal is to optimize the environment and systems to maximize all five characteristics. Examples of crop production systems using perlite hydroponics, nutrient film technique (NFT), ebb and flow, and aeroponics were studied for various root, rhizome, and herb leaf crops. Biomass data comparing aeroponic vs. soilless culture or field grown production of burdock root (*Arctium lappa*), stinging nettles herb and rhizome (*Urtica dioica*), and yerba mansa root and rhizome (*Anemopsis californica*) are presented, as well as smaller scale projects observing ginger rhizome (*Zingiber officinale*) and skullcap herb (*Scutellaria lateriflora*). Phytochemical concentration of marker compounds for burdock and yerba mansa in different growing systems are presented.**

Production of medicinal herb and root crops in controlled environments (CE) provides opportunities for improving the quality, purity, consistency, bioactivity, and biomass production of the raw material. Hydroponic systems in CE can produce high quality herb and root material free from accidental adulteration by weeds, soil, or environmental toxins such as heavy metals in soils. The CE is more conducive to controlling pests through the use of beneficial organisms in place of synthetic pesticides, thereby increasing the product's value in the eyes of environmentally conscious consumers and eliminating the possibility of accidental pesticide contamination. The CE can also produce a more consistent herbal raw material by accommodating clonal propagation techniques, allowing multiple harvests of both aerial parts and roots from a single crop, and extending the growing season. In some species, it may be possible to optimize for higher yields of specific secondary metabolites, or for higher yields of target organs, such as roots, rhizomes, or leaves.

Hydroponic systems include all systems that deliver the nutrients in a liquid form, with or without an aggregate medium to anchor the plant roots. Various medicinal crops were observed in different hydroponic systems: a perlite air-gap system, nutrient film technique (NFT), ebb and flow systems, and aeroponics. All four systems employed recirculating liquid solutions that are efficient in their use of water and fertilizers. The perlite air-gap system consists of a large reservoir of perlite with fertilizer solution at a depth adequate to keep the plants hydrated. NFT is a gutter (channel) system without any aggregate medium, and where the fertilizer solution is trickled past the roots. Ebb and flow systems are large shallow trays on benches or the floor where fertilizer solution is delivered to the plants by filling the trays (also called flood and drain). Ebb and flow systems may or may not use an aggregate medium. Aeroponics systems do not use aggregate media. In aeroponics, the roots of the crop are suspended in a spray chamber where they are fully accessible for monitoring and harvesting, permitting multiple harvests of roots from a single crop (Fig. 1). The aeroponic systems were designed and constructed by Native American Botanics Corp., each measuring 6 ft wide, 36 ft long, and holding up to 1,200 gal of recirculating nutrient solution in a reservoir directly under the plants. The aeroponic units were built in an A-frame shape, with multiple

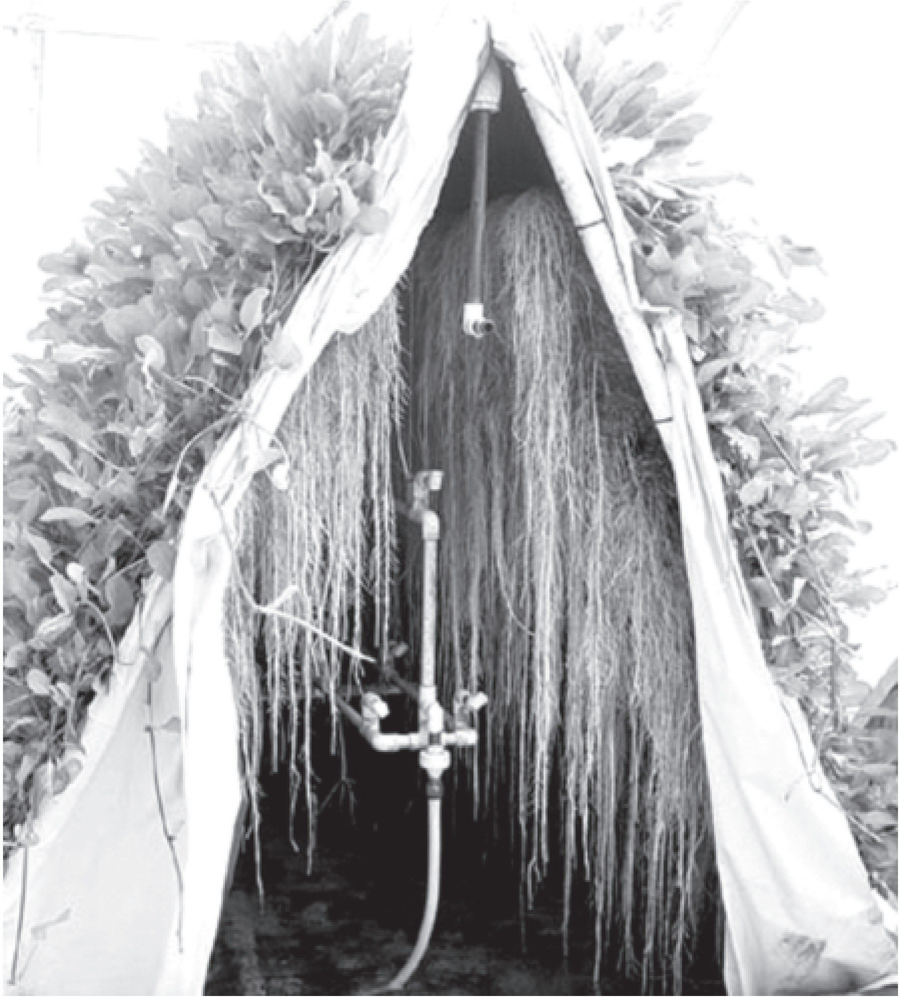

Fig. 1. Aeroponic A-frame unit opened to show *Anemopsis californica* (yerba mansa) roots (Native American Botanics Corp, Tucson, Ariz.).

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Table 1. Plant species with roots or rhizomes commonly used in the medicinal and phytopharmaceutical industries.

Latin name	Common name(s)	Plant parts used
Actaea racemosa	Black cohosh	Rhizomes and roots
Anemopsis californica	Yerba mansa	Rhizomes and roots
Angelica archangelica	Angelica	Roots and leaves
Angelica atropurpurea	Angelica	Roots and leaves
Angelica sinensis	Angelica	Roots and leaves
Arctium lappa	Burdock	Tap root
Arctium minus	Burdock	Tap root
Astragalus membranaceus	Astragalus	Tap root
Dioscorea quaternata	Wild yam	Rhizomes and tubers
Dioscorea villosa	Wild yam	Rhizomes and tubers
Echinacea angustifolium	Echinacea	Roots
Echinacea purpurea	Echinacea	Roots
Echinacea pallida	Echinacea	Roots
Glycyrrhiza glabra	Licorice	Rhizomes
Hydrastis canadensis	Goldenseal	Rhizomes
Ligusticum porteri	Oshá	tap root
Lomatium dissectum	Lomatium	Roots
Panax ginseng	Ginseng	Roots
Panax quinquefolium	Ginseng	Roots
Piper methysticum	Kava	Rhizomes and roots
Podophyllum peltatum	Mayapple	Rhizomes and roots
Sanguinaria canadensis	Bloodroot	Rhizomes
Symphytum officinale	Comfrey	Tap root
Trillium erectum	Trillium	Rhizome and roots
Urtica dioica	Stinging nettles	Rhizomes, roots, leaves
Valeriana officinalis	Valerian	Roots
Zingiber officinale	Ginger	Rhizomes

flat panels at 60° angles, permitting 1.7 times more growing area than the unit's footprint in the greenhouse. The A-frame structure allows use of vertical space to provide 372 ft^2 of crop-growing area in 216 ft^2 of greenhouse floorspace.

Medicinal and phytopharmaceutical crops are botanically diverse, and can be challenging to cultivate. The top twenty herbs sold in the US herbal dietary supplement market in 2004 (Blumenthal, 2005) represented seventeen different botanical families. Seven of the twenty harvested below-ground parts (roots and rhizomes), five used seeds, four were comprised of all aerial parts (leaves and flowers), three were fruits, and one product is from a tree bark. Many plant-based medicinal products incorporate roots and rhizomes (Table 1), although the scientific literature usually refers to all below-ground parts as roots. Anatomically, rhizomes are stem tissue, and can have very different phytochemical properties from true roots. In some species, the phytochemical profiles can be similar in rhizomes, roots, and leaves, although relative concentrations of individual constituents may vary among plant organs. When choosing which hydroponic system to use for production of a crop, it is imperative to know exactly what the below-ground architecture of the crop is, and which characteristics should be maximized.

Aeroponics appeared to be the most productive system in CE for medicinal crops where the herb (leaves and flowers) or roots were harvested. None of the four systems were ideal for rhizome production, although the simple perlite air-gap system did appear to be the best candidate for future work involving rhizome crops. Both NFT and ebb and flow systems appeared to minimize root production.

HERB CROPS

Mints. Several herb crops in the mint family were observed in CE using different hydroponic systems. Skullcap (*Scutellaria laterifolia*, Lamiaceae) produced very high yields of leaves and flowers in an A-frame aeroponic system, averaging 253 g dry herb per plant (n = 20) on the second harvest, at a planting density of about 0.8 plants per square foot. Multiple harvests per year of this long-lived perennial mint are possible in CE. Other members of the mint family, namely peppermint and catnip, also responded very well in both aeroponics and ebb and flow systems. The vertical aspect of an A-frame aeroponic design permits higher biomass production than the ebb and flow in the same area of the greenhouse, making aeroponics a very desirable system for high-yielding leaf crops.

RHIZOME CROPS

Ginger. Crops grown exclusively for their rhizomes can be difficult to manage in hydroponic systems, since multibranching rhizomes produce shoots that emerge in unpredictable patterns. Most commercial hydroponic systems are designed to accommodate plants with a uniform architecture, particularly at the base of the stem. Medicinal rhizome crops can be either pachymorphic (short length relative to width), or leptomorphic (long length relative to width). A loose, fine aggregate medium, such as perlite or sand, in a system with an open top is appropriate for either type of rhizome crop. The aggregate medium should provide proper drainage so that the roots of the plants have direct contact with fertilizer solution, but the rhizomes are not subjected to contact with the fertilizer salts.

Ginger (*Zingiber officinale*, Zingiberaceae) was grown in a prototype aeroponic unit specifically designed for the challenges of maximizing rhizome production (Hayden, Brigham and Giacomelli, 2004). This unique system incorporated a rhizome compartment filled with an aggregate medium suspended above an aeroponic spray chamber. The roots were able to penetrate through a porous interface down into the spray chamber, while the rhizomes were protected from direct contact with the fertilizer solution. In this small observation study, ginger plants reacted favorably to bottom heat, exhibiting earlier growth and larger rhizomes. The bottom heat was supplied by heating the pool of fertilizer solution below the plants.

ROOT CROPS

Burdock. A tap root crop was tested in aeroponics, using burdock (*Arctium lappa*, Asteraceae) as a model. The root yield after six months was impressive, averaging 227 g dry weight per plant, at a planting density of 0.5 plants per square foot in an A-frame aeroponic system (Pagliarulo and Hayden, 2002). Fifteen *A. lappa* plants grown for 6 months in the aeroponic system were tested for a phytochemical marker compound and the concentration of chlorogenic acid averaged 1.61 ± 0.61 mg·g^{-1} dry weight, which is comparable to the chlorogenic acid concentrations of burdock root products purchased from a local market as well as that reported by Wang et al. (2001) (Hayden, et al, 2004). The taproots harvested at 6 months were mature, with well-formed root bark and no evidence of abnormal growth.

ROOT AND RHIZOME CROPS

Yerba mansa. A similar experiment was conducted on another medicinal root crop, yerba mansa (*Anemopsis californica*, Saururaceae). This perennial crop is native to the riparian areas of the southwestern U.S and Northern Mexico, and is valued by local herbalists for its aromatic roots, rhizomes, and leaves. Although all parts of this herbaceous plant are used, the horizontal crown, or rhizome and any attached roots are the plant parts normally sold in the medicinal herb market. The rhizomes are rarely branched. The plant vegetatively propagates by runners, so mother plants were established in static tubs of perlite containing adequate levels of nutrient solution to keep the plants well fed and hydrated (an air-gap hydroponic system). Heat applied to the pool of nutrient solution below the perlite produced accelerated growth in early spring in an unheated greenhouse in Tucson, Arizona. In total, 800 daughter plants were removed from the mother plants and propagated in an ebb and flow tray for transplant into aeroponic units as soon as roots were established. The plants remained in the aeroponic system for eight months, establishing good root systems. Plants were also observed in an NFT system, but root production was severely reduced in the NFT, as compared to those grown in the aeroponic systems.

After trimming the roots and tops of all plants, half were moved into three-inch pots with soilless potting mix in preparation for transplant into a prepared field located in Pata-

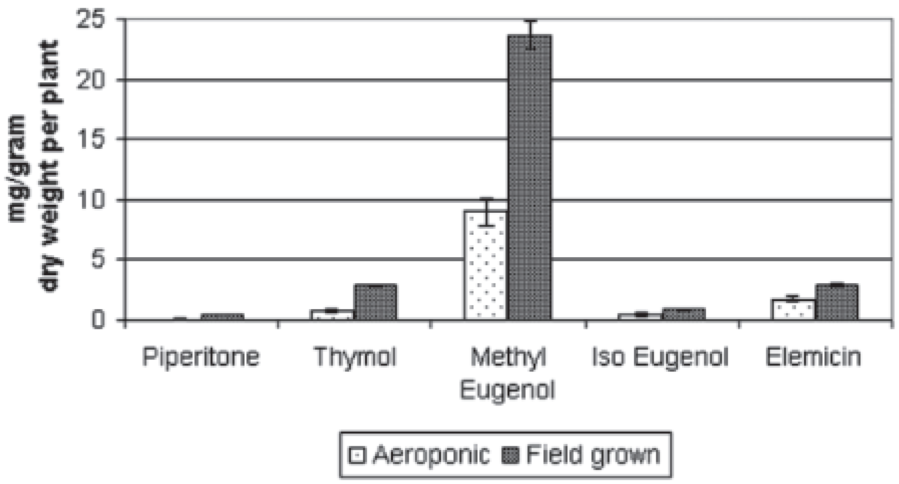

Fig. 2. Yields of selected monoterpenes in *Anemopsis californica* (yerba mansa) roots and rhizomes—aeroponic vs. field grown.

gonia, Arizona. In April 2004, 400 acclimated plants were transplanted into four rows, with one hundred plants per row, one foot spacing between plants within the row, six feet between the rows, and drip irrigation was installed (Native Seeds SEARCH, Tucson, Arizona). Plants were allowed to spread by runners to cover a three-foot wide row, at an original planting density of 0.3 mother plants per square foot. Another 392 plants were replanted back into aeroponic A-frame units in an unheated, but fan and pad cooled greenhouse. The planting density on the aeroponic panels was 6.3 mother plants per square foot, with 98 plants in each of four 15.5-ft^2 panels. In the A-frame configuration, this translates to 196 plants in an 18-ft^2 footprint, or 10.9 mother plants per square foot of greenhouse floorspace. Plants were permitted to produce runners, but the runners were not able to take root in the plastic-covered system (Fig. 1).

Harvest of 9-month-old field-grown and aeroponically grown yerba mansa plants was done in December 2004. The dry weight yield of field-grown roots and rhizome (16.7 ± 1.15 g/plant, n = 80) was significantly greater compared to the aeroponically grown roots and rhizome (13.5 ± 1.15 g/plant, n = 81). However, when recalculated as yield per square foot of floor or field space, the aeroponically grown crop yielded 23 times higher root or rhizome biomass than the field grown crop due to the high density, vertical planting scheme permitted in an A-frame structure.

Five monoterpenoid marker compounds were measured in the roots and rhizome of a subset of individual plants from both the aeroponic and field-grown treatments by GC-FID (gas chromatography–flame ionization detection) according to the methods described in Medina et al., 2005. Concentrations of all five compounds were significantly higher in the field-grown plants than aeroponically grown plants, when measured on a mg·g^{-1} dry weight basis (Fig. 2). The concentration of each compound (mg·g^{-1} dry weight ± standard error) in the aeroponically grown plants (n = 79) vs. field grown plants (n = 80) was found to be as follows: piperitone, 0.053 ± 0.03 vs. 0.478 ±0.03; thymol, 0.078 ± 0.12 vs. 2.86 ± 0.12; methyl eugenol, 9.03 ± 1.1 vs. 23.68 ± 1.1; iso- eugenol, 0.46 ± 0.1 vs. 0.89 ± 0.1; and elemicin, 1.75 ± 0.19 vs. 2.92 ± 0.19, respectively. There was no difference in the plant-to-plant variability of the concentration of any of the compounds; in this study field-grown plants produced roots and rhizomes with higher concentrations of marker compounds than the aeroponically grown plants, but with similar variability.

MULTI-PRODUCT CROP (HERB, RHIZOME AND ROOT)

Stinging nettles. Stinging nettles (*Urtica dioica*, Urticaceae) was grown in the A-frame aeroponic system, with soilless mix controls in a statistical study (Pagliorulo, Hayden, and Giacomelli, 2004). Both aerial parts and below-ground parts of stinging nettles are used in the herbal dietary supplement industry. Throughout the literature, there are conflicting and confusing terms describing the below-ground parts of stinging nettles, with most authors reporting use of roots in research and clinical trials (e.g., Sokeland, 2000; Testai et al., 2002; Kraus and Spiteller, 1990; Belaiche and Lievoux, 1991; Schottner et al., 1997). Other researchers report rhizomes (e.g., Weglarz and Roslon, 2000; World Health Organization, 1999). It is unclear in much of the literature if true roots, rhizomes, or a combination of both were used in the research, including earlier work published by this author (Pagliarulo et al., 2004). This nomenclature should be used carefully, as differences in biomass and bioactivity are likely between the two distinct plant organs.

Stinging nettles grown in an A-frame aeroponic unit produced equal aerial biomass but lower below-ground biomass, compared with controls grown in soilless potting mix. This is probably due to the greater rhizome production observed in the controls, whereas the aeroponically grown plants produced true roots and few rhizomes. The aeroponically grown plants did permit multiple root harvests from the same plants however, and the cumulative root yield from plants harvested twice was significantly higher than the harvest of two crops planted sequentially in the same aeroponic system (Pagliarulo, Hayden and Giacomelli, 2004). This study suggested that A-frame aeroponic systems may be superior for producing true roots, but are not ideal for rhizome production.

CONCLUSIONS

Hydroponic systems can be used to produce very clean, high-quality herb and root crops for the natural products industry. A-frame aeroponic systems increase the yield per square foot of greenhouse area by maximizing vertical space. Work is needed to improve the concentration of target compounds in specific crops, however the nature of controlled environment agriculture is conducive to such manipulations. Additional work is needed to develop and scale up a hydroponic system that can maximize rhizome biomass production.

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