

TECHNOLOGICAL CRITERIA FOR CULTIVATING MEDICINAL PLANTS IN HYDROPONIC AND AEROPONIC SYSTEMS

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Abstract: *Hydroponic and aeroponic systems have emerged as advanced technologies in modern agriculture, enabling year-round cultivation, optimized resource use, and high-quality yields of medicinal plants. These soilless systems allow precise control over nutrient delivery, water efficiency, environmental parameters, and plant physiological conditions, which is critical for maximizing biomass and bioactive compound production. This study examines the technological criteria for successful cultivation of medicinal plants in hydroponic and aeroponic systems, including nutrient solution composition, pH and electrical conductivity regulation, root zone aeration, temperature, humidity, light intensity, and system design. Species such as *Mentha piperita*, *Ocimum basilicum*, *Lavandula angustifolia*, and *Rosmarinus officinalis* were analyzed for their responses in terms of biomass accumulation, secondary metabolite production, and overall growth performance. The research identifies key technological challenges and presents integrative solutions to enhance plant growth, water and nutrient efficiency, and essential oil yield. Implementation of these criteria supports sustainable, high-efficiency, and scalable medicinal plant production under controlled environment agriculture.*

Keywords: *Hydroponics; Aeroponics; Medicinal plants; Technological criteria; Nutrient management; Biomass accumulation; Secondary metabolites; Controlled environment agriculture; Water use efficiency; System optimization.*

The global demand for medicinal plants has been increasing due to their essential role in pharmaceuticals, nutraceuticals, and cosmetic industries. Traditional soil-based cultivation faces several constraints, particularly in arid and semi-arid regions, where water scarcity, soil degradation, salinity, and nutrient limitations significantly reduce crop productivity and quality. Hydroponic and aeroponic systems, as controlled-environment agriculture technologies, offer solutions by eliminating soil dependence, optimizing nutrient delivery, and providing year-round cultivation capability.

Hydroponics involves growing plants in nutrient-enriched solutions, with techniques such as nutrient film technique (NFT), deep water culture (DWC), ebb-and-flow systems, and drip-based hydroponics. Aeroponics, in contrast, suspends plant roots in air and delivers nutrients via fine mist, maximizing oxygen availability and nutrient uptake

efficiency. Both systems allow precise regulation of critical growth parameters, including nutrient concentrations, pH, electrical conductivity, temperature, humidity, and light intensity.

Medicinal plants such as *Mentha piperita*, *Ocimum basilicum*, *Lavandula angustifolia*, and *Rosmarinus officinalis* require specific growth conditions to maximize biomass and bioactive compound accumulation. Essential oils, phenolics, flavonoids, and alkaloids are highly sensitive to environmental stress, nutrient imbalances, and water availability. Hydroponic and aeroponic systems can mitigate these constraints, improving plant growth rates, secondary metabolite concentrations, and overall yield.

Despite these advantages, successful cultivation in hydroponic and aeroponic systems requires adherence to precise technological criteria. This study focuses on identifying and evaluating these criteria, analyzing their effects on plant physiology, biomass production, and secondary metabolite synthesis, and providing practical recommendations for large-scale implementation.

Methodology

The methodology integrates experimental evaluation, literature synthesis, and agronomic assessment of hydroponic and aeroponic cultivation of medicinal plants.

1. Plant Material Selection:

Four medicinal plant species—*Mentha piperita*, *Ocimum basilicum*, *Lavandula angustifolia*, and *Rosmarinus officinalis*—were chosen due to their commercial importance, adaptability to soilless systems, and high-value secondary metabolite profiles. Seedlings were standardized in age and size prior to introduction into hydroponic and aeroponic systems.

2. System Design and Setup:

Hydroponic systems included NFT, DWC, and ebb-and-flow configurations, with controlled flow rates and root immersion periods.

Aeroponic systems were designed for nutrient misting every 5–15 minutes, with fine nozzles ensuring uniform root coverage. Oxygenation was maintained through misting and aeration pumps.

3. Nutrient Solution Management:

Nutrient solutions contained macro- and micro-nutrients tailored to species requirements.

pH was maintained at 5.5–6.5, and EC at 1.2–2.0 mS/cm.

Nutrient levels were adjusted based on weekly monitoring, preventing deficiencies or toxic accumulation of ions.

4. Environmental Control:

Light: LED and fluorescent lighting provided 250–350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of PAR, with photoperiods of 14–16 hours.

Temperature: maintained between 22–28°C for optimal physiological activity.

Relative humidity: 55–70% to reduce transpiration stress and maintain leaf turgor.

CO₂ enrichment: 400–800 ppm to enhance photosynthesis.

5. Growth and Physiological Monitoring:

Measurements included leaf area index, plant height, shoot and root biomass, chlorophyll content, and relative water content.

Secondary metabolites, particularly essential oils and phenolics, were quantified using GC-MS and spectrophotometry.

6. Data Analysis:

Statistical evaluation using ANOVA and regression analyses determined the significance of technological variables on growth and metabolite production.

Water use efficiency (WUE) was calculated as grams of biomass per liter of water applied.

Economic feasibility was assessed based on system setup costs, nutrient solution consumption, labor, and expected market value of medicinal biomass and essential oils.

Problems and Solutions

Problems:

1. Nutrient imbalances due to incorrect solution composition or fluctuating pH/EC reduce growth and bioactive compound accumulation.

2. Oxygen deficiency in hydroponic roots, particularly in DWC systems, limits nutrient uptake efficiency and biomass production.

3. Environmental fluctuations (temperature, light, humidity) can induce stress responses, reducing essential oil content.

4. Mechanical failures (pumps, nozzles, filters) cause uneven nutrient distribution and localized plant stress.

5. Pathogen susceptibility (root rot, waterborne diseases, algae growth) threatens plant health in closed systems.

Solutions:

1. Precision Nutrient Management: Continuous monitoring and automatic adjustment of pH and EC to ensure optimal nutrient availability.

2. Enhanced Aeration: Aeroponics inherently provides oxygen-rich conditions; hydroponic systems benefit from air stones, circulation pumps, and proper flow rates.

3. Environmental Stabilization: Automated climate control and lighting adjustments maintain optimal conditions, preventing stress-induced metabolite variation.

4. Preventive Maintenance: Regular inspection of mechanical components ensures uniform nutrient and water delivery.

5. Pathogen Management: UV sterilization, beneficial microbial inoculation, and strict hygiene reduce disease incidence.

Implementation of these solutions allows maximized biomass, enhanced essential oil and phenolic content, improved water and nutrient efficiency, and scalable, economically viable production.

Conclusion and Recommendations

Hydroponic and aeroponic systems provide highly efficient platforms for medicinal plant cultivation, enabling precise control over environmental and nutritional factors. The following recommendations support successful implementation:

1. Select species and cultivars adaptable to hydroponic and aeroponic systems with high secondary metabolite potential.
2. Maintain precise nutrient solution management, with continuous monitoring of pH and EC.
3. Ensure sufficient root oxygenation through aeration strategies or aeroponic design.
4. Implement automated environmental control systems to stabilize light, temperature, and humidity.
5. Conduct preventive pathogen management, including sterilization and beneficial microbial inoculation.
6. Train personnel on system operation, nutrient adjustment, and environmental monitoring.
7. Optimize economic evaluation by balancing system costs, water and nutrient Adherng savings, labor reduction, and projected market value.

Adhering to these technological criteria ensures year-round, high-quality production of medicinal plants with enhanced biomass and bioactive compound yield, contributing to sustainable, resource-efficient, and profitable cultivation systems.

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