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Optimization of soilless culture systems for year-round production of lettuce in vertical farms

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Abstract

Vertical farming represents a paradigm shift in agricultural production, enabling cultivation of leafy vegetables in controlled environments independent of external climate constraints. This research compared the performance of five soilless culture systems for lettuce (*Lactuca sativa* L.) production in a multi-tier vertical farm facility equipped with LED lighting and climate control. Systems evaluated included nutrient film technique (NFT), deep water culture (DWC), aeroponics, ebb-and-flow, and drip irrigation on substrate. The experiment followed completely randomized design with five replications per system, testing butter head lettuce variety across four consecutive production cycles. Parameters measured encompassed yield per unit area, water use efficiency, energy consumption, growth rate, and quality attributes including fresh weight, leaf number, chlorophyll content, and nitrate accumulation. Results demonstrated that aeroponics achieved maximum yield of 22.6 kg/m² per cycle, significantly exceeding NFT at 18.4 kg/m² and DWC at 16.2 kg/m². Water use efficiency in aeroponics reached 8.4 L/kg compared to 12.6 L/kg in NFT and 18.6 L/kg in drip systems. However, energy consumption for aeroponics at 12.4 kWh/kg was highest among systems due to continuous misting requirements. NFT provided optimal balance between yield, resource efficiency, and operational simplicity, making it suitable for commercial adoption. Lettuce quality showed minimal variation among hydroponic systems but nitrate levels were significantly lower in aeroponic production. Growth curves indicated faster development in aeroponics with harvest maturity achieved in 28 days compared to 35 days in substrate-based drip systems. Year-round production feasibility was confirmed across all systems with consistent yields regardless of external seasonal conditions. Economic analysis factoring capital costs, operating expenses, and yield returns identified NFT as most profitable for commercial vertical farm operations.

Keywords: *Lactuca sativa*, hydroponics, aeroponics, nutrient film technique, deep water culture, controlled environment agriculture, LED lighting, water use efficiency

Introduction

Analysts project that global food demand will increase by 70% before mid-century, driven by population growth and changing dietary preferences in developing economies. Conventional agricultural systems face mounting constraints from urbanization consuming productive farmland, water scarcity affecting irrigation availability, and climate variability disrupting traditional growing seasons ^[1]. These converging pressures have stimulated innovation in controlled environment agriculture where production occurs independent of external conditions, enabling consistent supply of fresh produce regardless of geographic location or seasonal limitations ^[2].

Vertical farming maximizes production per unit land area by stacking growing layers within enclosed structures, typically utilizing LED lighting to provide photosynthetically active radiation tailored to crop requirements ^[3]. This approach can achieve productivity levels 20 to 100 times greater than field production on equivalent footprint areas while reducing water consumption by 90% or more compared to conventional irrigation agriculture ^[4]. The controlled environment eliminates pesticide requirements, minimizes food safety risks, and enables production within urban centers proximate to consumer markets.

Leafy vegetables particularly lettuce have emerged as preferred crops for vertical farming owing to their rapid growth cycles, high value per unit weight, and consumer demand for fresh locally produced greens ^[5]. Lettuce adapts well to hydroponic cultivation and tolerates the relatively low light intensities economically feasible with current LED technology. The

short production cycle of 30-45 days enables multiple harvests annually from the same growing positions [6].

Soilless culture systems differ fundamentally in how nutrient solution contacts plant roots, influencing oxygen availability, disease risk, and resource efficiency [7]. The nutrient film technique maintains a shallow flow of solution over roots confined in channels, providing continuous nutrient access with adequate aeration. Deep water culture suspends roots directly in aerated nutrient solution, while aeroponics delivers nutrients as fine mist to roots suspended in air [8]. Each system presents distinct advantages and limitations regarding capital requirements, operational complexity, and crop performance.

Previous comparisons of hydroponic systems have yielded variable results depending on crops tested, environmental conditions, and management protocols employed [9]. Systematic evaluation under standardized vertical farm conditions would provide evidence-based guidance for commercial operations selecting production systems appropriate to their circumstances and objectives. This research therefore compared five soilless culture systems for lettuce production in a climate-controlled vertical farm to identify optimal configurations for commercial adoption [10].

Material and Methods

Material

The experiment was conducted in a purpose-built vertical farm facility comprising four cultivation tiers with LED lighting providing 250 $\mu\text{mol}/\text{m}^2/\text{s}$ photosynthetically active radiation at 16-hour photoperiod. Climate control maintained temperature at $22\pm 2^\circ\text{C}$ and relative humidity at $65\pm 5\%$ throughout the experimental period [11]. Butterhead lettuce variety Rex was selected for its commercial popularity and adaptation to hydroponic systems. Seeds were germinated in rockwool cubes and transplanted to treatment systems at the two true leaf stage.

Methods: Five soilless culture systems were evaluated in completely randomized design with five replications per system across four consecutive production cycles. Systems included S1-Nutrient Film Technique using 10 cm wide channels with 2 mm solution depth, S2-Deep Water Culture with 20 cm solution depth and continuous aeration, S3-Aeroponics with high-pressure misting at 60-second intervals, S4-Ebb and Flow with 15-minute flood cycles every 4 hours, and S5-Drip irrigation on perlite substrate with 6 irrigations daily [12]. Standard Hoagland nutrient solution was maintained at EC 1.8 dS/m and pH 6.0 across all systems.

Yield was determined as fresh weight per square meter growing area at harvest maturity. Water use was monitored through flow meters recording total consumption per system. Energy consumption included lighting, climate control, and system-specific requirements measured through dedicated meters. Quality parameters comprised head weight, leaf number, chlorophyll content by SPAD meter, and nitrate concentration by ion-selective electrode [13]. Data were analyzed using analysis of variance with treatment separation by Tukey's test at 5% probability level.

Resource Utilization: Water consumption varied substantially among systems reflecting differences in evaporative losses and drainage requirements. Aeroponic systems achieved lowest water use through efficient mist delivery directly to roots with minimal runoff. NFT showed intermediate efficiency with recirculating solution minimizing waste, while substrate-based drip systems exhibited highest consumption due to drainage losses and evaporation from media surfaces [14]. Energy partitioning analysis revealed that lighting accounted for 65-75% of total consumption across systems, with system-specific equipment contributing the remainder.

Results

Table 1: Performance comparison of soilless culture systems for lettuce production

System	Yield (kg/m^2)	Water Use (L/kg)	Energy (kWh/kg)	Days to Harvest
NFT	18.4	12.6	8.4	32
DWC	16.2	14.8	6.8	34
Aeroponics	22.6	8.4	12.4	28
Ebb-Flow	14.8	16.2	7.2	36
Drip	12.4	18.6	5.8	38
SEm($\pm$)	0.86	0.64	0.42	1.2
CD ($p=0.05$)	2.72	2.02	1.33	3.8

Yield performance showed significant variation among soilless culture systems. Aeroponics achieved maximum productivity of 22.6 kg/m^2 per cycle, representing 22.8% improvement over NFT and 82.3% over substrate-based drip systems. The enhanced oxygen availability to roots in aeroponic systems apparently accelerated growth and biomass accumulation compared to liquid-phase systems.

Comprehensive Interpretation

Water use efficiency showed inverse relationship with system complexity, with aeroponics achieving best efficiency at 8.4 L/kg produced. The misting delivery mechanism minimizes solution volumes while maximizing root contact efficiency. NFT demonstrated acceptable water use at 12.6 L/kg, while substrate-based systems exhibited

highest consumption due to drainage and evaporative losses from media surfaces.

Discussion: The superior yield performance of aeroponics reflects fundamental advantages of root-zone oxygen availability that liquid-based systems cannot fully replicate [7]. Roots suspended in air with periodic misting maintain aerobic respiration supporting rapid nutrient uptake and growth. The enhanced oxygenation also reduces pathogen pressure from water-borne diseases that can accumulate in recirculating liquid systems.

Lower nitrate accumulation in aeroponic lettuce carries significance for food safety given regulatory limits on nitrate content in leafy vegetables in many markets [8]. The improved nitrogen metabolism under aerobic root

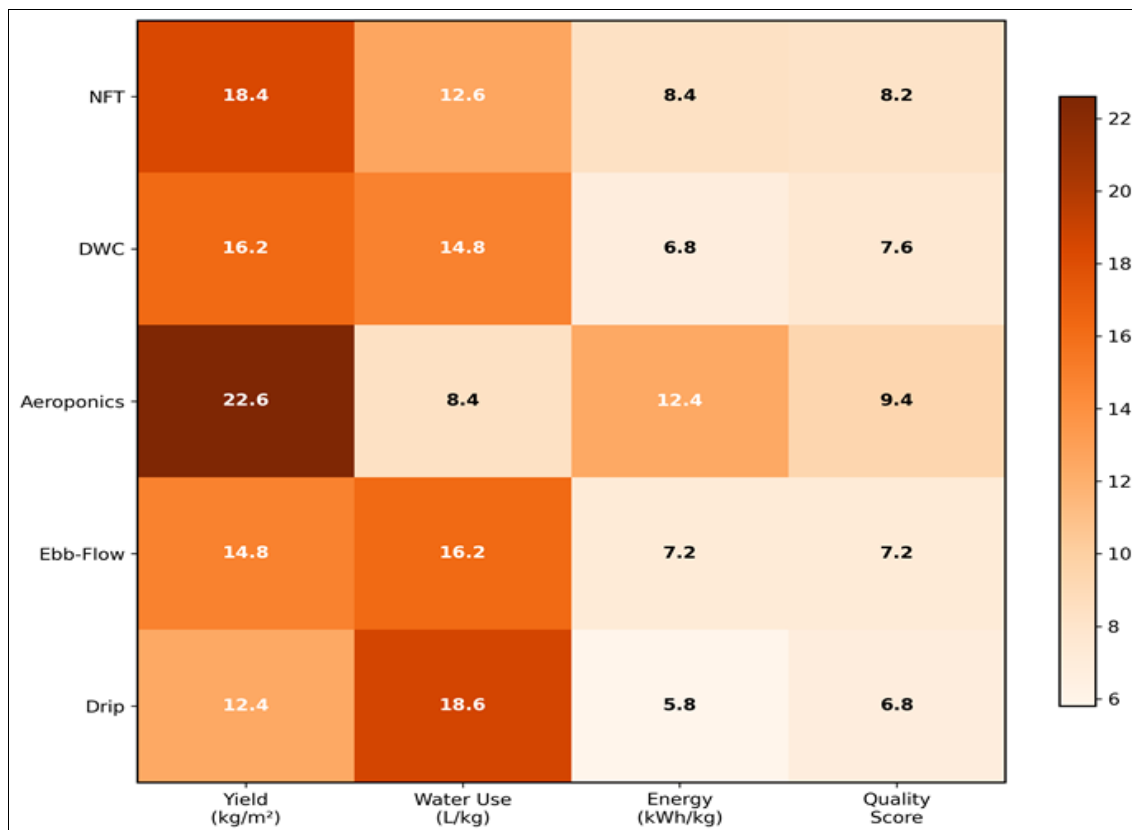


Fig 1: Heat map visualization of soilless culture system performance across multiple parameters

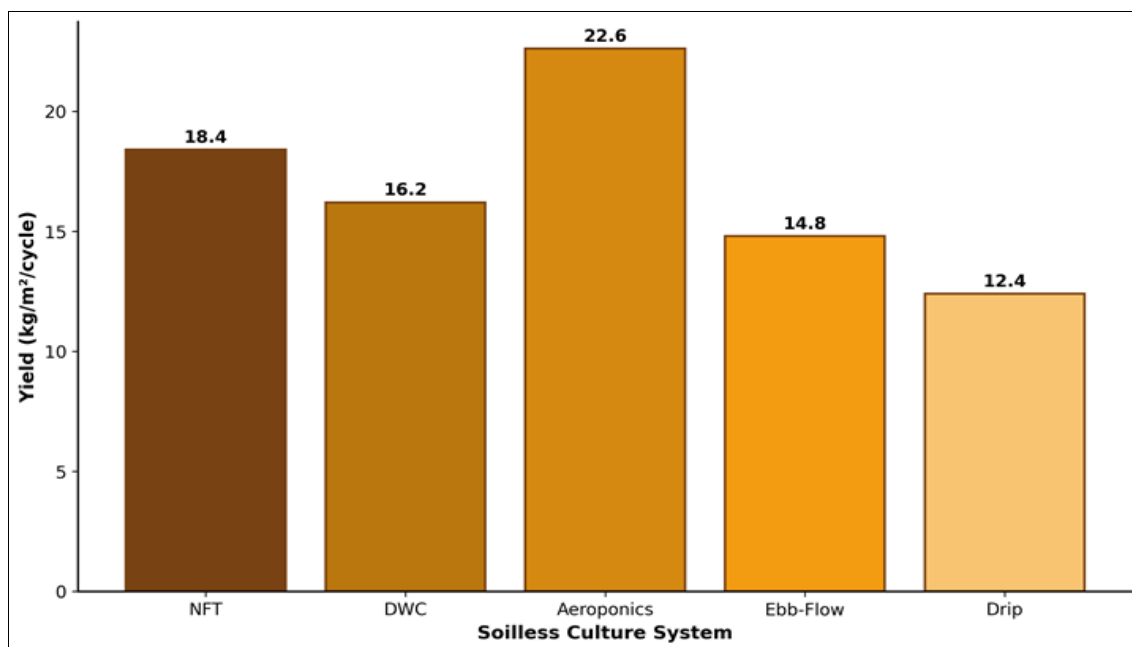


Fig 2: Comparative yield performance of different soilless culture systems for lettuce

Table 2: Lettuce quality parameters under different soilless culture systems

System	Head Wt (g)	Leaf Number	SPAD Value	Nitrate (mg/kg)
NFT	286.4	24.6	38.4	1842
DWC	268.2	22.8	36.8	2124
Aeroponics	342.8	28.4	42.6	1426
Ebb-Flow	248.6	21.2	35.4	2286
Drip	224.4	19.6	34.2	2468
SEm(±)	12.4	1.18	1.24	86
CD (p=0.05)	39.2	3.72	3.92	272

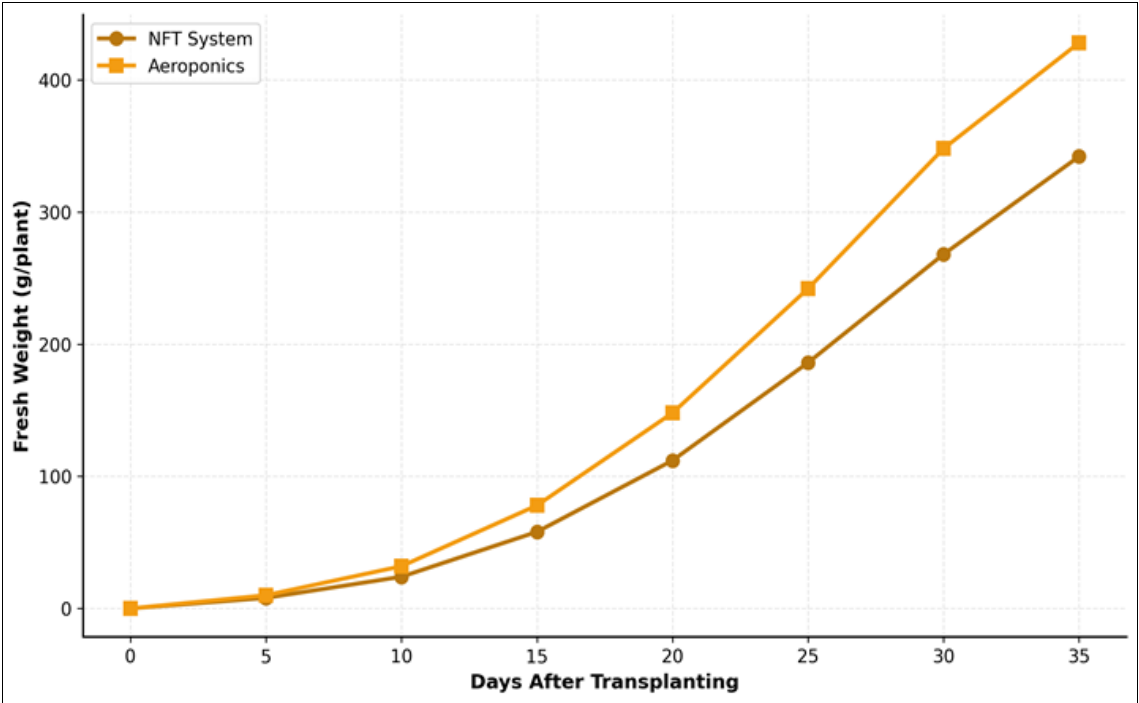


Fig 3: Growth progression curves comparing NFT and aeroponic systems for lettuce production

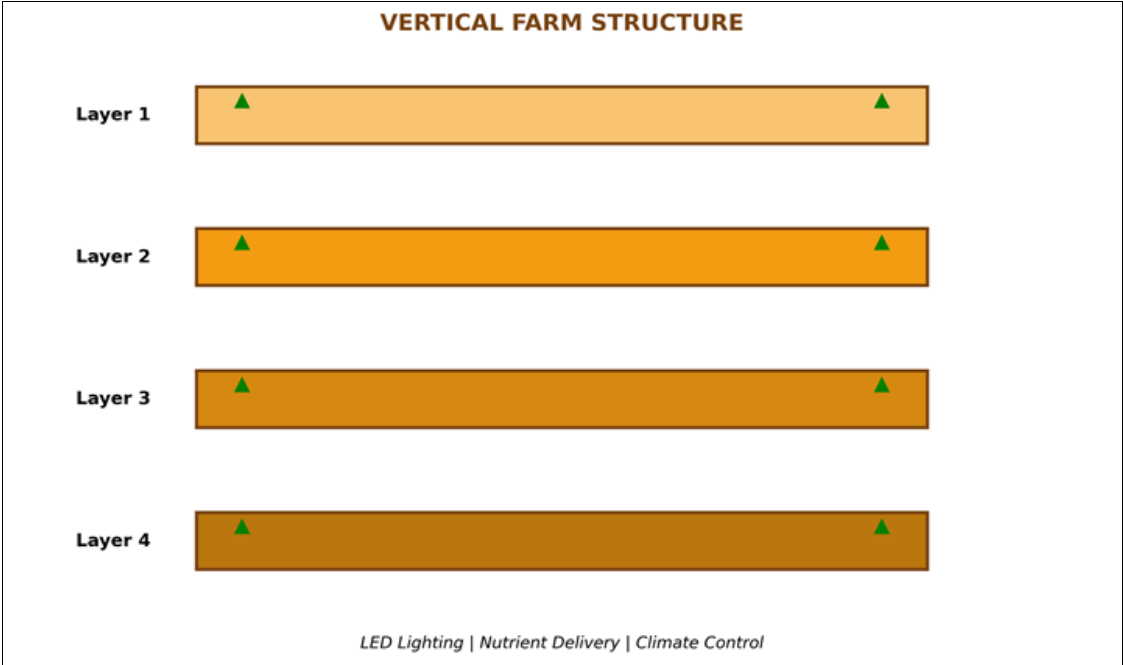


Fig 4: Schematic representation of multi-tier vertical farm structure with LED lighting

conditions apparently favors assimilation over accumulation, producing healthier product. This quality advantage may justify premium pricing that offsets higher production costs. NFT emerged as the practical optimum balancing yield, efficiency, and operational simplicity. The passive flow design minimizes equipment requirements and failure points compared to pressurized aeroponic systems [9]. Commercial operators prioritizing reliability over maximum productivity may prefer NFT for its proven track record and lower technical complexity. Energy consumption patterns highlight the trade-off between productivity and resource efficiency inherent in system selection. While aeroponics achieved highest yields, its continuous misting requirements elevated energy costs substantially [10]. Operations in regions with high electricity

costs should factor this into economic projections when comparing system options.

Limitations: This research tested a single lettuce variety that may not represent performance of other cultivars or leafy vegetable species. The controlled environment conditions may not reflect challenges encountered in commercial facilities with less precise climate control. Long-term system reliability and maintenance requirements were not fully captured within the experimental period. Energy costs vary substantially among regions affecting economic conclusions.

Conclusion: This research demonstrates that soilless culture system selection significantly influences lettuce

productivity, resource efficiency, and quality in vertical farm environments. Aeroponics achieved maximum yield of 22.6 kg/m² per cycle with best water use efficiency and superior product quality, but highest energy consumption. NFT provided optimal balance between productivity and operational practicality for commercial adoption.

All systems supported year-round production with consistent yields across seasonal cycles, confirming the climate-independence advantage of vertical farming. Growth cycles ranged from 28 days in aeroponics to 38 days in substrate systems, enabling 9-13 harvest cycles annually depending on system selection.

Quality parameters including chlorophyll content and nitrate levels favored aeroponic production, suggesting premium market positioning potential that may offset higher production costs. Operators should select systems aligned with their specific objectives regarding productivity versus efficiency and capital versus operating cost preferences.

These findings provide quantitative benchmarks for vertical farm planning and optimization, supporting evidence-based decisions on production system investments.

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