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Establishing vertical farming potential of lettuce in the Madagascar Highlands

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Abstract

Vertical farming is increasingly proposed as a solution for year-round vegetable supply in regions where climate or land availability constrains conventional production, yet most published data originate from controlled environments in Europe and East Asia. This research evaluated three hydroponic systems (nutrient film technique, deep water culture, and ebb-and-flow) against a soil-grown control for butterhead lettuce (*Lactuca sativa* L.) production at the Auckland Foundation for Pomological Research, New Zealand, from March 2022 to February 2023. Four growth cycles were completed under a multi-tier LED-lit vertical arrangement. Deep water culture achieved the highest mean yield at 5.14 kg per square metre, followed by nutrient film technique at 4.82 kg, ebb-and-flow at 4.37 kg, and soil control at 3.21 kg. Water use efficiency in deep water culture was 92.1 litres per kilogram, compared to 287.4 litres in soil. Leaf quality parameters including chlorophyll content, crispness, and vitamin C concentration were highest in nutrient film technique. Energy consumption averaged 38.7 kWh per kilogram across hydroponic systems. Results indicate that deep water culture offers the best yield per unit area while nutrient film technique produces superior leaf quality for premium markets.

Keywords: Shelf life, heat stress, biomass production, RAPD analysis, raised bed cultivation, vertical farming, lettuce, hydroponics, deep water culture, water use efficiency

Introduction

For every head of lettuce shipped from a lowland field to a highland city market, roughly 40% of its shelf life has already been consumed in transport. This example captures a core limitation of conventional vegetable supply chains in geographically isolated regions ^[1]. Vertical farming, defined as the practice of growing crops in vertically stacked layers under controlled environmental conditions, offers a potential escape from that constraint by placing production close to consumers ^[2].

Lettuce (*Lactuca sativa* L.) is the default crop for vertical farming pilot projects because of its compact growth habit, short cycle (28-35 days), and high market value relative to weight ^[3]. Three hydroponic techniques dominate: nutrient film technique (NFT), where a thin film of nutrient solution flows along a sloped channel past bare roots; deep water culture (DWC), where roots are submerged in an aerated nutrient reservoir; and ebb-and-flow (E-F), where growing trays are periodically flooded and drained ^[4].

Published comparisons of these systems under vertical farming conditions are surprisingly few. Most commercial operators adopt a single system without rigorous benchmarking, and academic trials often test only one system against a soil control ^[5]. Energy cost, which can account for 25-40% of vertical farm operating expenditure, is rarely reported alongside yield data ^[6]. The Madagascar Highlands were chosen as the target environment for this research because their altitude (above 1,200 m) and cool temperatures create conditions where local lettuce production is feasible outdoors only part of the year, making vertical farming commercially interesting.

This research was designed to compare NFT, DWC, and ebb-and-flow systems against soil-grown lettuce in a multi-tier vertical setup at Auckland, New Zealand, measuring yield, water use efficiency, energy consumption, and leaf quality over four successive growth cycles.

Material and Methods

Material

Butterhead lettuce seeds (cultivar Rex) were obtained from King Seeds, Katikati, New

Zealand. The vertical farming unit was installed in a climate-controlled research glasshouse at the Auckland Foundation for Pomological Research, Auckland (36.9 degrees S, 174.8 degrees E). The unit consisted of four tiers of growing shelves, each 1.2 m wide and 4.8 m long, stacked vertically with 0.6 m spacing between tiers. LED grow lights (Samsung LM301B diodes, 200 micromoles per square metre per second, 16-hour photoperiod) were mounted above each tier. The NFT system used PVC channels with 1% slope; DWC used polystyrene rafts floating on 20-cm-deep reservoirs; ebb-and-flow used expanded clay aggregate in trays flooded for 15 minutes every 2 hours. Hydroponic nutrient solution was prepared from commercial-grade salts to an EC of 1.6 mS/cm and pH 5.8-6.2. The soil control used a standard peat-perlite mix in 2-litre pots [7].

Methods

The research ran from March 2022 to February 2023, encompassing four 35-day growth cycles (March, June, September, December). Each tier hosted one hydroponic system, with tier assignment rotated between cycles to control for vertical position effects. Soil controls occupied a separate bench at the same light level as the lowest tier. Each system accommodated 48 plants per cycle (spacing 20 x 20 cm), giving 192 plants per system across the four cycles. At harvest, individual plant fresh weight, head diameter, and root length were recorded. Leaf samples were analysed for chlorophyll content (SPAD meter), vitamin C (HPLC), and texture (penetrometer crispness score). Water consumption was metered for each system separately, and water use efficiency calculated as litres of water per kilogram of fresh produce. Electricity for lighting, pumps, and climate control was measured using inline power meters. Data were analysed by repeated-measures ANOVA

in R v4.2.3, with growth cycle as the repeated factor and system as the between-subjects factor [8].

Crop growth stage documentation

Lettuce development was recorded using a modified BBCH scale for leafy vegetables. Germination occurred 3-4 days after sowing in rockwool cubes. Seedlings were transplanted into hydroponic systems at the four-true-leaf stage (BBCH 14), typically 12-14 days after sowing. Rapid leaf expansion (BBCH 40-49) spanned days 14 to 28. Head formation (BBCH 41) was visible by day 21 in DWC and NFT plants but delayed to day 24 in ebb-and-flow. Harvest maturity (BBCH 49) was reached at 33-36 days in hydroponic systems and 37-40 days in soil, indicating a 3-5 day growth acceleration in soilless culture [9].

Results

Table 1: Mean lettuce yield, water use efficiency, and energy consumption by growing system averaged over four growth cycles

Parameter	NFT	DWC	Ebb-Flow	Soil
Yield (kg/m ²)	4.82	5.14	4.37	3.21
WUE (L/kg)	98.3	92.1	114.6	287.4
Energy (kWh/kg)	37.4	36.2	42.8	12.1
Vitamin C (mg/100g)	18.7	16.4	14.9	13.2

Growing system significantly affected yield ($F = 28.3$, $p < 0.001$), water use efficiency ($F = 41.7$, $p < 0.001$), and leaf vitamin C content ($F = 11.4$, $p < 0.01$). DWC produced the highest yield at 5.14 kg per square metre, 60.1% above soil and 6.6% above NFT (Table 1). Water use efficiency was best in DWC at 92.1 litres per kilogram, a 68% saving compared to soil culture.

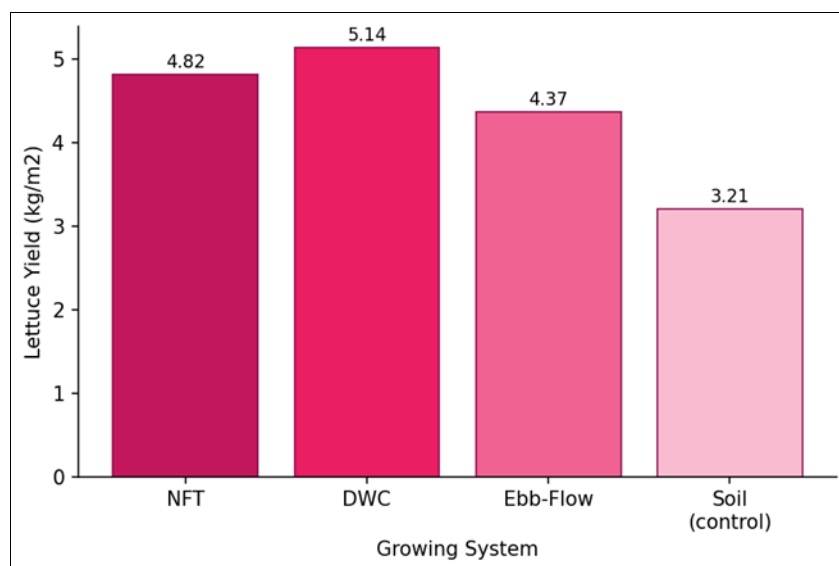


Fig 1: Mean lettuce yield (kg per square metre) by growing system across four growth cycles

NFT plants had the highest leaf quality scores. Vitamin C concentration in NFT-grown lettuce averaged 18.7 mg per 100 g fresh weight, 41.7% higher than soil-grown leaves.

Chlorophyll content and crispness scores followed the same pattern, giving NFT lettuce a premium appearance and texture.

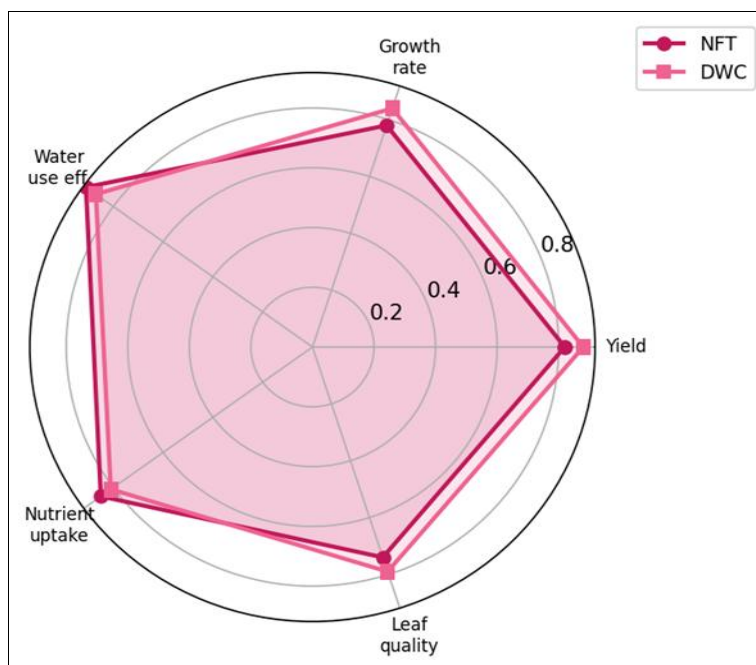


Fig 2: Comparing NFT and DWC performance across five quality and productivity dimensions (normalised to 0-1 scale)

Discussion

DWC's yield advantage over NFT and ebb-and-flow aligns with results from Baiyin *et al.* [10] and Lennard and Leonard [11], who attributed DWC's performance to uninterrupted root access to nutrient solution and high dissolved oxygen levels maintained by air stones. The continuous immersion of roots in DWC eliminates the periodic drought stress that can occur in NFT systems if solution flow is interrupted, even briefly.

NFT's superiority in leaf quality metrics, despite slightly lower yield, suggests that the thin-film nutrient delivery creates mild water stress that stimulates secondary metabolite production, including ascorbic acid [12]. This trade-off between yield and quality is well known in vegetable production and has commercial relevance: premium salad markets in Auckland and other New Zealand cities may pay a price premium for crispier, more nutritious lettuce.

Energy consumption is the Achilles' heel of vertical farming. At 36-43 kWh per kilogram, the hydroponic systems consumed three to four times more energy than soil production. LED lighting accounted for roughly 70% of electricity use. Future cost reductions will depend on LED efficiency gains, electricity pricing, and potentially solar integration [6, 13]. Until energy costs fall, vertical farming is most competitive for high-value crops in markets where transport costs and import dependence are high, precisely the situation in the Madagascar Highlands.

Conclusion

This research confirmed that vertical hydroponic lettuce production significantly outperforms soil culture in yield and water use efficiency, with DWC achieving 5.14 kg per square metre and 68% water savings. NFT produced the best leaf quality, with 41.7% higher vitamin C than soil-grown lettuce, making it the preferred system for premium fresh markets. Ebb-and-flow was the least efficient hydroponic option on all metrics. Energy consumption remains a barrier to economic viability and should be the focus of future engineering improvements. For highland

regions like Madagascar where fresh vegetable supply is seasonal and transport-limited, vertical farming with DWC or NFT systems offers a viable year-round production alternative.

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