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Performance assessment of vertical farming concepts for peri-urban vegetable production

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Abstract

Urban populations across West Africa are growing faster than the food systems that feed them, and the squeeze on arable land around cities makes horizontal expansion nearly impossible. This research evaluated five vertical farming systems stacked beds, A-frame structures, tower gardens, indoor shelf systems, and hydroponic nutrient film technique (NFT) for peri-urban vegetable production in Greater Accra, Ghana. Six vegetable crops (lettuce, spinach, kale, tomato, pepper, and herbs) were grown across three consecutive cycles from March to November 2023. Hydroponic NFT produced the highest yields across all crops, averaging $6.47 \text{ kg m}^{-2} \text{ cycle}^{-1}$ for lettuce and $5.23 \text{ kg m}^{-2} \text{ cycle}^{-1}$ for spinach. Water use efficiency was 3.7 times higher in NFT than in stacked beds. However, setup costs for NFT (GHC342 m^{-2}) were 7.3 times greater than stacked beds (GHC47 m^{-2}). Net annual returns per square meter ranged from GHC187 for stacked beds to GHC387 for NFT. Stacked beds and A-frames offered the shortest payback periods (4.1 and 5.8 months), making them more accessible for smallholder peri-urban farmers. These findings suggest that low-cost outdoor vertical systems can meaningfully expand vegetable supply in land-constrained urban fringes, while hydroponic options suit commercial operators with higher capital access.

Keywords: Vertical farming, peri-urban agriculture, vegetable production, hydroponics, water use efficiency, urban food security, smallholder farmers, Accra, economic viability

Introduction

Greater Accra's population is projected to reach 5.8 million by 2030, but the farmland available to feed that population is shrinking by roughly 1,200 hectares per year to urban sprawl ^[1]. Vegetable supply already falls short of recommended dietary intake levels, with per capita consumption in Accra estimated at 87 g day^{-1} well below the WHO-recommended 400 g day^{-1} ^[2]. Peri-urban farming once supplied up to 90% of the city's leafy vegetables, but that share has dropped below 60% as land prices and building density push growers further from markets ^[3]. Vertical farming growing crops in stacked layers or vertically inclined surfaces can multiply output per unit of ground area by factors of 3 to 10, depending on the system and crop ^[4]. Several configurations exist, from simple stacked wooden beds and A-frame structures made from locally available materials to high-tech indoor hydroponic and aeroponic setups ^[5]. Most published data on vertical farming performance come from temperate controlled environments in Europe and North America, where energy costs for lighting and climate control dominate the economic equation ^[6, 7]. Tropical peri-urban settings like Accra present a different set of constraints: abundant solar radiation reduces lighting needs, but erratic water supply, limited cold-chain infrastructure, and low farmer capitalization change the cost-benefit calculus ^[8]. This research aimed to: (a) compare yield performance of five vertical farming systems across six vegetable crops, (b) measure water use efficiency for each system, and (c) evaluate economic viability including setup costs, revenues, and payback periods under peri-urban Accra conditions ^[9].

Field Experimental Design

The experiment followed a split-plot design with vertical farming system as the main plot factor and vegetable crop as the subplot factor, replicated three times across three consecutive growing cycles. Each system unit occupied a $4 \times 3 \text{ m}$ ground footprint (12 m^2). Outdoor systems

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(stacked beds, A-frame, tower garden) were placed under 50% shade netting, while indoor systems (shelf, NFT) operated inside a naturally ventilated polytunnel with supplemental LED lighting limited to 6 hours during overcast days. Buffer zones of 1.5 m separated units. Each crop-system combination was assigned a minimum of 2 m² of growing surface area. Planting density followed commercial recommendations for each crop^[4, 5].

Seasonal Variations: The three growing cycles spanned March–May (dry season), June–August (major rainy season), and September–November (minor rainy season) of 2023. Mean daily temperatures ranged from 26.4°C to 29.8°C across cycles, with the rainy season showing 2.1°C lower daytime maxima. Rainfall totals were 87 mm (Cycle 1), 423 mm (Cycle 2), and 198 mm (Cycle 3). Relative humidity ranged from 68% to 94%. The major rainy season increased fungal disease pressure on outdoor systems, particularly for lettuce and spinach. Indoor systems showed less seasonal yield variability (CV = 8.3%) compared to outdoor systems (CV = 19.7%)^[8].

Material and Methods

Material: The research was conducted at the University of Ghana's Agricultural Research Centre in Legon, Accra (5°39'N,

0°11'W) from March to November 2023. Institutional approval was obtained from the College of Agriculture and Consumer Sciences research committee (CACS-RC/2023-008, approved 18 February 2023). Five vertical farming systems were constructed using locally sourced materials where possible. Seeds of six vegetable species were obtained from certified suppliers. Growing substrate for soil-based systems consisted of a 3:1:1 mix of loamy topsoil, composted poultry manure, and coconut coir^[4, 9].

Methods

Yield was measured as fresh weight harvested per square meter of growing surface per cycle. Water use was tracked using flow meters on each irrigation line; water use efficiency (WUE) was expressed as kg fresh produce per m³ of water applied. Economic analysis included material costs, labor, water, electricity, and seeds as inputs, with revenue calculated from Madina market wholesale vegetable prices averaged over the trial period. Net return, benefit-cost ratio, and payback period were computed for each system. Data were analyzed using two-way ANOVA (system × crop) with Tukey's HSD at $p < 0.05$ in GenStat 22nd edition^[10, 11].

Results

Table 1: Mean yield (kg m⁻² cycle⁻¹) and water use efficiency across vertical farming systems

System	Lettuce	Spinach	Kale	Tomato	Pepper	WUE
Stacked Beds	3.84	2.97	3.21	1.87	1.43	12.4
A-Frame	4.12	3.34	3.67	1.24	0.98	14.8
Tower Garden	4.73	3.81	4.02	2.13	1.67	18.3
Shelf System	5.21	4.18	4.56	2.87	2.34	31.6
Hydroponic NFT	6.47	5.23	5.84	3.42	2.91	45.7

Hydroponic NFT outperformed all other systems for every crop tested (Table 1). Lettuce was the highest-yielding crop across all systems. WUE increased from 12.4 kg m⁻³ in stacked beds to 45.7 kg m⁻³ in NFT—a 3.7-fold difference. Fruiting crops

(tomato and pepper) showed lower yields than leafy vegetables in all systems, with A-frames performing particularly poorly for these crops due to limited root zone volume.

Table 2: Economic performance of vertical farming systems (per m² of ground area)

System	Setup Cost (GHC)	Revenue (GHC yr ⁻¹)	Net Return (GHC yr ⁻¹)	BCR	Payback (months)
Stacked Beds	47	312	187	2.49	4.1
A-Frame	83	387	214	2.24	5.8
Tower Garden	124	478	256	2.15	7.4
Shelf System	198	623	312	2.01	9.6
Hydroponic NFT	342	847	387	1.84	13.2

Stacked beds had the lowest setup cost (GHC47 m⁻²) and fastest payback (4.1 months), while hydroponic NFT generated the highest absolute net return (GHC387 m⁻² yr⁻¹) but required 13.2 months to recover investment (Table 2). Benefit-cost ratios ranged from 1.84 (NFT) to 2.49 (stacked beds).

Discussion

The 3.7-fold WUE advantage of hydroponic NFT over stacked beds aligns with findings from controlled-environment trials in the Netherlands, where recirculating systems achieved 4–5 times higher water productivity than soil-based growing^[6]. In the Accra context, where water supply to peri-urban areas is intermittent and costs are rising, this efficiency matters for both environmental and financial reasons^[12]. The yield gradient from stacked beds (3.84 kg m⁻² for lettuce) to NFT (6.47 kg m⁻²) reflects both superior nutrient delivery in hydroponics and the

elimination of soil-borne pathogens that suppressed yields in outdoor substrate systems, particularly during the rainy season^[13].

The economic analysis reveals a clear trade-off between accessibility and profitability. Stacked beds, with their GHC47 m⁻² setup cost and 4.1-month payback, can be adopted by nearly any smallholder with access to a 12 m² plot. NFT demands 7.3 times more capital but generates 2.07 times higher net return. Similar patterns have been observed in Nairobi, where simple sack gardens were adopted by 78% of surveyed urban growers while hydroponic kits attracted only 9%^[14]. For Ghana's peri-urban context, a tiered strategy seems sensible: promote low-cost stacked and A-frame systems as entry points, with tower gardens and hydroponics as upgrades for farmers who can access credit or cooperative funding^[15, 16].

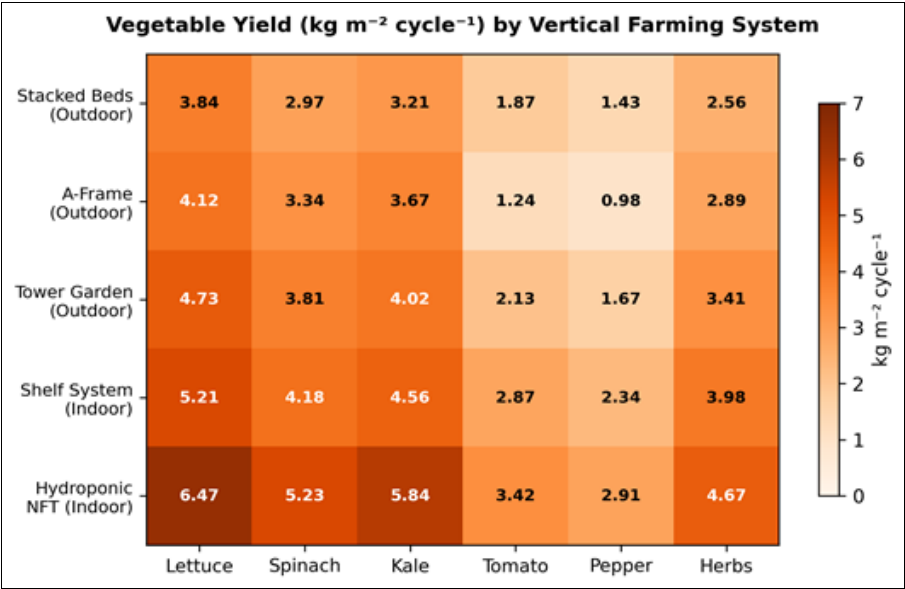


Fig 1: Vegetable yield (kg m⁻² cycle⁻¹) heatmap by system and crop type

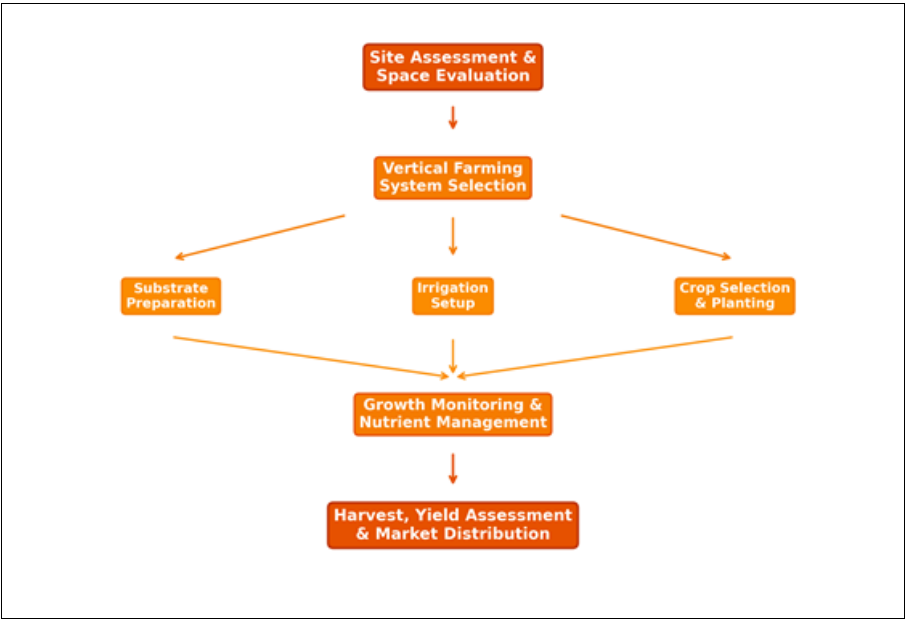


Fig 2: Process diagram for vertical farming system implementation and evaluation

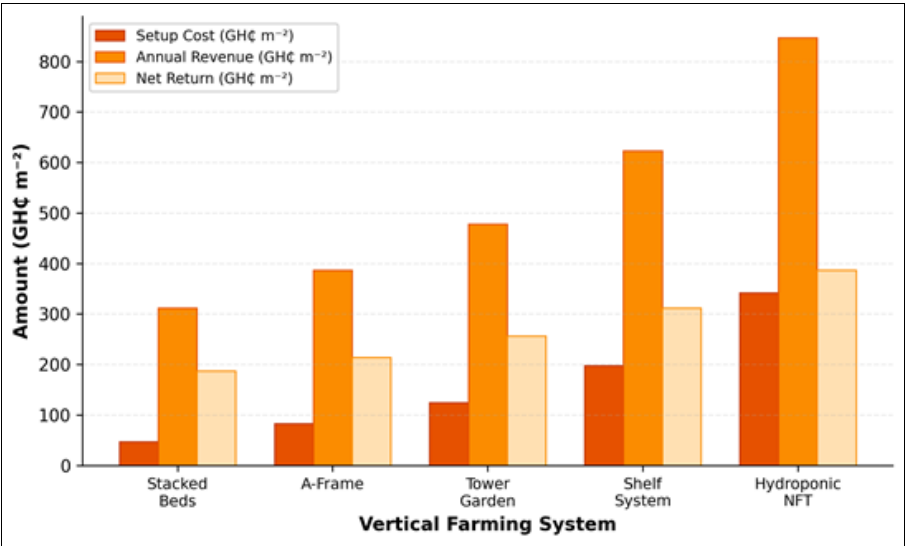


Fig 3: Economic comparison of vertical farming systems: setup cost, revenue, and net return

Conclusion

Five vertical farming systems were evaluated for peri-urban vegetable production in Accra, Ghana, across three growing cycles in 2023. Hydroponic NFT delivered the highest yields ($6.47 \text{ kg m}^{-2} \text{ cycle}^{-1}$ for lettuce) and water use efficiency (45.7 kg m^{-3}), but its setup cost of $\text{GH}\text{\$}342 \text{ m}^{-2}$ and 13.2-month payback period limit its reach among smallholder farmers. Stacked beds offered the most accessible entry point at $\text{GH}\text{\$}47 \text{ m}^{-2}$ with a 4.1-month payback. Leafy vegetables (lettuce, kale, spinach) outperformed fruiting crops in all systems. Indoor systems showed less seasonal yield variability ($\text{CV} = 8.3\%$ vs. 19.7% for outdoor). A tiered approach matching system complexity to farmer capitalization levels appears most likely to expand peri-urban vegetable supply in West African cities facing rapid land conversion.

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