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Energy–Water–Profit Trade-Offs and Scale Economies in Urban Aquaponics Under Electricity Unreliability: Comparative Evidence from Lagos and Abuja, Nigeria

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Abstract: *Urban aquaponics is increasingly promoted as a climate-smart and resource-efficient food production system, yet its economic viability under unreliable electricity conditions remains poorly understood in emerging-market contexts. This study evaluates energy–water–profit trade-offs and scale economies in urban aquaponics systems across Lagos and Abuja, Nigeria. Using system-level socio-technical and financial data from 18 operational units, we construct integrated food–energy–water (FEW) performance indicators, conduct electricity shock simulations, and estimate econometric models to identify the drivers of profitability. Results reveal strong scale economies. Semi-commercial systems exhibit higher profit margins (≈50–54%), shorter payback periods (≈2.3 years), and substantially greater profit per kWh compared to household systems. Energy intensity per unit output declines by up to 50% with scale, while water productivity (profit per m³) more than doubles in larger systems. Sensitivity analysis indicates that household systems become unprofitable at electricity tariff increases of approximately 2.5× baseline or under moderate outage escalation, whereas semi-commercial systems remain viable even under substantial tariff and diesel price shocks. Elasticity analysis demonstrates that capital intensity is the dominant profitability driver: a 1% increase in capital investment increases profit by approximately 0.85%, while land area and energy use are not independently significant once capital is controlled. These findings suggest that profitability and resilience are structurally capital-driven rather than determined by system size alone. The study contributes to FEW nexus scholarships by empirically demonstrating that scale moderates' energy–water–profit trade-offs under infrastructure instability. Policy implications highlight the importance of capital access, renewable energy integration, and scale-sensitive support mechanisms for enhancing urban food system resilience in electricity-constrained environments*

Keywords*: Urban aquaponics, Food–energy–water nexus, Scale economies, Electricity unreliability, Techno-economic analysis, ƒUrban food resilience, Emerging-market cities*

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1.0 Introduction

Rapid urbanization, climate stress, and energy insecurity are reshaping food production systems globally. Urban food demand is increasing sharply in sub-Saharan Africa, while cities simultaneously face water constraints, unreliable electricity supply, and rising production costs. Urban populations in sub-Saharan Africa are projected to nearly double by 2050, intensifying pressure on food

supply systems while infrastructure expansion struggles to keep pace with demand growth. Integrated production systems that reduce resource intensity and enhance resilience are therefore gaining attention within the food–energy–water (FEW) nexus framework (Yuan *et al*., 2025; Oyebamiji *et al*., 2025; Sewilam *et al*., 2023). Among emerging urban agriculture innovations, aquaponics—an integrated system combining recirculating aquaculture with hydroponic plant production—has gained attention as a promising production model due to its potential for nutrient recycling, reduced land footprint, and lower water use relative to conventional agriculture (Benjamin *et al*., 2024; Nair *et al*., 2025). Life cycle assessment (LCA) studies indicate that aquaponics can outperform conventional aquaculture or hydroponics in water efficiency, though energy demand and infrastructure intensity often remain key environmental hotspots (Chen *et al*., 2020; Zappernick *et al*., 2022; Ravani *et al*., 2024). Recent assessments of industrial and decoupled systems further highlight trade-offs between biological performance, capital intensity, and energy use (Kalvakaalva *et al*., 2023; Guan *et al*., 2025; Schoor *et al*., 2023). Despite growing technical literature, economic performance remains a central uncertainty for commercial adoption. Profitability in aquaponics is highly sensitive to system scale, energy cost, labor intensity, and market price structure (Folorunso *et al*., 2025; Goda *et al*., 2025). Techno-economic analyses suggest that semi-commercial systems may achieve higher margins and shorter payback periods due to economies of scale in infrastructure and labor utilization (Zappernick *et al*., 2022). However, such findings are context-dependent and rarely examined under conditions of persistent electricity unreliability.

Energy supply quality is a critical constraint in many African cities. Nigeria, in particular, experiences frequent grid outages that compel producers to rely on diesel generators or hybrid systems, significantly increasing operating costs and emissions (Jacal *et al*., 2022; Tapang *et al*., 2023; Kweka, G. J. 2024). Empirical studies show that unreliable electricity reduces productivity, increases input costs, and distorts investment decisions (Wen *et al*., 2022; Mbedzi *et al*., 2023). For energy-intensive systems such as recirculating aquaculture and aquaponics—where pumps, aerators, and filtration must operate continuously—electricity unreliability may fundamentally alter techno-economic viability (Ayuso-Virgili *et al*., 2023; Alnemar *et al*., 2025).

Within the FEW nexus perspective, aquaponics represents a tightly coupled production system. Energy use drives water circulation, oxygenation, and nutrient transfer, while biological efficiency ultimately determines output value and profitability. Recent urban modeling work has emphasized that trade-offs between food yield, energy demand, and resource circularity must be quantified to assess system sustainability (Yuan *et al*., 2025; Francisco *et al*., 2024). However, most nexus-oriented aquaponics studies are conducted in high-income contexts with a relatively stable electricity supply. Empirical evidence from emerging-market cities facing chronic grid unreliability remains limited. As a result, the interaction between infrastructure instability and aquaponics profitability remains insufficiently understood.

Furthermore, while environmental performance has been widely studied through LCA (Chen *et al*., 2020; Chen *et al*., 2020; Greenfeld *et al*., 2021), fewer studies explicitly quantify the economic–energy coupling—such as profit per kWh, energy cost share of OPEX, or energy intensity of profit—especially across system scales. Understanding whether larger systems achieve not only higher output but also greater energy productivity and economic resilience is therefore critical for evaluating scale economies in urban aquaponics.

These structural challenges are particularly pronounced in rapidly urbanizing African cities where electricity reliability and food

system resilience are simultaneously constrained. Nigeria provides a compelling case for investigating these dynamics. Urban centers such as Lagos and Abuja differ in population density, infrastructure reliability, and market access, yet both face electricity instability and rising food demand. Aquaculture development in Nigeria has expanded in recent years (Ogunji *et al*., 2023), but integrated aquaponics remains understudied at the urban systems level. Comparative, multi-city empirical analyses are scarce.

This study addresses these gaps by examining energy–water–profit trade-offs and scale economies in urban aquaponics systems across Lagos and Abuja. Using detailed socio-technical and economic datasets, we quantify. Specifically, the study evaluates techno-economic performance indicators (capital expenditure, operating costs, revenue, return on investment, and payback period), energy intensity metrics (kWh per unit output, profit per kWh, and energy cost share), and water productivity indicators. It further examines how system scale (household versus semi-commercial) influences capital efficiency, energy productivity, and resilience under conditions of electricity unreliability.

Integrating economic, energy, and water performance metrics within a comparative urban framework, this study contributes to three strands of literature: (i) aquaponics techno-economic viability, (ii) FEW nexus sustainability assessment, and (iii) energy reliability impacts on productive systems. Beyond academic contributions, the study provides evidence to inform urban agriculture policy, investment planning, and renewable energy integration strategies in electricity-constrained cities. The findings provide empirical evidence from an emerging-market context where electricity instability materially shapes food system performance—an aspect underrepresented in current high-income-dominated research.

Ultimately, this research seeks to determine whether urban aquaponics can operate as a resilient and economically viable urban food infrastructure under electricity unreliability, and whether scaling up production improves or constrains energy–water–profit performance within emerging-market cities.

2. 0 Method

2.1 Study Design and Data Collection

This study employs a cross-sectional, comparative empirical design to assess techno-economic performance and energy–water–profit trade-offs in urban aquaponics systems across two Nigerian cities: Lagos and Abuja. A cross-sectional design was selected because operational aquaponics systems differ substantially in scale, technology configuration, and energy access conditions, making comparative system-level evaluation more appropriate than longitudinal monitoring.

Primary data were collected from operational aquaponics systems between 2024 and 2025 through structured socio-technical and financial surveys administered to system operators. Systems were identified through purposive sampling based on operational status, accessibility, and willingness of operators to provide detailed technical and financial information. Only actively functioning systems with at least one completed production cycle were included. The final dataset comprises (i) Lagos: 12 systems (6 household-scale; 6 semi-commercial) and (ii) Abuja: 6 systems (aquaponics, backyard integrated systems, and recirculating aquaculture systems). The Abuja sample includes integrated backyard aquaponics and recirculating aquaculture systems due to the limited number of fully commercial aquaponics installations in the city. For econometric comparability, only systems with complete financial and energy data were retained in regression analysis (n = 17–18, depending on variable availability and model specification after data cleaning and completeness checks)

The dataset included those shown in Table 1. Data quality checks included consistency verification between reported production

volumes, energy consumption records, and financial statements where available. Outliers were cross-validated with operators to minimize reporting errors./ All monetary values are reported in Nigerian Naira (₦).

Table 1: Key Variables for Aquaponics System Assessment

Category	Variable	Unit / Description
Technical Variables	Grow bed area	m^2
	Fish tank volume	Liters (L)
	Stocking density and survival rate	Fish/m^3 (%)
	Production cycles per year	Cycles/year
	Fish output	kg/year
	Crop output	kg/year
Energy Variables	Daily or monthly electricity consumption	kWh
	Electricity tariff	₦/kWh
	Diesel consumption	Liters/month
	Diesel price	₦/liter
	Grid outage frequency	Days/week
	Backup availability	Generator / Solar
Water Variables	Make-up (top-up) water	L or m^3/month
	Discharge volume	L or m^3/month
	Water cost	₦/m^3
Financial Variables	Capital expenditure (CAPEX)	₦
	Operational expenditure (OPEX)	₦
	Revenue	₦
	Profit	₦

2.2 Construction of FEW–Energy–Profit Indicators

To quantify resource efficiency and nexus trade-offs, raw system-level data were transformed into standardized performance indicators.

2.2.1 Energy Indicators

Annual electricity consumption was calculated for Lagos using equation 1 whereas equation 2 was applied for the Abuja system

$$\text{Annual kWh} = \text{Daily kWh} \times 365 \quad (1)$$

$$\text{Annual kWh} = \text{Monthly kWh} \times 12 \quad (2)$$

Variables associated with derived energy productivity metrics included

$$Profit\ per\ kWh = \frac{\text{Profit}}{\text{Annual kWh}} \quad (3)$$

$$KWh\ per\ ₦1\ \text{million profit} = \frac{\text{Annual kWh}}{\text{Profit}/1{,}000{,}000} \quad (4)$$

$$\text{Energy cost share of OPEX (\%)} = \frac{\text{Annual energy cost}}{\text{OPEX}} \times 100 \quad (5)$$

These metrics, expressed as equations 3 to 5 were implemented to capture the energy–profit coupling central to the study.

2.2.2 Water Indicators (Abuja Systems)

Water volumes were normalized to cubic meters (m^3). Consequently, the annual water use was calculated using equation 6, while equations 7 and 8 were used to calculate water productivity metrics. These indicators quantify water efficiency within the FEW nexus framework.

$$\text{Annual water} = \text{Monthly make-up water} \times 12 \quad (6)$$

$$m^3\text{per kg total output} = \frac{\text{Annual water } (m^3)}{\text{Annual fish + crop output (kg)}} \quad (7)$$

$$\textbf{Profit per } m^3\textbf{water} = \frac{\text{Profit}}{\text{Annual water } (m^3)} \quad (8)$$

2.2.3 Capital and Scale Indicators

To assess scale economies, we computed profit energy (%), return on investment (ROI) and payback period (years) using equations 9 to 11

$$Profit\ margin\ (\%) = \frac{\text{Profit}}{\text{Revenue}} \times 100 \quad (9)$$

Return on investment (ROI):

$$Return\ on\ investment\ (ROI) = \frac{\text{Profit}}{\text{CAPEX}} \quad (10)$$

$$Paynack\ period\ (years) = \frac{\text{CAPEX}}{\text{Profit}} \quad (11)$$

These indicators isolate operational efficiency from pure size effects.

2.3 Sensitivity Analysis: Electricity and Diesel Shocks

To evaluate system resilience under unreliable electricity conditions, scenario-based simulations were conducted for aquaponic systems in Abuja. The analysis modeled three primary shock scenarios, including a 20% increase in electricity tariff, a 30% increase in diesel price, and an increase in grid outage frequency by two additional days per week. These scenarios were used to assess operational stability and cost sensitivity under energy supply disruptions. For systems with backup generation, diesel consumption was scaled proportionally to outage increases. Adjusted OPEX under each scenario was computed using equation 12. The profit under each scenario was calculated using equation 13 and while the Break-even tariff multipliers were estimated using equation 14 as:

$$\text{OPEX}_{new} = \text{OPEX}_{baseline} + \Delta\text{Energy Cost} \quad (12)$$

$$\text{Profit}_{new} = \text{Revenue} - \text{OPEX}_{new} \quad (13)$$

$$1 + \frac{\text{Profit}}{\text{Annual grid energy cost}} \quad (14)$$

This identifies the maximum electricity price increase sustainable before profitability collapses.

2.4 Econometric Model Specification

Two regression approaches were used to identify the drivers of profitability.

2.4.1 Profit Margin Model (Operational Efficiency)

To examine efficiency independent of absolute system size, we estimated the profit margin using the following equation

$$\text{Profit Margin}_i = \alpha + \beta_1 \text{Scale}_{m^2,i} + \beta_2 \text{Annual kWh}_i + \beta_3 \text{Outage Days}_i + \beta_4 \text{CAPEX}_i + \varepsilon_i \quad (15)$$

This model isolates operational drivers of margin performance.

2.4.2 Log–Log Elasticity Model (Scale Effects)

To quantify elasticities and reduce heteroskedasticity, we estimated:

$$\log(\text{Profit}_i) = \alpha + \beta_1 \log(\text{Scale}_i) + \beta_2 \log(\text{Energy}_i) + \beta_3 \log(\text{CAPEX}_i) + \varepsilon_i \quad (16)$$

The coefficients in the above model have the following significance(i) A 1% increase in capital corresponds to β% change in profit and (ii) a 1% increase in scale corresponds to β% change in profit. Ordinary Least Squares (OLS) estimation was applied. Robustness checks included examination of multicollinearity and exclusion of non-positive observations before log transformation.

2.5 Analytical Rationale

The analytical framework integrates the following

(i) **Descriptive FEW indicators** (resource productivity)
(ii) **Shock simulations** (resilience under grid unreliability)
(iii) **Efficiency regression** (profit margin determinants)
(iv) **Elasticity regression** (capital-driven scale economies)

Also, the multi-layered approach allows identification of:

(i) Whether energy is a cost burden or productive input,
(ii) Whether scale improves operational efficiency,
(iii) Whether capital intensity drives profitability,
(iv) Whether larger systems exhibit greater resilience to electricity volatility.

3. 0 Results and Discussion

3.1 Descriptive Food–Energy–Water (FEW) Performance Indicators

3.1.1 Lagos Systems: Scale Effects on Energy Use and Economic Performance

Table 2 presents the mean techno-economic and energy performance indicators for Lagos aquaponics systems categorized by operational scale. Semi-commercial systems exhibit substantially larger production infrastructure, with tank volumes and cultivation areas approximately six times greater than household systems. Although absolute energy consumption increases by approximately 215%, profitability expands disproportionately, with mean profit rising nearly elevenfold. This divergence indicates nonlinear scale economies. Energy productivity improves markedly as systems expand: profit generated per unit of electricity increases from ₦116.8 to ₦404.8 kWh^{-1}, while energy required to generate ₦1 million profit declines by approximately 71%. These results suggest that fixed energy requirements—such as pumping and aeration—are distributed over larger production outputs, thereby reducing energy intensity per unit economic return. Higher profit margins and shorter payback periods observed in semi-commercial systems further indicate improved capital utilization efficiency, consistent with economies of scale in integrated aquaculture–hydroponic operations.

3.1.2 Abuja Systems: Integrated FEW Nexus Performance

Abuja systems provide additional insight into water–energy interactions within the FEW nexus due to the availability of detailed water-use records. Mean system-level indicators are summarized in Table 3.

Scaling effects simultaneously improve economic, energy, and water performance. Semi-commercial systems achieve a 50% reduction in energy intensity and a 58% reduction in water intensity relative to household operations. Concurrently, economic water productivity more than doubles. The reduction in energy cost share—from 18.4% to 11.7% of operating expenses—indicates that energy expenditures become proportionally less constraining as production scale increases. These findings demonstrate that scale expansion enhances resource coupling efficiency, a central principle of the FEW nexus framework, whereby improvements in one resource dimension reinforce gains.

Table 2. Mean Techno-Economic and Energy Performance Indicators for Lagos Aquaponics Systems by Scale

Indicator	Household Systems	Semi-Commercial Systems
Tank volume (L)	1,592	9,767
Grow bed area (m^2)	13.5	59.0
Annual energy use (kWh yr^{-1})	2,470	7,787
Capital expenditure, CAPEX (₦)	896,667	7,350,000
Annual operating expenditure, OPEX (₦)	440,000	3,150,000
Annual revenue (₦)	728,333	6,300,000
Annual profit (₦)	288,333	3,150,000
Profit margin (%)	39.6	50.0
Return on investment (ROI)	0.32	0.43
Payback period (years)	3.11	2.33
Profit per energy use (₦ kWh^{-1})	116.8	404.8
Energy intensity of profit (kWh per ₦1 million profit)	8,579	2,471

Table 3. Mean Food–Energy–Water Nexus Performance Indicators for Abuja Aquaponics Systems

Indicator	Household Aquaponics	Semi-Commercial Aquaponics
System scale (m^2)	24	120
Annual output (kg yr^{-1})	1,140	7,900
Annual grid electricity use (kWh yr^{-1})	3,720	12,960
Annual water use (m^3 yr^{-1})	220	650
Annual profit (₦)	471,068	3,047,422
Profit margin (%)	48.7	54.3
Return on investment (ROI)	0.52	0.61
Energy cost share (%)	18.4	11.7
Energy intensity (kWh kg^{-1} output)	3.26	1.64
Water intensity (m^3 kg^{-1} output)	0.19	0.08
Profit per unit water use (₦ m^{-3})	2,141	4,688

3..1.2 Energy–Profit Trade-Offs Across Cities

Comparative analysis across Lagos and Abuja reveals consistent relationships between energy consumption and profitability. Larger systems consume more total electricity but convert energy inputs into economic output more efficiently.

In Lagos, profit increases by approximately 992% between household and semi-commercial categories, while energy consumption rises by only 215%. Consequently, profit per kWh increases by 246%, confirming increasing returns to energy utilization.

Similarly, Abuja systems demonstrate declining energy intensity with scale, as kWh per kilogram of output decreases by half. The declining share of energy costs within total operating expenditure further indicates improved operational efficiency.

Collectively, these results suggest that energy in aquaponics systems functions primarily as a productive enabling input rather than a proportional cost burden. Efficiency gains arise from improved infrastructure utilization, continuous system operation, and reduced relative overhead costs at larger scales.

3.1.3 Sensitivity Analysis and System Resilience Under Electricity Shocks

Scenario simulations were conducted to evaluate system resilience under electricity price volatility and supply disruptions. Profit outcomes under selected shock scenarios are summarized in Table 4.

Household systems exhibit high vulnerability to electricity disruptions. Moderate outage escalation alone eliminates profitability in small systems reliant on backup generation, primarily due to increased diesel dependence. In contrast, semi-commercial systems maintain positive profit levels across all simulated scenarios, demonstrating greater operational resilience. Larger capital bases allow fixed energy costs to be absorbed more effectively and enable investment in more efficient backup configurations. Break-even electricity tariff multipliers further quantify resilience differences as shown in Table 5. Semi-commercial aquaponics systems in Abuja remain profitable even when electricity tariffs increase more than thirteenfold, indicating strong structural buffering against energy price shocks.

Table 4. Profit Response of Representative Abuja Systems Under Electricity Shock Scenarios

System	Baseline Profit (₦)	Tariff +20%	Diesel +30%	Outages +2 days/week	Combined Shock
Abuja_HH_1	575,953	522,000	401,000	−48,047	−573,647
Abuja_SC_3	3,112,000	3,042,000	2,821,000	2,610,000	2,488,000

Table 5. Electricity Tariff Break-Even Multipliers by System Type

System Type	Tariff Break-Even Multiplier
Lagos Household	2.56×
Lagos Semi-Commercial	6.40×
Abuja Household Aquaponics	2.47×
Abuja Semi-Commercial Aquaponics	13.09×

3.1.4 Econometric Analysis of Profitability Drivers

To further examine system vulnerability under energy price fluctuations, the econometric analysis incorporates variables representing electricity tariffs and outage frequency. The results indicate that while short-term increases in electricity prices negatively affect profit margins for household systems, semi-commercial systems exhibit substantial buffering due to capital-intensive infrastructure and backup energy capacity. These findings confirm that structural investment mediates the impact of energy price shocks on operational efficiency.

3.1.4.1 Profit Margin Model: Operational Efficiency Determinants

The profit margin regression model explains 71.3% of variation in profitability (R^2 = 0.713), with all coefficients statistically significant ($p < 0.01$).

Model results indicate that production scale and energy use positively influence profit margins, suggesting improved operational efficiency as system size expands. The positive coefficient for outage days likely reflects the presence of larger systems equipped with backup power infrastructure rather than beneficial outage effects themselves.

Conversely, CAPEX exhibits a negative association with margin ratios, implying that high initial investments reduce short-term proportional returns despite increasing absolute profit levels.

Overall, the model confirms that operational efficiency improves systematically with scale expansion.

3.1.4.2 Log–Log Elasticity Model: Structural Drivers of Profit

The elasticity model demonstrates strong explanatory power ($R^2 = 0.947$; model $p < 0.000001$), indicating that profit variation is largely explained by structural system characteristics.

Capital investment emerges as the only statistically significant determinant of profitability. A 1% increase in CAPEX corresponds to an approximately 0.85% increase in profit, indicating strong capital-driven productivity effects.

Neither land area nor energy consumption independently explains profit once capital intensity is controlled, suggesting that infrastructure quality and technological investment, not physical size alone—drive economic performance. The log–log elasticity model further highlights the relative insensitivity of profitability to energy price shocks in capital-intensive systems. While energy use alone does not significantly explain profit once CAPEX is accounted for, scale and energy inputs act as channels through which capital investment mitigates vulnerability. This aligns with observed patterns where semi-commercial systems maintain profitability under simulated tariff increases and outages, emphasizing that capital deepening, rather than operational

energy consumption, drives economic resilience (Table 6).

Table 6. Profit Elasticities from Log–Log Regression Model

Variable	Elasticity	p-value
log(CAPEX)	0.852	<0.001
log(Scale)	0.204	0.223
log(Energy)	0.292	0.343

3.1.5 Integrated Synthesis

Across descriptive, simulation, and econometric analyses, four consistent patterns emerge:

Strong scale economies: Semi-commercial systems achieve higher profit margins, reduced payback periods, and lower resource intensity. Improved resource productivity with scale: Energy and water efficiency increase simultaneously, supporting FEW nexus optimizations.

Disproportionate vulnerability of small systems: Electricity unreliability primarily threatens household-scale profitability.

Capital-driven profitability: Economic performance is determined primarily by capital deployment rather than land area or energy consumption alone.

Taken together, the results demonstrate that urban aquaponics operating under electricity unreliability exhibits capital-mediated scale economies, in which energy acts as an enabling production input whose productivity improves as system scale and technological investment increase.

3.2 Discussion

3.2.1 Scale Economies and Structural Efficiency in Urban Aquaponics

The results provide strong empirical evidence that urban aquaponics systems exhibit pronounced scale economies under electricity-constrained conditions. Across both Lagos and Abuja, semi-commercial systems achieved higher profit margins, shorter payback periods, and substantially greater resource productivity compared with household-scale systems. Importantly, these gains occurred despite higher absolute energy consumption, indicating that efficiency improvements arise from structural rather than purely technological factors.

Economies of scale in aquaponics emerge primarily from the distribution of fixed operational energy loads—such as pumping, aeration, filtration, and monitoring—across larger production volumes. Household systems bear nearly identical baseline energy requirements but produce significantly lower output, leading to higher energy intensity per unit of production and profit. As system size increases, marginal energy consumption grows more slowly than output value, resulting in declining energy intensity and improved economic efficiency.

This finding aligns with techno-economic studies suggesting that aquaponics profitability improves beyond subsistence scales due to infrastructure utilization efficiencies. However, the present study extends existing literature by demonstrating that scale economies remain robust even under unreliable electricity supply, a condition rarely examined empirically. The results therefore challenge assumptions derived from high-income contexts where energy reliability is largely taken for granted.

3.2.2 Energy as a Productive Input Within the FEW Nexus

A central contribution of this study is the empirical demonstration that energy functions as a productive enabling input rather than merely an operating cost in aquaponics systems. Conventional agricultural analyses often treat energy expenditures as cost burdens that reduce profitability. In contrast, the observed increase in profit per kWh with system scale indicates that energy productivity improves as biological and infrastructural processes become more integrated.

Within the food–energy–water (FEW) nexus framework, aquaponics represents a tightly coupled system in which energy drives water circulation and oxygenation, enabling nutrient recycling and biological productivity. Improvements in energy efficiency therefore propagate across water and food subsystems simultaneously. The

Abuja results clearly illustrate this coupling: reductions in energy intensity coincided with reductions in water intensity and increases in economic water productivity.

These findings support nexus theory predictions that integrated systems can achieve synergistic efficiencies when resource flows are optimized collectively rather than independently. Larger systems appear better able to stabilize biological cycles, maintain optimal hydraulic conditions, and reduce resource losses, thereby enhancing multi-resource productivity.

3.2.3 Infrastructure Instability and Differential Vulnerability Across Scales

Electricity unreliability emerged as a critical determinant of system resilience. Sensitivity simulations revealed that household aquaponics systems become unprofitable under moderate increases in outage frequency or energy prices, whereas semi-commercial systems remain economically viable even under severe energy shocks.

This divergence highlights the role of scale-mediated resilience. Larger systems benefit from several structural advantages:

Greater revenue buffers relative to fixed energy costs;

Higher capital capacity enabling investment in backup power systems;

Improved operational continuity during grid disruptions;

Lower proportional dependence on diesel generation.

Small systems, by contrast, experience rapid cost escalation when outages increase because diesel fuel substitutes expensive grid electricity without corresponding increases in output. As a result, energy unreliability disproportionately penalizes small-scale producers, potentially reinforcing structural inequalities in urban food production systems.

These findings extend broader development economics literature showing that unreliable electricity suppresses productivity in emerging economies. The present study demonstrates that this mechanism operates strongly within technologically integrated food systems, where continuous operation is biologically required rather than economically optional.

3.2.4 Capital Intensity as the Dominant Driver of Profitability

The econometric elasticity analysis provides a key structural insight: profitability is primarily driven by capital investment rather than physical scale or energy consumption alone. The strong and statistically significant elasticity of profit with respect to CAPEX indicates that technological configuration and infrastructure quality determine economic outcomes more than system area.

This result suggests that "scale" in aquaponics should be interpreted as capital deepening rather than simply spatial expansion. Investments in efficient pumps, filtration systems, automation, and optimized system design likely improve biological stability and reduce operational inefficiencies, thereby increasing returns.

The insignificance of land area and energy consumption once capital is controlled implies that energy and scale act as intermediate channels through which capital exerts influence. In other words, capital enables efficient energy use rather than energy independently generating profit.

This capital-driven dynamic distinguishes aquaponics from traditional agriculture, where land is often the primary production constraint. Urban aquaponics instead resembles controlled-environment agriculture and other technology-intensive production systems in which productivity depends largely on engineered infrastructure.

3.2.5 Implications for Urban Food System Resilience

The findings have important implications for urban food resilience strategies in electricity-constrained environments. Policymaking often promotes small-scale urban agriculture as an accessible pathway to food security; however, the results indicate that very small aquaponics systems may be structurally

vulnerable under unstable infrastructure conditions.

Rather than uniform promotion of household systems, policies may need to prioritize:

cooperative or clustered semi-commercial systems, access to affordable capital financing, integration of renewable energy technologies, and scale-sensitive subsidy structures.

The high tariff break-even multipliers observed for semi-commercial systems suggest that larger installations could function as resilient urban food infrastructure capable of withstanding substantial energy market volatility. Such systems may therefore play a strategic role in climate-resilient urban food planning.

4.2.6 Contributions to FEW Nexus and Aquaponics Literature

This study advances three major research domains. First, it contributes empirical evidence to aquaponics techno-economic literature by demonstrating scale-dependent profitability under real operating conditions rather than modeled scenarios.

Second, it strengthens FEW nexus scholarships by quantifying energy–water–profit coupling using integrated performance indicators, showing that efficiency gains occur simultaneously across resource dimensions.

Third, it expands research on infrastructure reliability by showing how electricity instability reshapes production economics in integrated agricultural systems within emerging-market cities.

Importantly, most previous nexus studies focus on high-income regions with stable infrastructure. By providing comparative evidence from Lagos and Abuja, this study highlights how infrastructure constraints fundamentally alter sustainability dynamics.

4.7 Limitations and Future Research Directions

Several limitations should be acknowledged. The cross-sectional design captures system performance at a single period and may not fully represent long-term learning effects or seasonal variability. Sample size constraints also limit exploration of heterogeneous management practices and technology configurations.

Future research should incorporate longitudinal monitoring, life-cycle environmental assessment integrated with financial performance, and evaluation of renewable energy hybridization scenarios. Additional comparative studies across African cities would further clarify how infrastructure conditions mediate aquaponics sustainability outcomes.

4.0 Conclusion

This study investigated energy–water–profit trade-offs and scale economies in urban aquaponics systems operating under conditions of unreliable electricity in Lagos and Abuja, Nigeria. By integrating techno-economic analysis, food–energy–water (FEW) nexus indicators, shock simulations, and econometric modeling, the research provides empirical evidence on how infrastructure instability shapes the viability of technology-intensive urban food production systems in emerging-market contexts.

The findings demonstrate clear and consistent scale economies across both cities. Semi-commercial aquaponics systems achieved higher profit margins, shorter payback periods, and substantially greater resource productivity than household-scale systems. Although larger systems consumed more energy in absolute terms, energy intensity per unit output and per unit profit declined markedly with scale, indicating improved operational efficiency. Simultaneous reductions in water intensity and increases in profit per cubic meter further confirm that scaling enhances integrated resource efficiency within the FEW nexuses.

Electricity unreliability emerged as a decisive constraint affecting system resilience. Sensitivity analyses revealed that household systems are highly vulnerable to tariff increases and outage escalation, often becoming unprofitable under moderate energy shocks. In contrast, semi-commercial

systems maintained positive profitability even under severe electricity price and reliability disruptions, supported by stronger revenue buffers and more efficient energy utilization. These results suggest that infrastructure instability disproportionately affects smaller systems and may limit the effectiveness of purely household-based urban aquaponics promotion strategies.

Econometric results further indicate that profitability is primarily driven by capital intensity rather than physical scale or energy consumption alone. The strong elasticity of profit with respect to capital investment shows that technological configuration and infrastructure quality underpin economic performance. Energy and land area become secondary determinants once capital deployment is considered, implying that scale advantages arise mainly through capital deepening and improved system design.

Collectively, the study advances FEW nexus scholarships by empirically demonstrating that scale moderates' energy–water–profit trade-offs under infrastructure uncertainty. Urban aquaponics functions as a tightly coupled socio-technical system in which energy acts as an enabling productive input whose efficiency improves with system maturity and investment level. These insights extend existing aquaponics literature, which has largely been derived from high-income contexts with stable electricity supply, by revealing how unreliable infrastructure fundamentally reshapes sustainability outcomes.

From a policy perspective, the results highlight the importance of facilitating access to capital financing, promoting renewable or hybrid energy integration, and designing scale-sensitive support mechanisms for urban agriculture. Rather than uniformly encouraging small household installations, development strategies may achieve greater resilience and economic sustainability by supporting clustered or semi-commercial aquaponics systems capable of absorbing energy volatility.

This study is limited by its cross-sectional design and sample size, which may not fully capture temporal variability or technological learning effects. Future research should incorporate longitudinal performance monitoring, life-cycle environmental assessments, and evaluation of renewable energy hybridization pathways to further clarify long-term sustainability dynamics.

In conclusion, urban aquaponics can operate as a viable and resilient component of urban food infrastructure in electricity-constrained environments, but its success depends fundamentally on capital investment and system scale. Under unreliable electricity conditions, profitability and resource efficiency are not constrained by energy use itself but by the capacity of systems to convert energy inputs into productive outputs efficiently. Scaling and capital deepening therefore represent critical pathways for enhancing urban food system resilience in rapidly urbanizing emerging-market cities.

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Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

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Authors' Contribution

Samuel Awolumate conceptualized the study, designed the research framework, and coordinated data collection across Lagos and Abuja. Buba B. Shani developed the methodology, performed data analysis, and conducted the FEW nexus and energy–profit simulations. Adekunle James Okhogbe contributed to econometric modeling, validation of results, and manuscript preparation. All authors interpreted findings, critically revised the manuscript for intellectual content, and approved the final version for publication.