

COMPARATIVE COST-EFFECTIVENESS ANALYSIS OF AN AUTOMATED HOME HYDROPONIC SYSTEM

Matej Gocník^{*1}, Jozef Dubovec¹, Andrea Ecková²

¹AQUASTOW s. r. o., Bratislava, Slovak Republic

²Prague University of Economics and Business, Czech Republic

This study presents a comparative cost-effectiveness analysis of a custom-engineered automated home hydroponic device (the Display Unit) for fresh basil (*Ocimum basilicum* L.) production relative to retail purchasing, assessed from the end-consumer perspective. A framework incorporating unit production cost (UPC), return on investment (ROI), and payback period (PBP) was applied across a 61-day cultivation trial across five prototype units, under two device-price scenarios (prototype: 4,990.11 €; estimated market price: 3,911.40 €) and two retail segments (standard: 27.25 €·kg⁻¹; premium: 57.39 €·kg⁻¹), with and without food waste rate (FWR) correction. UPC under the market-price scenario reached 90.20 €·kg⁻¹, exceeding the standard and premium references by 231% and 57%. ROI was negative across all analytical variants (-42.48% to -153.21%), with PBP undefined under the standard segment and exceeding the device lifetime under the premium segment. Threshold analysis confirmed that cost-competitiveness against the standard segment is unachievable through single-parameter optimisation. Heatmap sensitivity analysis demonstrated that the Display Unit already operates within the cost-competitive zone at the observed yield level under the premium segment with FWR correction and achieves full cost-competitiveness upon yield optimisation. FWR correction improved ROI by 14–37 percentage points, confirming the harvest-on-demand principle as a genuine cost advantage.

Keywords: cost-effectiveness, home hydroponic system, unit production cost, food waste rate

Introduction

Modern agriculture faces challenges that threaten both the stability of the food system and environmental sustainability. Approximately 14% of the world's food is lost post-harvest, while an additional 17% is wasted at the retail and consumer levels (FAO, 2019). Global population growth, projected to reach 11 billion by the end of the century, will require a more than 60% increase in grain production (Roser et al., 2013; Godfray et al., 2010).

However, conventional farming is reaching its physical limits: 50% of the world's habitable land is already dedicated to agriculture, and an additional 3.4 million km² of cropland will be required by 2050 to meet demand. This expansion is the primary driver of habitat loss, threatening nearly 88% of terrestrial vertebrate species with extinction (Ritchie & Roser, 2019; Williams et al., 2021). Furthermore, one-third of the planet's land is severely degraded due to intensive agricultural practices (IPBES, 2018).

In response to these pressures, autonomous growing systems and modular hydroponic architectures have emerged as viable alternatives. These systems operate independently of climate, season, and geographic location, providing a buffer against climate-related disruption and enabling intensified land use (Asseng et al., 2020). By enabling food production close to the point of consumption, such systems can shorten supply chains and reduce food losses (Abdelouhahid et al., 2020; Golian et al., 2025).

Economic viability, however, remains the most persistent barrier to wider adoption. Electricity for artificial lighting and climate control alone can account for more than half of total operating costs, leaving many crops non-competitive with conventional market prices (Asseng et al., 2020; Olle and Viršile, 2013). This tension between environmental promise and economic cost is increasingly framed within the European Union's bioeconomy and circular economy agendas (European Commission, 2018).

Almost all existing cost-effectiveness and feasibility research concerns large-scale, commercial vertical farms or controlled-environment facilities producing for wholesale markets (Asseng et al., 2020). Yet rigorous

assessment from the end consumer's perspective remains scarce. This study addresses that gap.

The aim is to conduct a comparative cost-effectiveness analysis of a custom-engineered automated home hydroponic device (the Display Unit) using fresh basil (*Ocimum basilicum* L.) as a reference crop, assessed relative to retail purchasing from the perspective of the end consumer.

To this end, a consumer-oriented analytical framework is developed and applied, incorporating unit production cost calculation (UPC), return on investment (ROI), and payback period (PBP) analysis across two device-price scenarios: prototype cost (DU-P) and estimated market price (DU-M), and two analysis levels: without and with food waste rate (FWR) correction.

To achieve this aim, the following research questions were formulated:

- ❑ RQ1: What is the UPC of fresh basil cultivated in the Display Unit under both device-price scenarios (DU-P, DU-M), and how does it compare to standard and premium retail prices, with and without FWR correction?
- ❑ RQ2: What is the ROI and PBP of the Display Unit over its assumed operational lifetime across device-price scenarios, retail segments, and FWR levels – and under which conditions, if any, is the investment recoverable?
- ❑ RQ3: Under what combinations of device price, biomass yield, and electricity consumption would the Display Unit achieve cost-competitiveness with retail purchasing (ROI = 0%), and how do these threshold conditions differ between the standard and premium retail segments?
- ❑ RQ4: How does the FWR correction affect the comparative cost assessment, and to what extent does the Display Unit's harvest-on-demand principle represent a structural advantage over retail purchasing in terms of effective consumer cost?

Materials and Methods

Analytical framework

The analysis adopts the perspective of the end consumer – an individual household user operating the Display Unit for personal herb production. Only direct monetary expenditures are considered: operational costs (electricity, water, nutrients, citric acid, seeds) and device amortisation. The functional unit is 1 kg of edible fresh basil biomass (*Ocimum basilicum* L.) at the point of consumption, defined as harvestable aerial parts (leaves and stems) after removal of roots.

Two time horizons apply. The experimental horizon comprises a single 61-day growing cycle, replicated across five Display Unit prototypes operated simultaneously. The economic horizon, used for ROI and PBP calculations, is 10 years (device lifetime estimated from design specifications), assuming six cycles per year ($365 \div 61 \approx 6$). Two device-price scenarios are applied throughout: DU-P (actual prototype manufacturing cost of 4,990.11 €) and DU-M (estimated market price of 3,911.40€ projected by the developers). All comparisons are performed against two retail segments: standard (mean 27.25 €·kg⁻¹) and premium (mean 57.39 €·kg⁻¹), and at two analytical levels: primary analysis (no food waste correction) and extended analysis with food waste rate correction.

Description of the display unit

The Display Unit is a custom-engineered, self-contained automated hydroponic growing system designed for domestic use and intended for cultivation of a broad range of herbs and vegetables. Each unit houses six vertical growing pillars with a total capacity of 48 plants per cycle, a 140-litre water and nutrient solution reservoir with a top-fed drip irrigation system. The full-spectrum LED lighting (400–700 nm, PAR 250–300 μmol·m⁻²·s⁻¹) with enhanced red, ultraviolet, and infrared peaks and the Peltier-based thermoelectric climate control enable year-round operation. A microcontroller-based system autonomously manages photoperiod, nutrient delivery, electrical conductivity (EC), pH, temperature, and ventilation without continuous user intervention.

Experimental design

The experiment was conducted between December 2025 and January 2026 across five prototype units operated simultaneously in an unheated industrial facility with no thermal insulation in Nitra, Slovakia, subject to ambient winter temperatures of 3–8 °C. This substantially increased thermal regulation demand relative to typical domestic conditions, a factor explicitly acknowledged when interpreting electricity consumption. Sweet basil (*Ocimum basilicum* L.) was cultivated in 65 mm net pots with stone wool medium, 48 plants per unit per cycle (61 days). Nutrient solution was maintained at EC 1.2–1.4 dS·m⁻¹; pH was regulated with citric acid. Mean photoperiod was 16 h·d⁻¹; air temperature was 24–25 °C (light) and 18–19 °C (dark). Harvest was performed at visual maturity (full leaf development, canopy closure prior to floral initiation); only edible aerial biomass was weighed.

Data collection and measurement methods

Electricity consumption was measured continuously at 500 ms intervals (accuracy ±0.1% for active energy). Cumulative energy consumption per cycle was derived from the integration of instantaneous power readings over the cycle duration, expressed in kWh·cycle⁻¹. Water, nutrient, and citric acid volumes were recorded using graduated vessels. Edible fresh biomass was

determined by individual plant weighing (resolution 0.1 g). Of 240 seeded plants, 234 reached harvest (survival rate 97.5%).

Retail prices for fresh-cut basil were collected on 8 May 2026 across six Slovak retail channels (seven price observations), encompassing conventional supermarkets, speciality retailers, and online platforms. Only fresh-cut basil was included, potted basil was excluded. For each retailer, the following data were recorded: retailer name, package weight, package price, date of measurement, and the resulting unit price expressed in €·kg⁻¹. The survey was a single-point measurement, temporal variability was not assessed. All prices include value-added tax (VAT). Given the limited sample size ($n = 7$), the survey is intended to provide a reference benchmark for the economic comparison rather than a statistically representative characterisation of the retail market.

Unit production cost

The UPC is defined as the total cost of producing 1 kg of edible fresh basil biomass in the Display Unit, expressed in €·kg⁻¹. The UPC comprises two components:

$$UPC = \frac{OPEX + C_{amortization}}{Y}$$

where: OPEX – comprises five operating cost items:

$$OPEX = C_{electricity} + C_{water} + C_{nutrient} + C_{citric_acid} + C_{seed}$$

where: Y – edible fresh biomass yield per cycle (kg·cycle⁻¹); $C_{electricity}$ – electricity consumption (kWh·cycle⁻¹) × tariff; C_{water} – water volume (l·cycle⁻¹) × tariff; $C_{nutrient}$ – nutrient volume (ml·cycle⁻¹) × unit price; $C_{citricacid}$ – mass consumed (kg·cycle⁻¹) × unit price; C_{seed} – 0.19 €·cycle⁻¹ (one packet shared across five units); $C_{amortisation} = P / (L \times N)$, where P – device price, $L = 10$ years, $N = 6$ cycles·year⁻¹

Labour, installation, O & M, and end-of-life disposal costs are excluded, retail reference prices equally exclude consumer's time. O & M data are unavailable at the prototype stage, end-of-life disposal costs were assumed negligible because household electronic waste is collected through producer responsibility schemes established under the EU WEEE Directive. UPC is calculated under both device-price scenarios (UPC_DU-P, UPC_DU-M).

For comparability, UPC_retail (also referred to as Retail) is defined analogously as the mean retail purchase price (€·kg⁻¹) paid by the consumer to obtain 1 kg of fresh basil through retail channels.

Food waste rate (FWR) correction

The primary analysis assumes full consumption of all basil produced or purchased. The extended analysis incorporates FWR at two levels, applied to two distinct analytical purposes.

The retail FWR is set at 29% (De Laurentiis et al., 2018), representing the share of fresh fruit and vegetables purchased by EU households is wasted. This is acknowledged as a category-level rather than herb-specific figure and treated as a conservative estimate given the high perishability of fresh herbs. The Display Unit FWR is set at 10%, a conservative assumption reflecting its harvest-on-demand functionality (this value is not empirically measured).

FWR correction of UPC – to express the effective cost per kilogram of basil consumed, UPC is adjusted for each system independently using its respective FWR:

$$UPC_{adj} = \frac{UPC_{nominal}}{1 - FWR}$$

FWR correction for economic return metrics – for the calculation of annual saving and derived metrics (ROI, PBP), a combined retail-side adjustment is applied:

$$UPC_{retail, eff} = UPC_{retail} \times \frac{(1 - FWR_{DU})}{(1 - FWR_{retail})}$$

Economic return metrics

ROI and PBP were selected as directly interpretable indicators of household-scale system performance.

ROI quantifies the net financial return over the assumed Display Unit lifetime:

$$ROI = \frac{(AS \times L) - P}{P} \times 100$$

where: AS – annual saving (€·year⁻¹); L – device lifetime (10 years); P – device price (€)

Annual saving is defined as:

$$AS = (UPC_{retail} - OPEX_{per_kg}) \times Y \times N$$

under FWR – corrected analysis, UPC_{retail} is replaced by $UPC_{retail, eff}$

where: $OPEX_{per_kg} = OPEX \div Y$ (€·kg⁻¹); Y – mean edible fresh biomass yield per cycle (kg·cycle⁻¹); N – number of cycles per year (6 cycles·year⁻¹)

A negative AS indicates net annual overpayment, resulting in negative ROI.

PBP expresses the number of years required for cumulative savings to recover the acquisition cost:

$$PBP = \frac{P}{AS} \quad \text{or} \quad PBP = \frac{P}{AS_{adj}}$$

PBP is meaningful only when $AS > 0$, otherwise it is reported as *N/A*. The interpretive threshold is $PBP \leq 10$ years, corresponding to the assumed device lifetime.

ROI and PBP are calculated across eight combinations arising from two device-price scenarios × two retail segments × two analytical levels.

Threshold analysis – methodology

Where ROI is negative under current operating conditions, threshold analysis is applied to identify the minimum parameter adjustments required to achieve $ROI = 0\%$. Within this study, cost-competitiveness is operationalised through the ROI metric rather than through unit-price parity alone: even when UPC_{DU} equals UPC_{retail} the Display Unit may not be cost-competitive from the consumer perspective, as the acquisition cost has not yet been recovered through accumulated savings. Three parameters are examined based on their dominant UPC contribution: device market price (via amortisation), electricity consumption and biomass yield (denominator effect):

Threshold device price:

$$P^* = (UPC_{retail} - OPEX_{per_kg}) \times Y \times N \times L$$

Threshold biomass yield:

$$Y^* = \frac{(P + OPEX \times N \times L)}{(UPC_{retail} \times N \times L)}$$

Threshold electricity consumption:

$$E^* = \frac{(UPC_{retail} \times Y \times N \times L - OPEX_{excl_el} \times N \times L - P)}{p_{el} \times N \times L}$$

under FWR – corrected analysis, UPC_{retail} is replaced by $UPC_{retail, eff}$

where: $OPEX_{excl_el}$ – OPEX per cycle excluding electricity cost; p_{el} – electricity price

Heatmap sensitivity visualisation

To capture the combined effect of simultaneous parameter variation, a panel heatmap visualisation maps two-dimensional ROI surfaces (device price × electricity consumption) across three discrete yield levels as separate panels: BASE (1,587 kg·cycle⁻¹, observed), MID (1,904 kg·cycle⁻¹, +20%), and HIGH (2,221 kg·cycle⁻¹, +40%). Device price ranges from 300 to 3,911 € (12 values); electricity from 50 to 349 kWh·cycle⁻¹ (12 values). Cells are colour-coded: dark green ($ROI \geq 20\%$, strongly cost-competitive), light green ($0\% \leq ROI < 20\%$, marginally cost-competitive), and red ($ROI < 0\%$, not cost-competitive). Three scenarios are presented: Retail_STD without FWR, Retail_STD with FWR, and Retail_PREM with FWR. All other parameters are held at the observed values. The MID and HIGH yield levels are considered realistic, as improvements of 20–40% have been reported for hydroponic basil through optimisation of electrical conductivity, photoperiod, LED spectrum, and nutrient management (Saha et al., 2016; Rahman et al., 2021; Ren et al., 2022).

Results and Discussion

Experimental outcomes

All five prototype units completed a cultivation trial of identical length (61 days), confirming the consistency of the cultivation protocol. Detailed results are presented in Table 1.

Electricity consumption was the only parameter with meaningful inter-unit variability, attributable to ambient temperature fluctuations in the unheated facility during winter (3–8 °C). This value represents an upper bound relative to typical domestic conditions, where ambient temperatures are higher and more stable. Electricity consumption, and consequently all UPC values, should therefore be interpreted as conservative estimates from the household perspective. Water, nutrient, citric acid, and seed consumption were identical across all cycles, reflecting the standardised input protocol. The low standard deviation in edible fresh biomass yield confirms the protocol's consistency and supports the representativeness of the mean yield value used in all subsequent economic calculations.

Retail price reference benchmark

Retail prices for fresh-cut basil ranged from 22.49 to 66.33 €·kg⁻¹ across the seven observations (Table 2). A natural price discontinuity between 35.90 and 46.33 €·kg⁻¹, with no observations in this interval, was used to define two segments: standard (≤ 40 €·kg⁻¹; mean: 27.25 ± 5.47 €·kg⁻¹, $n = 4$) and premium (> 40 €·kg⁻¹; mean: 57.39 ± 8.30 €·kg⁻¹, $n = 3$).

Unit production cost analysis

The cost structure of the Display Unit is dominated by two items (Table 3): electricity and amortisation together account for approximately 95% of the UPC, while the remaining inputs collectively contribute less than 5%. This concentration identifies device price and electricity consumption as the only parameters with meaningful cost-reduction potential.

Table 1 Experimental outcomes across five Display Unit prototypes during a single 61-day basil cultivation trial

	Unit	Prototype 1	Prototype 2	Prototype 3	Prototype 4	Prototype 5	Mean	SD
Cycle length	days	61	61	61	61	61	61	0.00
Edible fresh biomass yield	kg-cycle ⁻¹	1.563	1.608	1.593	1.571	1.597	1.587	0.017
Electricity consumption	kWh-cycle ⁻¹	337.8	356.9	344.5	361.3	345.3	349.2	8.63
Water consumption	l-cycle ⁻¹	220.0	220.0	220.0	220.0	220.0	220.0	0.00
Nutrient consumption	ml-cycle ⁻¹	420.0	420.0	420.0	420.0	420.0	420.0	0.00
Citric acid	kg-cycle ⁻¹	0.30	0.30	0.30	0.30	0.30	0.30	0.00
Seed packets used	pkts-cycle ⁻¹	0.2	0.2	0.2	0.2	0.2	0.20	0.00

Source: Own experiment

Table 2 Retail price reference benchmark for fresh-cut basil

Retailer	Package weight (g)	Package price (€)	Price (€·kg ⁻¹)	Segment
Yeme	30	1.99	66.33	premium
Tesco	20	1.19	59.50	premium
Lunys	30	1.39	46.33	premium
Zdravé ovocie	n/a*	n/a*	22.49	standard
Fruvita	n/a*	n/a*	22.61	standard
Košík.sk	100	3.59	35.90	standard
Košík.sk	500	13.99	27.98	standard

Segment	Mean price (€·kg ⁻¹)	SD (€·kg ⁻¹)
Retail_STD	27.25	5.47
Retail_PREM	57.39	8.30

Source: Own retail price survey

*Product sold by weight; price represents the directly stated per-kilogram retail price

Table 3 UPC breakdown by cost item under DU-P and DU-M scenario

Cost item	€·cycle ⁻¹ (DU-P)	€·kg ⁻¹ (DU-P)	Share of total UPC (%)	€·cycle ⁻¹ (DU-M)	€·kg ⁻¹ (DU-M)	Share of total UPC (%)
Cost_electricity	71.93	45.34	44.65	71.93	45.34	50.26
Cost_water	0.26	0.17	0.16	0.26	0.17	0.18
Cost_nutrient	4.03	2.54	2.50	4.03	2.54	2.82
Cost_citric_acid	1.50	0.95	0.93	1.50	0.95	1.05
Cost_seed	0.19	0.12	0.12	0.19	0.12	0.13
Cost_amortization	83.17	52.42	51.63	65.19	41.09	45.55
Total	161.08	101.53	100.00	143.10	90.20	100.00

Source: Own research

Table 4 UPC under primary and extended analysis

	w/o FWR	DU-adjusted (DU_FWR = 10%)	Retail-adjusted (RETAIL_FWR = 29%)
UPC_DU-P (€·kg ⁻¹)	101.53	112.81	X
UPC_DU-M (€·kg ⁻¹)	90.20	100.22	X
Retail_STD (€·kg ⁻¹)	27.25	X	38.37
Retail_PREM (€·kg ⁻¹)	57.39	X	80.83

Source: Own research

Under primary analysis, the UPC_DU exceeds the retail reference price in both segments (Table 4). The gap against the standard segment is prohibitively large, effectively precluding cost-competitiveness through incremental optimisation. The narrower differential against the premium segment is analytically significant, as it positions the Display Unit within a market context where non-monetary attributes (freshness, provenance,

and harvest-on-demand convenience) partially offset the quantified cost disadvantage.

FWR correction narrows the differential through a structurally asymmetric effect: the higher retail FWR inflates the UPC_retail substantially more than the conservative DU FWR assumption raises UPC_DU. This asymmetry reflects the fundamental advantage of the harvest-on-demand model.

Economic return analysis

Across all eight analytical variants, annual savings were negative against the standard retail segment and positive against the premium segment (Table 5). *ROI* over the 10-year device lifetime was negative across all eight variants, ranging from -42.48% to -153.21%. PBP was undefined under the standard segment, while defined for the four premium-segment variants, yet substantially exceeding the assumed 10-year device lifetime in all cases. Under current operating conditions, the Display Unit investment is not financially recoverable.

ROI variation across the eight variants is driven primarily by retail segment (57–93 p.p. improvement when switching from standard to premium) and secondarily by FWR correction (14–37 p.p.). Market positioning thus has a substantially greater bearing on economic performance than food waste behaviour of the consumer. These results lead to the conclusion that cost competitiveness, if achievable at all, is structurally confined to the premium segment.

Threshold and heatmap sensitivity analysis

Threshold analysis was conducted exclusively for the DU-M scenario, as it represents the consumer-relevant price point. Results are presented in Tables 6 and 7.

Against the standard retail segment, no single parameter adjustment achieves $ROI = 0\%$ under either analytical level. Threshold DU-M prices and electricity consumption values are negative, and threshold yields substantially exceed the agronomically feasible range. Against the premium segment

without *FWR* correction, threshold conditions become mathematically feasible, yet their practical achievability remains questionable or unlike. Under the Retail_PREM with *FWR* correction, threshold conditions are both mathematically feasible and plausibly achievable.

Given that real-world product development inherently involves the simultaneous optimisation of multiple design parameters rather than isolated adjustments, the cost-effectiveness question needs to be reframed from a single to a multi-dimensional design optimisation problem. Therefore, a panel heatmap analysis is applied to explore the combined effect of concurrent parameter variation and to map the two-dimensional *ROI* surface across all three yield levels and scenarios (Table 8–10).

Under the Scenarios 1 and 2, cost-competitive combinations are absent across virtually the entire parameter space at all three yield levels. Even at the HIGH yield level and minimum electricity consumption, no commercially realistic combination achieves $ROI \geq 0\%$. *FWR* correction marginally expands the feasible zone but does not alter the fundamental conclusion: the standard retail segment does not represent a viable target market.

The Scenario 3 produces fundamentally different results. At the BASE yield level, the cost-competitive zone already covers nearly the entire parameter space, with only a limited number of cells in the high-price, high-electricity region remaining red. At the MID yield level, only a single red cell persists. At the HIGH yield level, the entire parameter space is cost-competitive, with all the cells classified as strongly cost-competitive ($ROI \geq 20\%$).

Three actionable conclusions emerge from the combined threshold and heatmap analyses. First, the premium retail segment is the only viable target market. Second, electricity consumption is the most technically tractable

Table 5 *ROI* and PBP across device-price scenarios, retail segments, and FWR correction

Variant	UPC_DU (€·kg ⁻¹)	Annual saving (€)	<i>ROI</i> (%) over 10 years	PBP (years)
DU-P vs. Retail_STD. w/o FWR	101.53	-208.12	-141.71%	N/A
DU-P vs. Retail_STD. with FWR	112.81	-138.72	-127.80%	N/A
DU-P vs. Retail_PREM. w/o FWR	101.53	78.80	-84.21%	63.3
DU-P vs. Retail_PREM. with FWR	112.81	224.98	-54.91%	22.2
DU-M vs. Retail_STD. w/o FWR	90.20	-208.12	-153.21%	N/A
DU-M vs. Retail_STD. with FWR	100.22	-138.72	-135.47%	N/A
DU-M vs. Retail_PREM. w/o FWR	90.20	78.80	-79.85%	49.6
DU-M vs. Retail_PREM. with FWR	100.22	224.98	-42.48%	17.4

Source: Own research

Table 6 Threshold parameter values required to achieve $ROI = 0\%$

Threshold Parameter	Retail_STD w/o FWR	Retail_STD with FWR	Retail_PREM w/o FWR	Retail_PREM with FWR
DU-M price (€)	-2,081.24	-1,387.21	787.99	2,249.84
Edible fresh biomass yield (kg·cycle ⁻¹)	5.252	4.144	2.494	1.967
Electricity consumption (kWh·cycle ⁻¹)	-135.68	-79.53	96.46	214.73

Source: Own research

Table 7 Required change in threshold parameters relative to experimentally observed base values

Threshold parameter	Retail_STD w/o FWR	Retail_STD with FWR	Retail_PREM w/o FWR	Retail_PREM with FWR
Threshold DU-M price vs. current DU-M price (% change)	-153.21%	-135.47%	-79.85%	-42.48%
Threshold yield/cycle vs. current mean yield/cycle (% change)	231.07%	161.17%	57.18%	24.00%
Threshold electricity consumption vs. current electricity consumption (% change)	-138.86%	-122.78%	-72.37%	-38.50%

Source: Own research

Table 8 Heatmap: Scenario 1: RETAIL_STD, without FWR

Scenario 1: RETAIL_STD, without FWR													
PANEL 1: BASE 1,587 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	438.81%	223.29%	115.52%	61.64%	29.31%	7.76%	-7.63%	-19.18%	-35.34%	-46.12%	-53.82%	-58.67%
	80	315.21%	149.13%	66.08%	24.56%	-0.35%	-16.96%	-28.82%	-37.72%	-50.17%	-58.48%	-64.41%	-68.15%
	100	232.81%	99.69%	33.12%	-0.16%	-20.13%	-33.44%	-42.95%	-50.08%	-60.06%	-66.72%	-71.47%	-74.47%
	130	109.21%	25.53%	-16.32%	-37.24%	-49.79%	-58.16%	-64.14%	-68.62%	-74.89%	-79.08%	-82.07%	-83.95%
	150	26.81%	-23.91%	-49.28%	-61.96%	-69.57%	-74.64%	-78.26%	-80.98%	-84.78%	-87.32%	-89.13%	-90.27%
	180	-96.79%	-98.07%	-98.72%	-99.04%	-99.23%	-99.36%	-99.45%	-99.52%	-99.61%	-99.68%	-99.72%	-99.75%
	200	-179.19%	-147.51%	-131.68%	-123.76%	-119.01%	-115.84%	-113.58%	-111.88%	-109.50%	-107.92%	-106.79%	-106.07%
	230	-302.79%	-221.67%	-181.12%	-160.84%	-148.67%	-140.56%	-134.76%	-130.42%	-124.33%	-120.28%	-117.38%	-115.55%
	250	-385.19%	-271.11%	-214.08%	-185.56%	-168.45%	-157.04%	-148.89%	-142.78%	-134.22%	-128.52%	-124.44%	-121.87%
	280	-508.79%	-345.27%	-263.52%	-222.64%	-198.11%	-181.76%	-170.08%	-161.32%	-149.05%	-140.88%	-135.04%	-131.35%
	300	-591.19%	-394.71%	-296.48%	-247.36%	-217.89%	-198.24%	-184.20%	-173.68%	-158.94%	-149.12%	-142.10%	-137.67%
	349	-793.75%	-516.25%	-377.50%	-308.12%	-266.50%	-238.75%	-218.93%	-204.06%	-183.25%	-169.37%	-159.46%	-153.21%
PANEL 2: MID 1,904 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	611.71%	327.03%	184.68%	113.51%	70.81%	42.34%	22.01%	6.76%	-14.59%	-28.83%	-39.00%	-45.41%
	80	488.11%	252.87%	135.24%	76.43%	41.15%	17.62%	0.82%	-11.78%	-29.43%	-41.19%	-49.59%	-54.89%
	100	405.71%	203.43%	102.28%	51.71%	21.37%	1.14%	-13.31%	-24.14%	-39.31%	-49.43%	-56.65%	-61.21%
	130	282.11%	129.27%	52.84%	14.63%	-8.29%	-23.58%	-34.50%	-42.68%	-54.15%	-61.79%	-67.25%	-70.69%
	150	199.71%	79.83%	19.88%	-10.09%	-28.07%	-40.06%	-48.62%	-55.04%	-64.03%	-70.03%	-74.31%	-77.01%
	180	76.11%	5.67%	-29.56%	-47.17%	-57.73%	-64.78%	-69.81%	-73.58%	-78.87%	-82.39%	-84.90%	-86.49%
	200	-6.29%	-43.77%	-62.52%	-71.89%	-77.51%	-81.26%	-83.94%	-85.94%	-88.75%	-90.63%	-91.97%	-92.81%
	230	-129.89%	-117.93%	-111.96%	-108.97%	-107.17%	-105.98%	-105.12%	-104.48%	-103.59%	-102.99%	-102.56%	-102.29%
	250	-212.29%	-167.37%	-144.92%	-133.69%	-126.95%	-122.46%	-119.25%	-116.84%	-113.47%	-111.23%	-109.62%	-108.61%
	280	-335.89%	-241.53%	-194.36%	-170.77%	-156.61%	-147.18%	-140.44%	-135.38%	-128.31%	-123.59%	-120.22%	-118.09%
	300	-418.29%	-290.97%	-227.32%	-195.49%	-176.39%	-163.66%	-154.56%	-147.74%	-138.19%	-131.83%	-127.28%	-124.41%
	349	-620.85%	-412.51%	-308.34%	-256.25%	-225.00%	-204.17%	-189.29%	-178.13%	-162.50%	-152.08%	-144.64%	-139.95%
PANEL 3: HIGH 2,221 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	784.61%	430.76%	253.84%	165.38%	112.31%	76.92%	51.65%	32.69%	6.15%	-11.54%	-24.18%	-32.15%
	80	661.01%	356.60%	204.40%	128.30%	82.64%	52.20%	30.46%	14.15%	-8.68%	-23.90%	-34.77%	-41.63%
	100	578.61%	307.16%	171.44%	103.58%	62.87%	35.72%	16.33%	1.79%	-18.57%	-32.14%	-41.83%	-47.95%
	130	455.01%	233.00%	122.00%	66.50%	33.20%	11.00%	-4.86%	-16.75%	-33.40%	-44.50%	-52.43%	-57.43%
	150	372.61%	183.56%	89.04%	41.78%	13.43%	-5.48%	-18.98%	-29.11%	-43.29%	-52.74%	-59.49%	-63.75%
	180	249.01%	109.40%	39.60%	4.70%	-16.24%	-30.20%	-40.17%	-47.65%	-58.12%	-65.10%	-70.09%	-73.23%
	200	166.61%	59.96%	6.64%	-20.02%	-36.01%	-46.68%	-54.30%	-60.01%	-68.01%	-73.34%	-77.15%	-79.55%
	230	43.01%	-14.20%	-42.80%	-57.10%	-65.68%	-71.40%	-75.48%	-78.55%	-82.84%	-85.70%	-87.74%	-89.03%
	250	-39.39%	-63.64%	-75.76%	-81.82%	-85.45%	-87.88%	-89.61%	-90.91%	-92.73%	-93.94%	-94.81%	-95.35%
	280	-162.99%	-137.80%	-125.20%	-118.90%	-115.12%	-112.60%	-110.80%	-109.45%	-107.56%	-106.30%	-105.40%	-104.83%
	300	-245.39%	-187.24%	-158.16%	-143.62%	-134.89%	-129.08%	-124.92%	-121.81%	-117.45%	-114.54%	-112.46%	-111.15%
	349	-447.95%	-308.77%	-239.18%	-204.38%	-183.51%	-169.59%	-159.65%	-152.19%	-141.75%	-134.79%	-129.82%	-126.69%

Source: Own research

Note: values represent ROI (%) over the 10-year device lifetime at the given combination of DU-M price and electricity consumption per cycle, assuming the edible fresh biomass yield specified for each panel; dark green cells: $ROI \geq 20\%$ (strongly cost-competitive); light green cells: $0\% \leq ROI < 20\%$ (marginally cost-competitive); red cells: $ROI < 0\%$ (not cost-competitive).

Table 9 Heatmap: Scenario 2: RETAIL_STD, with FWR

Scenario 2: RETAIL_STD, with FWR													
PANEL 1: BASE 1,587kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	670.15%	362.09%	208.06%	131.05%	84.84%	54.03%	32.03%	15.52%	-7.58%	-22.98%	-33.99%	-40.93%
	80	546.55%	287.93%	158.62%	93.97%	55.17%	29.31%	10.84%	-3.02%	-22.41%	-35.34%	-44.58%	-50.41%
	100	464.15%	238.49%	125.66%	69.25%	35.40%	12.83%	-3.29%	-15.38%	-32.30%	-43.58%	-51.64%	-56.73%
	130	340.55%	164.33%	76.22%	32.17%	5.73%	-11.89%	-24.48%	-33.92%	-47.13%	-55.94%	-62.24%	-66.21%
	150	258.15%	114.89%	43.26%	7.45%	-14.04%	-28.37%	-38.60%	-46.28%	-57.02%	-64.18%	-69.30%	-72.53%
	180	134.55%	40.73%	-6.18%	-29.63%	-43.71%	-53.09%	-59.79%	-64.82%	-71.85%	-76.54%	-79.90%	-82.01%
	200	52.15%	-8.71%	-39.14%	-54.35%	-63.48%	-69.57%	-73.92%	-77.18%	-81.74%	-84.78%	-86.96%	-88.33%
	230	-71.45%	-82.87%	-88.58%	-91.43%	-93.15%	-94.29%	-95.11%	-95.72%	-96.57%	-97.14%	-97.55%	-97.81%
	250	-153.85%	-132.31%	-121.54%	-116.15%	-112.92%	-110.77%	-109.23%	-108.08%	-106.46%	-105.38%	-104.62%	-104.13%
	280	-277.45%	-206.47%	-170.98%	-153.23%	-142.59%	-135.49%	-130.42%	-126.62%	-121.29%	-117.74%	-115.21%	-113.61%
	300	-359.85%	-255.91%	-203.94%	-177.95%	-162.36%	-151.97%	-144.55%	-138.98%	-131.18%	-125.98%	-122.27%	-119.93%
	349	-562.40%	-377.44%	-284.96%	-238.72%	-210.98%	-192.48%	-179.27%	-169.36%	-155.49%	-146.24%	-139.63%	-135.47%
PANEL 2: MID 1,904 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	889.32%	493.59%	295.73%	196.80%	137.44%	97.86%	69.60%	48.40%	18.72%	-1.07%	-15.20%	-24.12%
	80	765.72%	419.43%	246.29%	159.72%	107.77%	73.14%	48.41%	29.86%	3.89%	-13.43%	-25.80%	-33.60%
	100	683.32%	369.99%	213.33%	135.00%	88.00%	56.66%	34.28%	17.50%	-6.00%	-21.67%	-32.86%	-39.92%
	130	559.72%	295.83%	163.89%	97.92%	58.33%	31.94%	13.10%	-1.04%	-20.83%	-34.03%	-43.45%	-49.40%
	150	477.32%	246.39%	130.93%	73.20%	38.56%	15.46%	-1.03%	-13.40%	-30.72%	-42.27%	-50.52%	-55.72%
	180	353.72%	172.23%	81.49%	36.12%	8.89%	-9.26%	-22.22%	-31.94%	-45.55%	-54.63%	-61.11%	-65.20%
	200	271.32%	122.79%	48.53%	11.40%	-10.88%	-25.74%	-36.34%	-44.30%	-55.44%	-62.87%	-68.17%	-71.52%
	230	147.72%	48.63%	-0.91%	-25.68%	-40.55%	-50.46%	-57.53%	-62.84%	-70.27%	-75.23%	-78.77%	-81.00%
	250	65.32%	-0.81%	-33.87%	-50.40%	-60.32%	-66.94%	-71.66%	-75.20%	-80.16%	-83.47%	-85.83%	-87.32%
	280	-58.28%	-74.97%	-83.31%	-87.48%	-89.99%	-91.66%	-92.85%	-93.74%	-94.99%	-95.83%	-96.42%	-96.80%
	300	-140.68%	-124.41%	-116.27%	-112.20%	-109.76%	-108.14%	-106.97%	-106.10%	-104.88%	-104.07%	-103.49%	-103.12%
	349	-343.23%	-245.94%	-197.29%	-172.97%	-158.38%	-148.65%	-141.70%	-136.49%	-129.19%	-124.32%	-120.85%	-118.66%
PANEL 3: HIGH 2,221 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	1.108.49%	625.09%	383.40%	262.55%	190.04%	141.70%	107.17%	81.27%	45.02%	20.85%	3.58%	-7.31%
	80	984.89%	550.93%	333.96%	225.47%	160.37%	116.98%	85.98%	62.73%	30.19%	8.49%	-7.01%	-16.79%
	100	902.49%	501.49%	301.00%	200.75%	140.60%	100.50%	71.86%	50.37%	20.30%	0.25%	-14.07%	-23.11%
	130	778.89%	427.33%	251.56%	163.67%	110.93%	75.78%	50.67%	31.83%	5.47%	-12.11%	-24.67%	-32.59%
	150	696.49%	377.89%	218.60%	138.95%	91.16%	59.30%	36.54%	19.47%	-4.42%	-20.35%	-31.73%	-38.91%
	180	572.89%	303.73%	169.16%	101.87%	61.49%	34.58%	15.35%	0.93%	-19.25%	-32.71%	-42.32%	-48.39%
	200	490.49%	254.29%	136.20%	77.15%	41.72%	18.10%	1.23%	-11.43%	-29.14%	-40.95%	-49.39%	-54.71%
	230	366.89%	180.13%	86.76%	40.07%	12.05%	-6.62%	-19.96%	-29.97%	-43.97%	-53.31%	-59.98%	-64.19%
	250	284.49%	130.69%	53.80%	15.35%	-7.72%	-23.10%	-34.09%	-42.33%	-53.86%	-61.55%	-67.04%	-70.51%
	280	160.89%	56.53%	4.36%	-21.73%	-37.39%	-47.82%	-55.28%	-60.87%	-68.69%	-73.91%	-77.64%	-79.99%
	300	78.49%	7.09%	-28.60%	-46.45%	-57.16%	-64.30%	-69.40%	-73.23%	-78.58%	-82.15%	-84.70%	-86.31%
	349	-124.07%	-114.44%	-109.63%	-107.22%	-105.78%	-104.81%	-104.13%	-103.61%	-102.89%	-102.41%	-102.06%	-101.85%

Source: Own research

Note: values represent *ROI* (%) over the 10-year device lifetime at the given combination of DU-M price and electricity consumption per cycle, assuming the edible fresh biomass yield specified for each panel; dark green cells: *ROI* ≥ 20% (strongly cost-competitive); light green cells: 0% ≤ *ROI* < 20% (marginally cost-competitive); red cells: *ROI* < 0% (not cost-competitive).

Table 10 Heatmap: Scenario 3: RETAIL_PREM, with FWR

Scenario 3: RETAIL_PREM, with FWR													
PANEL 1: BASE 1,587kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	1882.50%	1089.50%	693.00%	494.75%	375.80%	296.50%	239.86%	197.38%	137.90%	98.25%	69.93%	52.06%
	80	1758.90%	1015.34%	643.56%	457.67%	346.14%	271.78%	218.67%	178.84%	123.07%	85.89%	59.33%	42.58%
	100	1676.50%	965.90%	610.60%	432.95%	326.36%	255.30%	204.54%	166.48%	113.18%	77.65%	52.27%	36.26%
	130	1552.90%	891.74%	561.16%	395.87%	296.70%	230.58%	183.35%	147.94%	98.35%	65.29%	41.68%	26.78%
	150	1470.50%	842.30%	528.20%	371.15%	276.92%	214.10%	169.23%	135.58%	88.46%	57.05%	34.61%	20.46%
	180	1346.90%	768.14%	478.76%	334.07%	247.26%	189.38%	148.04%	117.04%	73.63%	44.69%	24.02%	10.98%
	200	1264.50%	718.70%	445.80%	309.35%	227.48%	172.90%	133.91%	104.68%	63.74%	36.45%	16.96%	4.66%
	230	1140.90%	644.54%	396.36%	272.27%	197.82%	148.18%	112.73%	86.14%	48.91%	24.09%	6.36%	-4.82%
	250	1058.50%	595.10%	363.40%	247.55%	178.04%	131.70%	98.60%	73.78%	39.02%	15.85%	-0.70%	-11.14%
	280	934.90%	520.94%	313.96%	210.47%	148.38%	106.98%	77.41%	55.24%	24.19%	3.49%	-11.29%	-20.62%
	300	852.50%	471.50%	281.00%	185.75%	128.60%	90.50%	63.29%	42.88%	14.30%	-4.75%	-18.36%	-26.94%
	349	649.95%	349.97%	199.98%	124.98%	79.99%	49.99%	28.56%	12.49%	-10.01%	-25.01%	-35.72%	-42.48%
PANEL 2: MID 1,904 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	2344.14%	1366.48%	877.66%	633.24%	486.59%	388.83%	319.00%	266.62%	193.30%	144.41%	109.50%	87.46%
	80	2220.54%	1292.32%	828.22%	596.16%	456.93%	364.11%	297.81%	248.08%	178.46%	132.05%	98.90%	77.98%
	100	2138.14%	1242.88%	795.26%	571.44%	437.15%	347.63%	283.68%	235.72%	168.58%	123.81%	91.84%	71.66%
	130	2014.54%	1168.72%	745.82%	534.36%	407.49%	322.91%	262.49%	217.18%	153.74%	111.45%	81.25%	62.18%
	150	1932.14%	1119.28%	712.86%	509.64%	387.71%	306.43%	248.37%	204.82%	143.86%	103.21%	74.18%	55.86%
	180	1808.54%	1045.12%	663.42%	472.56%	358.05%	281.71%	227.18%	186.28%	129.02%	90.85%	63.59%	46.38%
	200	1726.14%	995.68%	630.46%	447.84%	338.27%	265.23%	213.05%	173.92%	119.14%	82.61%	56.53%	40.06%
	230	1602.54%	921.52%	581.02%	410.76%	308.61%	240.51%	191.86%	155.38%	104.30%	70.25%	45.93%	30.58%
	250	1520.14%	872.08%	548.06%	386.04%	288.83%	224.03%	177.74%	143.02%	94.42%	62.01%	38.87%	24.26%
	280	1396.54%	797.92%	498.62%	348.96%	259.17%	199.31%	156.55%	124.48%	79.58%	49.65%	28.27%	14.78%
	300	1314.14%	748.48%	465.66%	324.24%	239.39%	182.83%	142.42%	112.12%	69.70%	41.41%	21.21%	8.46%
	349	1111.58%	626.95%	384.63%	263.47%	190.78%	142.32%	107.70%	81.74%	45.39%	21.16%	3.85%	-7.07%
PANEL 3: HIGH 2,221 kg/cycle of edible fresh biomass yield	DU-M (€)→ Elec (kWh/cycle)↓	300	500	750	1000	1250	1500	1750	2000	2500	3000	3500	3911
	50	2805.78%	1643.47%	1062.31%	771.73%	597.39%	481.16%	398.13%	335.87%	248.69%	190.58%	149.07%	122.87%
	80	2682.18%	1569.31%	1012.87%	734.65%	567.72%	456.44%	376.94%	317.33%	233.86%	178.22%	138.47%	113.39%
	100	2599.78%	1519.87%	979.91%	709.93%	547.95%	439.96%	362.82%	304.97%	223.97%	169.98%	131.41%	107.07%
	130	2476.18%	1445.71%	930.47%	672.85%	518.28%	415.24%	341.63%	286.43%	209.14%	157.62%	120.82%	97.59%
	150	2393.78%	1396.27%	897.51%	648.13%	498.51%	398.76%	327.50%	274.07%	199.25%	149.38%	113.75%	91.27%
	180	2270.18%	1322.11%	848.07%	611.05%	468.84%	374.04%	306.32%	255.53%	184.42%	137.02%	103.16%	81.79%
	200	2187.78%	1272.67%	815.11%	586.33%	449.07%	357.56%	292.19%	243.17%	174.53%	128.78%	96.10%	75.47%
	230	2064.18%	1198.51%	765.67%	549.25%	419.40%	332.84%	271.00%	224.63%	159.70%	116.42%	85.50%	65.99%
	250	1981.78%	1149.07%	732.71%	524.53%	399.63%	316.36%	256.88%	212.27%	149.81%	108.18%	78.44%	59.67%
	280	1858.18%	1074.91%	683.27%	487.45%	369.96%	291.64%	235.69%	193.73%	134.98%	95.82%	67.84%	50.19%
	300	1775.78%	1025.47%	650.31%	462.73%	350.19%	275.16%	221.56%	181.37%	125.09%	87.58%	60.78%	43.87%
	349	1573.22%	903.93%	569.29%	401.97%	301.57%	234.64%	186.84%	150.98%	100.79%	67.32%	43.42%	28.33%

Source: Own research

Note: values represent *ROI* (%) over the 10-year device lifetime at the given combination of DU-M price and electricity consumption per cycle, assuming the edible fresh biomass yield specified for each panel; dark green cells: *ROI* ≥ 20% (strongly cost-competitive); light green cells: 0% ≤ *ROI* < 20% (marginally cost-competitive); red cells: *ROI* < 0% (not cost-competitive).

optimisation lever. Third, yield optimisation is a high-leverage, low-capital-cost development priority, as agronomic improvements alone are sufficient to shift the system from a predominantly cost-competitive BASE to a fully cost-competitive HIGH configuration.

Collectively, these results demonstrate that a commercially viable configuration of the Display Unit is achievable within the premium retail segment without fundamental redesign of the system architecture. Concurrent optimisation of the device price, electricity consumption, and yield further improves ROI and reduces the required adjustment in any individual parameter, reinforcing the case for a multi-dimensional development approach.

Conclusion

This study developed and applied a consumer-oriented cost-effectiveness framework to evaluate the economic viability of an automated home hydroponic device (the Display Unit) for fresh basil (*Ocimum basilicum* L.) production, benchmarked against retail purchasing across standard and premium market segments under primary and FWR-corrected analysis.

In response to RQ1, UPC under the market-price scenario (DU-M) reached 90.20 €·kg⁻¹, exceeding the standard and premium retail reference by 231% and 57%, respectively. FWR correction narrowed but did not close the cost differential, reducing the gap against the standard and premium segment to 161% and 24%.

In response to RQ2, ROI was negative across all eight analytical variants, ranging from -42.48% to -153.21%, and PBP, while defined for the four premium-segment variants, substantially exceeded the assumed 10-year device lifetime in all cases. The investment is not financially recoverable within its operational lifetime under any current parameter combination.

In response to RQ3, threshold analysis confirmed that cost-competitiveness against the standard retail segment is unachievable through single-parameter optimisation under any analytical level. Against the premium segment with FWR correction, break-even is achievable through isolated adjustment of any single parameter. Panel heatmap analysis further demonstrated that the Display Unit already operates within the cost-competitive zone at the BASE yield level under the premium segment with FWR correction and achieves full cost-competitiveness across the entire parameter space at the HIGH yield level.

In response to RQ4, FWR correction consistently improved ROI by 14–37 percentage points across all variants. The harvest-on-demand structure of the Display Unit represents a genuine structural advantage over pre-packaged retail basil, supporting the systematic inclusion of FWR correction in future cost-effectiveness comparisons between home cultivation systems and retail purchasing.

Overall, these findings provide a replicable methodological framework and quantitative development targets applicable to the broader and rapidly growing category of automated home hydroponic devices. Future research should extend the analysis to multiple crops, incorporate seasonal electricity variation through year-round measurement, and empirically validate the assumed FWR under real household conditions.

Conflict of Interest

The authors declare that they are simultaneously the developers of the Display Unit prototype. While all assumptions are explicitly identified and transparently reported throughout the manuscript, this dual role represents a potential conflict of interest that readers should consider when interpreting results, particularly those dependent on author-defined parameters such as device lifetime and estimated market price.

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Contact address

Matej Gocník
AQUASTOW s. r. o.
Dunajská 15A 811 08 Bratislava, Slovak Republic
✉ matej.gocnik@aquastow.eu

