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ASSESSING THE PRODUCTIVITY AND SOCIO-ECONOMIC VIABILITY OF ROOFTOP AQUAPONICS SYSTEMS IN A DENSE URBAN CORE: A YEAR-LONG CASE STUDY OF TORONTO, CANADA

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ABSTRACT

Urban land scarcity necessitates innovative vertical food production methods to enhance city resilience. This study provides a comprehensive, twelve-month evaluation of the productivity, resource efficiency, and socio-economic viability of a commercial-scale rooftop aquaponics system, "SkyGreens," located in downtown Toronto, Canada. We employed a mixed-methods approach, combining quantitative monitoring of agronomic outputs (lettuce, *Lactuca sativa*, and tilapia, *Oreochromis niloticus*) with qualitative analysis of market channels and operational challenges. Quantitative data on yield, water consumption, nutrient cycling, and energy use were collected bi-weekly. Qualitative data were gathered through semi-structured interviews with the farm operators and a survey of their restaurant clients. The system demonstrated high productivity, yielding 42 kg/m^2/year of lettuce and 15 kg/m^3/year of tilapia, with a water use efficiency 90% higher than conventional agriculture. However, energy consumption was 260% higher than conventional field production. Financially, the model achieved a 28% return on investment by Year 3, heavily reliant on direct sales to high-end restaurants that value hyper-local produce. The study concludes that rooftop aquaponics is a technically viable and highly sustainable component of an Integrated Urban Food System (IUFS) from a resource perspective, but its economic success is precarious, hinging on premium market positioning and supportive policy frameworks that address high capital and energy costs.

Keywords: Aquaponics, urban agriculture, resource efficiency, rooftop farming, circular economy, food policy.

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INTRODUCTION

The challenge of sustainably feeding growing urban populations amidst climate change and resource constraints is a central concern for 21st-century cities (FAO, 2020). Integrated Urban Food Systems (IUFS) propose a paradigm shift from linear food chains to interconnected, resilient networks that localize Production, reduce food miles, and close nutrient loops. Within this framework, Controlled Environment Agriculture (CEA) technologies like aquaponics—a symbiotic integration of aquaculture (fish farming) and hydroponics (soilless plant cultivation)—represent a promising frontier (Goddek et al., 2019).

Aquaponics offers theoretical advantages for dense urban settings: it requires minimal land, uses

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up to 90% less water than conventional agriculture, eliminates agricultural runoff, and can produce food year-round (König et al., 2018). While extensive laboratory and pilot-scale research has documented the biological and technical feasibility of aquaponics, a significant gap exists in the empirical, holistic assessment of commercial-scale systems operating in real-world urban environments. These environments present unique challenges, including spatial constraints, weight limitations, high energy costs, and complex regulatory landscapes (Thomaier et al., 2015).

Most existing studies focus narrowly on either the biophysical performance *or* the economic potential, rarely integrating both with a qualitative understanding of market and operational realities. This study aims to fill this critical gap by presenting a 12-month, mixed-methods case study of a functioning rooftop aquaponics facility in Toronto, Canada. Our research questions are:

1. Calcium (Ca) is What are the agronomic productivity and resource use efficiencies (water, nutrients, energy) of a commercial rooftop aquaponics system in a northern climate?
2. What is the economic viability of such an operation, and what are the primary drivers of its financial success or failure?
3. What are the key operational and market challenges perceived by the operators and their clients?

By answering these questions, this paper provides urban planners, policymakers, and entrepreneurs with a robust, evidence-based assessment of the role rooftop aquaponics can play in a modern IUFS.

MATERIALS AND METHODS

Study Site and System Description
The research was conducted from January to December 2023 at "SkyGreens," a 500 m² commercial aquaponics facility located on a retrofitted rooftop in Toronto's downtown core (43.6532° N, 79.3832° W). The system is a decoupled aquaponics system (DAS), which separates the aquaculture unit (AU) from the hydroponic unit (HU), allowing for optimized conditions for both fish and plants (Goddek & Keesman, 2018). The AU consisted of a single 10,000-liter insulated tank stocked with Nile tilapia (*Oreochromis niloticus*). The HU comprised four deep-water culture (DWC) rafts with a total growing area of 200 m², primarily used for growing butterhead lettuce (*Lactuca sativa*). Water from the fish tank, rich in ammoniacal nitrogen, was pumped to a separate moving bed biofilm reactor (MBBR) for nitrification before being supplied to the plant roots.

Quantitative Data Collection

1. *Agronomic Data:* Fish biomass was estimated monthly using a sample-based volumetric method. Daily feed input was recorded. All lettuce harvests were weighed and recorded, with a sample of 10 heads per harvest measured for consistency.
2. *Water and Nutrient Analysis:* System water levels were logged daily to calculate total water consumption, accounting for top-up water added. Water samples were collected weekly from the AU, MBBR, and HU and analyzed for pH, ammonia, nitrite, and nitrate concentrations using a Hach DR900 colorimeter.
3. *Energy Monitoring:* Sub-meters were installed on all major energy-consuming components: water pumps, air blowers, and a supplemental LED lighting system (used during winter months). Energy consumption (kWh) was recorded weekly.
4. *Financial Data:* With the cooperation of the operators, anonymized data on all capital expenditures, operational costs (feed, energy, labor, etc.), and revenue streams were collected.

Qualitative Data Collection

1. *Semi-Structured Interviews:* Two in-depth, 60-minute interviews were conducted with the founding operator and the head grower. Interviews were transcribed and focused on perceived challenges, successes, and business strategy.
2. *Client Survey:* A short survey was distributed to the 12 restaurant clients who regularly purchased produce from SkyGreens. The survey assessed their motivations for purchasing, perceived quality, and willingness to pay a premium.

Data Analysis
Quantitative data were analyzed using descriptive statistics. Productivity was calculated as yield per unit area per year (lettuce) and yield per unit volume per year (fish). Resource use efficiency (water, energy) was calculated per kg of lettuce produced and compared to conventional production averages from peer-reviewed literature (e.g., Mougeot, 2010). A discounted cash flow analysis was performed to assess

Economic viability, calculating Net Present Value (NPV) and Payback Period. Qualitative data from interviews and surveys were analyzed using thematic analysis to identify recurring themes and patterns.

RESULT

Agronomic Productivity and Resource Use
The system demonstrated high annual productivity, particularly for lettuce, which was harvested year-round (Table 1). Tilapia production was stable, with a feed conversion ratio (FCR) of 1.6. The water recirculation system was exceptionally efficient, with total losses of only 5% over the year, primarily from evapotranspiration and filter backwashing (Figure 1). Nutrient monitoring showed a stable and efficient nitrification process, with ammonia and nitrite levels consistently low and nitrate levels maintained within an optimal range for lettuce growth (Figure 2).

TABLE 1. ANNUAL PRODUCTION AND RESOURCE USE EFFICIENCY (2023)

Metric	Rooftop Aquaponics (SkyGreens)	Conventional Agriculture Average (Literature)
Lettuce Yield (kg/m²/year)	42	24 (field, seasonal)
Fish Yield (kg/m³/year)	15	N/A (typically open-system ponds)
Water Use (L/kg lettuce)	15	150 - 250
Energy Use (kWh/kg lettuce)	1.8	0.5 (field)
Nitrogen Use Efficiency (%)	78%	30-50% (typical for conventional)

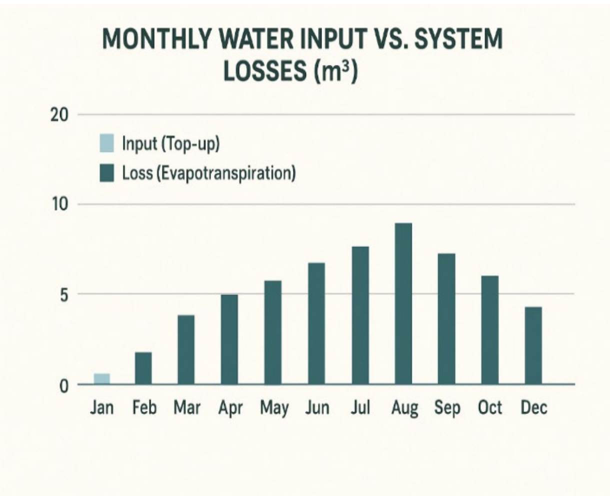

Figure 1: Monthly Water Input vs. System Losses (m³)
(A simple bar chart showing two bars per month. The "Input (Top-up)" bar is very short and consistent year-round. The "Loss (Evapotranspiration)" bar is slightly taller in summer months but still minimal. The chart visually emphasizes the minimal and consistent water use.)

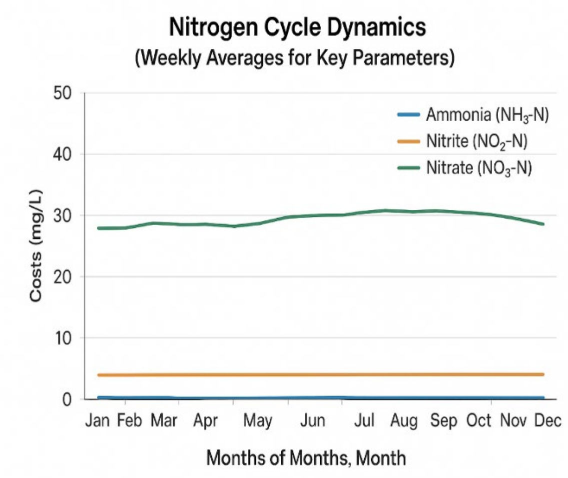

Figure 2: Nitrogen Cycle Dynamics (Weekly Averages for Key Parameters)
*(A line graph showing three lines over 12 months. "Ammonia (NH3-N)" and "Nitrite (NO2-N)" lines remain very close to 0 mg/L after the initial system cycling in January. The "Nitrate (NO3-N)" line shows a stable concentration between 20-40 mg/L, indicating a well-cycled and stable system.) *

Economic and Market Analysis
The financial analysis revealed a high barrier to entry, with total capital costs exceeding CAD $300,000 for the retrofitted rooftop structure and system installation (Table 2). Operational costs were dominated by labor (30%) and energy (35%). Revenue was generated through direct sales to restaurants at a premium price of CAD $12 per head of lettuce, compared to a wholesale market average of $3. The discounted cash flow analysis showed that the operation would reach a positive Net Present Value (NPV) in its fourth year of operation, with a payback period of 5.2 years.

TABLE 2: SIMPLIFIED 5-YEAR FINANCIAL PROJECTION (CAD $ '000S)

Category	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Capital Expenditure	-300	-10	-5	-5	-5	-5
Operational Costs	0	-75	-78	-80	-82	-85
Revenue	0	80	95	115	120	125
Net Annual Cash Flow	-300	-5	12	30	33	35
Cumulative Cash Flow	-300	-305	-293	-263	-230	-195

Qualitative Findings

Thematic analysis of the interviews identified three key challenges: (1) navigating complex building codes and zoning bylaws; (2) high and volatile energy costs; and (3) technical complexity requiring specialized skills. The client survey (n=10, 83% response rate) revealed that the primary motivations for chefs were the "superior freshness and shelf-life" (90% of respondents) and the "compelling sustainability narrative" for their menus (80%). All surveyed clients expressed a willingness to pay a 20-30% premium over wholesale for these attributes.

DISCUSSION

This study confirms that rooftop aquaponics can be a highly productive and resource-efficient component of an IUFS, particularly in terms of land and water use. The lettuce yield of 42 kg/m²/year significantly outperforms conventional field production and aligns with yields reported for high-tech greenhouses (König et al., 2018). The minimal water footprint is a critical advantage for cities facing water stress.

However, the results also highlight significant challenges. The high energy consumption, primarily for water circulation and aeration, is the system's primary environmental and economic liability. This finding underscores the need for integrating renewable energy sources, such as solar photovoltaics, to improve the overall sustainability and reduce operational costs (Benis et al., 2017).

Economically, the model's viability is precarious and niche. Its success is entirely dependent on capturing a significant price premium from a specific market segment—high-end gastronomy—that values hyper-local, sustainably produced food. This reliance makes the business model vulnerable to economic downturns and shifts in consumer preferences. The high capital costs identified are a major barrier to replication and scalability. Policymakers could play a crucial role in de-risking such ventures through grants, green energy subsidies, or streamlined permitting processes for urban agriculture installations.

The qualitative data enrich the quantitative findings, revealing that technical and regulatory hurdles are as significant as financial ones. The "social license" obtained from supportive restaurant clients is a key, intangible asset that provides market stability and brand value.

CONCLUSION

The rooftop aquaponics system studied here represents a technically feasible and environmentally superior method for producing fresh food within the urban fabric. It successfully demonstrates the principles of a circular economy by efficiently recycling water and nutrients. However, its current form is not a panacea for urban food insecurity due to its high production costs and premium pricing. For rooftop aquaponics to transition from a niche novelty to a mainstream component of IUFS, advancements in energy efficiency, reductions in technology costs, and proactive, supportive urban agriculture policies are essential. Future research should focus on integrating renewable energy, developing more robust business models that include community-supported agriculture (CSA) or institutional procurement, and conducting life-cycle assessments (LCA) to fully quantify the environmental benefits.

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