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Hydroponics-Based Romaine Lettuce Production in Peri- Urban Areas: Market Competitiveness Study in Greater Bandung Metropolitan Region

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Abstract
This study investigated the market competitiveness of hydroponics-based romaine lettuce production in peri-urban areas of the Greater Bandung Metropolitan Region, Indonesia, and addressed critical knowledge gaps regarding economic viability and strategic positioning of controlled environment agriculture in rapidly urbanizing tropical contexts. Employing a comprehensive mixed-methods approach, the research integrated technical performance data from fifteen commercial hydroponic farms over six production cycles spanning 18 months, detailed economic analysis of production costs and profitability indicators, competitive market assessment through Porter's Five Forces and SWOT frameworks, and consumer preference surveys administered to 384 respondents across diverse socioeconomic segments. Results demonstrated that hydroponic systems achieved superior technical performance with 35.6% higher yields, 87.3% marketable quality rates, and 11.4 annual production cycles compared to conventional cultivation, translating into substantial economic returns averaging 58.4% ROI and 2.12 revenue-cost ratios despite capital requirements nearly five times higher than traditional systems. Market analysis revealed that competitive advantage emerged through integrated management of production efficiency, premium retail channel access commanding 130.7% price premiums, and medium-scale operations, with consumer willingness to pay significantly influenced by quality perceptions, food safety concerns, and information provision. The study concludes that hydroponic romaine lettuce production represents an economically viable and competitive agricultural strategy in peri-urban metropolitan regions when technical proficiency, strategic marketing, and adequate scale are simultaneously achieved, though success requires coordinated support addressing knowledge gaps, market access barriers, and capital constraints.

Keywords: hydroponic agriculture; market competitiveness; peri-urban farming; romaine lettuce production, greater bandung metropolitan region

INTRODUCTION

The accelerating pace of global urbanization has fundamentally transformed agricultural landscapes, compelling policymakers and researchers to reconceptualize food production systems within and around metropolitan regions. Urban and peri-urban agriculture (UPA) has emerged as a critical strategy for enhancing food security, reducing carbon footprints associated with long-distance food transportation, and providing economic opportunities for communities in transition zones between rural and urban settings (Kavga et al., 2019). Within this paradigm shift, controlled environment agriculture, particularly hydroponic systems, has gained prominence as a viable solution to overcome land scarcity and environmental constraints characteristic of densely populated areas (Eigenbrod & Gruda, 2015).

The Greater Bandung Metropolitan Region (GBMR), Indonesia's third-largest metropolitan area, exemplifies the complex interplay between rapid urban expansion and the persistent need for sustainable local food systems. As urban populations continue to burgeon, the demand for fresh, high-quality vegetables has intensified, creating both challenges and opportunities for innovative agricultural practices. This confluence of urbanization pressures, technological innovation, and shifting consumer preferences establishes a compelling context for examining the market viability of hydroponic vegetable production in peri-urban settings. The present study investigates the market competitiveness of hydroponics-based romaine lettuce production within the GBMR, offering insights into the economic sustainability and strategic positioning of controlled environment agriculture in rapidly urbanizing tropical regions.

Contemporary agricultural development discourse increasingly emphasizes the integration of technology-driven production methods to address the multifaceted challenges posed by climate change, resource depletion, and demographic transitions (Van Dijk et al., 2021). Hydroponics, defined as the cultivation of plants in nutrient-enriched water solutions without soil, represents a sophisticated approach to optimizing resource efficiency while maximizing yield per unit area (Resh, 2022). This soilless cultivation technique encompasses various system configurations, including Nutrient Film Technique (NFT), Deep Water Culture (DWC), and drip irrigation systems, each offering distinct advantages in terms of water conservation, nutrient management, and scalability (Lages Barbosa et al., 2015).

The theoretical foundation for understanding hydroponic agriculture's role in urban contexts draws from principles of sustainable intensification, which advocates for increased productivity without compromising environmental integrity or social equity (Pretty et al., 2018). Market competitiveness, within this framework, extends beyond conventional price-based metrics to encompass quality differentiation, supply chain efficiency, and alignment with evolving consumer values regarding food safety and environmental responsibility (Aprile et al., 2016). The conceptual lens of competitive advantage, originally developed by Porter (1985) and subsequently refined for agricultural contexts, provides analytical tools for assessing how hydroponic producers can establish and maintain market positions against traditional field-grown alternatives. Furthermore, the peri-urban context introduces unique considerations related to land-use competition, proximity to consumer markets, and the transitional nature of socioeconomic structures, necessitating a nuanced understanding of both opportunities and constraints facing hydroponic enterprises (Zasada, 2011).

Despite the growing body of literature on urban agriculture and hydroponics, a critical gap persists regarding the economic viability and market positioning of hydroponic vegetable

production in the specific context of rapidly urbanizing metropolitan regions in Southeast Asia. Existing studies have predominantly focused on technical performance parameters such as yield optimization, nutrient solution management, and crop quality in controlled environment systems (Sublett et al., 2018). While these technical investigations provide valuable insights, they offer limited guidance for understanding the complex market dynamics, consumer acceptance patterns, and competitive strategies that ultimately determine the sustainability of hydroponic enterprises in real-world settings (Specht et al., 2014). Moreover, the majority of market- oriented research on hydroponic produce has been conducted in developed economies with established supply chains and distinct consumer profiles, limiting the applicability of findings to emerging markets characterized by different price sensitivities, quality perceptions, and distribution infrastructures (Nechita & Rezeanu, 2019).

The Greater Bandung Metropolitan Region presents a particularly underexplored case, where rapid urbanization coincides with a strong tradition of vegetable consumption, yet systematic analysis of how hydroponic producers can effectively compete in this evolving market landscape remains conspicuously absent from the literature. This knowledge gap is particularly problematic given that investment decisions, policy interventions, and agricultural extension programs require evidence-based understanding of market competitiveness factors specific to regional contexts. The absence of comprehensive studies examining the intersection of production costs, pricing strategies, consumer preferences, and competitive positioning for hydroponic romaine lettuce in peri-urban Indonesian settings thus represents a significant limitation in both academic discourse and practical agricultural development efforts.

The urgency of addressing this research gap is underscored by several converging trends that demand immediate scholarly attention and empirical investigation. First, Indonesia's national food security strategy increasingly emphasizes the role of urban and peri-urban agriculture in meeting the nutritional needs of growing metropolitan populations, with government policies actively promoting technology adoption among small- and medium-scale farmers. Second, the COVID-19 pandemic has exposed vulnerabilities in long-distance food supply chains, catalyzing renewed interest in local food production systems and accelerating consumer awareness regarding the origins and production methods of fresh produce. Third, climate change impacts, particularly irregular rainfall patterns and increasing temperatures in West Java, are compromising traditional field-based vegetable production, making controlled environment systems increasingly attractive as climate-resilient alternatives (Islami et al., 2022).

Additionally, the GBMR is experiencing rapid demographic and economic transitions, with an expanding middle class exhibiting heightened preferences for food quality, safety, and convenience, creating potential market opportunities for premium hydroponic products (Wertheim-Heck & Raneri, 2019). The window for establishing competitive hydroponic enterprises in this region is time-sensitive, as market structures, consumer perceptions, and regulatory frameworks are currently in flux, and early entrants with strategic positioning may secure lasting advantages. Furthermore, the potential replicability of findings from this study to other rapidly urbanizing metropolitan regions across Southeast Asia amplifies its significance, as similar dynamics of urbanization, agricultural transition, and food system transformation characterize cities from Jakarta to Manila to Bangkok. This confluence of policy imperatives, environmental pressures, market evolution, and knowledge gaps necessitates immediate and rigorous investigation into the market competitiveness of hydroponic production systems in peri-urban contexts.

A comprehensive review of recent literature reveals both progress and persistent limitations in understanding hydroponic agriculture's market dimensions in urban and peri-urban settings. Examined consumer acceptance of hydroponic vegetables in Bogor, Indonesia, finding that product freshness and perceived safety were primary drivers of purchase intention, though price sensitivity remained a significant barrier for mainstream market penetration. Expanding this consumer-oriented perspective, Maulidi et al., (2021) conducted a comparative analysis of production costs between hydroponic and conventional lettuce cultivation in East Java, revealing that while initial capital investments for hydroponic systems were substantially higher, operational efficiencies and premium pricing potential could offset these costs within two to three production cycles. International research explored the economic feasibility of rooftop hydroponic farms in European cities, demonstrating that proximity to consumers and reduced transportation costs contributed significantly to competitive positioning, though their findings may have limited transferability to tropical climates and different market structures.

Investigating supply chain dynamics, Othman et al., (2020) analyzed distribution channels for urban-grown vegetables in Kuala Lumpur, identifying that direct-to- consumer and partnership arrangements with premium retailers yielded higher profit margins compared to traditional wholesale markets. Furthermore, Nofianti et al., (2022) assessed the technical and economic performance of NFT-based hydroponic systems in West Java, documenting yield advantages but noting that inconsistent product quality and limited market knowledge constrained profitability for smallholder producers. Consumer preference studies by (J Stewart–Knox et al., 2022) in Bangkok revealed that hydroponic produce commanded price premiums of 30-50% over conventional alternatives, but only when accompanied by effective branding and transparent communication regarding production methods. Despite these valuable contributions, the existing literature exhibits fragmentation across disciplinary boundaries, with technical agricultural research rarely integrated with market analysis, and consumer studies often disconnected from production economics, highlighting the need for comprehensive investigations that bridge these analytical domains.

The present study addresses these identified gaps through a distinctive research approach that integrates production economics, market analysis, and consumer behavior within the specific context of peri-urban hydroponic agriculture in the Greater Bandung Metropolitan Region. Unlike previous investigations that have examined these dimensions in isolation, this research adopts a holistic framework that simultaneously considers the cost structures of hydroponic romaine lettuce production, competitive positioning relative to conventional field-grown alternatives, and the market perception factors that influence consumer willingness to pay premium prices (Moremi et al., n.d.). The novelty of this study extends to its geographical focus, as the GBMR represents a unique case study of rapid urbanization in a tropical climate with distinct cultural food preferences and market structures that differ substantially from previously studied contexts in temperate regions or more developed Asian economies.

Methodologically, this research advances the field by employing a mixed-methods approach that combines detailed farm-level cost accounting, comparative market experiments, and consumer surveys to generate insights that are simultaneously rigorous and practically applicable for producers, policymakers, and investors. The study's temporal relevance is particularly significant, as data collection occurred during a period of accelerated interest in local food systems following pandemic-induced supply chain disruptions, capturing market dynamics that may characterize the post-COVID agricultural landscape (Hobbs, 2020). Furthermore, by focusing specifically on romaine lettuce, a high-value leafy green with

significant consumer demand in Indonesian urban markets but relatively understudied compared to other lettuce varieties, this research fills a specific product-level knowledge gap. The analytical framework developed here integrates resource-based view theory and market orientation concepts to explain how hydroponic producers can develop sustainable competitive advantages through strategic resource deployment and customer-centric positioning. This comprehensive approach distinguishes the current investigation from previous piecemeal efforts and positions it to make substantive contributions to both scholarly understanding and practical agricultural development in rapidly urbanizing tropical regions.

This study pursues three interrelated objectives that collectively address the research gaps identified above while generating actionable knowledge for multiple stakeholder groups. The primary objective is to comprehensively assess the production cost structure and economic efficiency of hydroponics-based romaine lettuce cultivation in peri-urban areas of the Greater Bandung Metropolitan Region, providing detailed benchmarks for capital investment requirements, operational costs, and profitability trajectories under varying market scenarios. The secondary objective focuses on analyzing the competitive positioning of hydroponic romaine lettuce relative to conventionally grown alternatives, examining price premiums, quality differentials, supply chain efficiencies, and market access strategies that enable or constrain market penetration. The tertiary objective investigates consumer perceptions, preferences, and willingness to pay for hydroponic produce, identifying the key attributes that drive purchasing decisions and the market segments most receptive to premium-priced hydroponic vegetables.

The expected benefits of this research extend across academic, practical, and policy domains, offering theoretical contributions to understanding agricultural competitiveness in peri-urban contexts, providing evidence-based guidance for entrepreneurs and farmers considering hydroponic investments, and informing government policies related to urban agriculture support and food system resilience. The practical implications include the development of strategic frameworks that hydroponic producers can employ to optimize their market positioning, the identification of critical success factors that determine enterprise viability, and recommendations for supply chain innovations that enhance market access for peri-urban agricultural producers.

For policymakers, the findings will illuminate how regulatory frameworks, infrastructure investments, and extension services can be designed to effectively support the development of competitive hydroponic agriculture sectors that contribute to urban food security, rural-urban livelihood transitions, and sustainable land use in metropolitan regions. Ultimately, this research aspires to demonstrate that with appropriate strategies and enabling conditions, hydroponic agriculture in peri-urban settings can achieve market competitiveness while simultaneously advancing environmental sustainability, nutritional security, and economic opportunity in rapidly urbanizing tropical landscapes.

RESEARCH METHOD

This study employed a comprehensive mixed-methods research design that integrated quantitative production economics analysis with qualitative market assessment to examine the competitiveness of hydroponics-based romaine lettuce production in the peri-urban areas of the Greater Bandung Metropolitan Region. The mixed-methods approach was particularly appropriate for this investigation as it enabled the simultaneous examination of objective production and cost parameters alongside subjective market perceptions and competitive dynamics, thereby providing a holistic understanding of market competitiveness that neither

purely quantitative nor qualitative methods could achieve independently (Fetters et al., 2013). The research was conducted in three purposively selected peri-urban districts of the Greater Bandung Metropolitan Region, specifically Bandung Regency, West Bandung Regency, and Cimahi City, where hydroponic farming activities have emerged as viable agricultural alternatives amidst ongoing urbanization pressures.

These locations were chosen based on their transitional characteristics between urban and rural zones, accessibility to Bandung's primary consumer markets within a 25-kilometer radius,and the presence of established hydroponic lettuce producers operating commercially for at least two complete production cycles. The study adopted a convergent parallel design wherein quantitative data on production performance and economics were collected concurrently with qualitative data on market positioning and consumer preferences, with subsequent integration during the interpretation phase to generate comprehensive insights into market competitiveness (Fetters et al., 2013). This methodological framework aligns with established approaches in agricultural economics research where complex market phenomena require triangulation of multiple data sources to ensure validity and practical applicability (Junaedi, 2025).

The quantitative component of this research involved detailed technical and economic data collection from fifteen commercially operating hydroponic romaine lettuce farms across the study area, selected through purposive sampling to represent diverse scales of operation ranging from small-scale units with 200 planting holes to medium-scale facilities with up to 2,000 planting holes. Technical production data were systematically recorded over six consecutive production cycles spanning an 18-month period from January 2023 to June 2024, encompassing key performance indicators including fresh weight yield per plant, marketable yield percentage, crop growth rate, production cycle duration, and quality parameters such as leaf color intensity, crispness, and shelf life assessed through standardized horticultural evaluation protocols. The hydroponic systems examined included Nutrient Film Technique (NFT) configurations with PVC pipe diameters of 3 inches, water flow rates maintained at 1-2 liters per minute, and nutrient solution electrical conductivity regulated between 1.2-1.8 mS/cm following modified Hoagland's solution formulations appropriate for tropical lettuce cultivation.

Economic data collection employed structured farm record- keeping instruments that captured comprehensive cost categories including initial capital investments in infrastructure and equipment, recurring operational expenses for seeds, nutrients, electricity, labor, and packaging materials, as well as detailed revenue data from various marketing channels including direct farm- gate sales, partnerships with supermarkets, and online platforms. Market analysis data were obtained through structured interviews with twenty-five key informants representing different nodes in the vegetable supply chain, including hydroponic farmers, conventional lettuce producers, wholesale traders, retail managers, and agricultural extension officers, complemented by direct observation of pricing dynamics and product positioning at ten major modern retail outlets and five traditional vegetable markets across Bandung metropolitan area.

The competitive environment was systematically assessed using Porter's Five Forces framework adapted for agricultural markets, examining the bargaining power of suppliers and buyers, threat of new entrants, threat of substitute products, and intensity of competitive rivalry, with data triangulated from farmer interviews, retailer assessments, and secondary market reports (Dias et al., 2023). Additionally, a SWOT analysis was conducted through facilitated focus group discussions with twelve hydroponic farmers to identify internal

strengths and weaknesses of hydroponic production systems alongside external opportunities and threats in the evolving market landscape.

The consumer preference component employed a cross-sectional survey administered to 384 respondents determined through Slovin's formula with a 5% margin of error, selected using stratified random sampling across four socioeconomic segments based on monthly household expenditure quintiles to ensure representativeness of Bandung's diverse consumer base. The structured questionnaire, pretested with thirty respondents and refined for clarity and cultural appropriateness, comprised four sections measuring demographic characteristics, vegetable purchasing behaviors, awareness and perceptions of hydroponic produce, and willingness to pay for hydroponic romaine lettuce relative to conventional alternatives through choice-based conjoint analysis. Data quality was ensured through rigorous enumerator training, pilot testing of instruments, and implementation of internal consistency checks during fieldwork, with survey administration conducted at strategic locations including modern supermarkets, traditional markets, and residential neighborhoods to capture diverse purchasing contexts.

Quantitative data analysis employed descriptive statistics, comparative analysis using independent samples t-tests and ANOVA to assess differences between hydroponic and conventional production systems, and multiple regression analysis to identify determinants of production costs and profitability using SPSS version 26 and Microsoft Excel for data management and statistical computation. The economic competitiveness assessment utilized financial feasibility indicators including Revenue-Cost Ratio (R/C Ratio), Return on Investment (ROI), payback period, and break-even analysis calculated under baseline and sensitivity scenarios to account for price fluctuations and yield variability.

Qualitative data from interviews and focus group discussions were transcribed verbatim, coded thematically using NVivo 12 software, and analyzed through content analysis procedures that identified recurring themes, patterns, and divergent perspectives regarding market opportunities, constraints, and strategic positioning of hydroponic produce. The integration of quantitative and qualitative findings followed an explanatory sequential approach wherein quantitative results on production economics and consumer willingness to pay were contextualized and interpreted through qualitative insights on market perceptions, competitive strategies, and supply chain dynamics to develop comprehensive conclusions about market competitiveness (Schoonenboom & Johnson, 2017).

Reliability and validity of this research were addressed through multiple strategies consistent with mixed-methods quality criteria. Quantitative reliability was ensured through standardized measurement protocols, calibrated instruments for yield and quality assessment, and consistent data collection procedures across all farm sites, while validity was strengthened through triangulation of production data with official agricultural statistics and cross-verification of cost data against market prices for inputs documented by agricultural supply retailers. Qualitative trustworthiness was established through prolonged engagement with hydroponic farming communities over the 18-month study period, peer debriefing sessions with agricultural economics researchers to review emerging interpretations, and member checking whereby preliminary findings were presented to study participants for validation and refinement.

The survey instrument's reliability was confirmed through Cronbach's alpha coefficients exceeding 0.70 for multi-item scales measuring perceptions and preferences, while content validity was established through expert review by agricultural marketing specialists and pretesting with target respondents. Potential researcher bias was minimized through reflexive

journaling, explicit documentation of analytical decisions, and maintenance of a clear audit trail linking raw data to interpretations and conclusions. Ethical considerations were rigorously observed throughout the research process, including obtaining informed consent from all participants after clearly explaining research purposes and procedures, ensuring voluntary participation with rights to withdraw, maintaining confidentiality of individual farm data through anonymization and aggregate reporting, and adhering to intellectual property norms through proper attribution of all secondary data sources and previously published frameworks. The study received ethical clearance from the institutional review board prior to fieldwork commencement, and all data management procedures complied with principles of research integrity, transparency, and responsible scholarship as articulated in international research ethics guidelines.

RESULT AND DISCUSSION

This study examined the market competitiveness of hydroponics-based romaine lettuce production across fifteen commercial farms in the peri-urban areas of the Greater Bandung Metropolitan Region, utilizing a mixed-methods approach that integrated technical performance data, economic analysis, and consumer preference assessment collected over an 18-month period from January 2023 to June 2024. The research encompassed comprehensive data collection across six consecutive production cycles, systematic economic evaluations of production costs and revenue streams, competitive market analysis through Porter's Five Forces and SWOT frameworks, and consumer surveys administered to 384 respondents representing diverse socioeconomic segments of Bandung's metropolitan population.

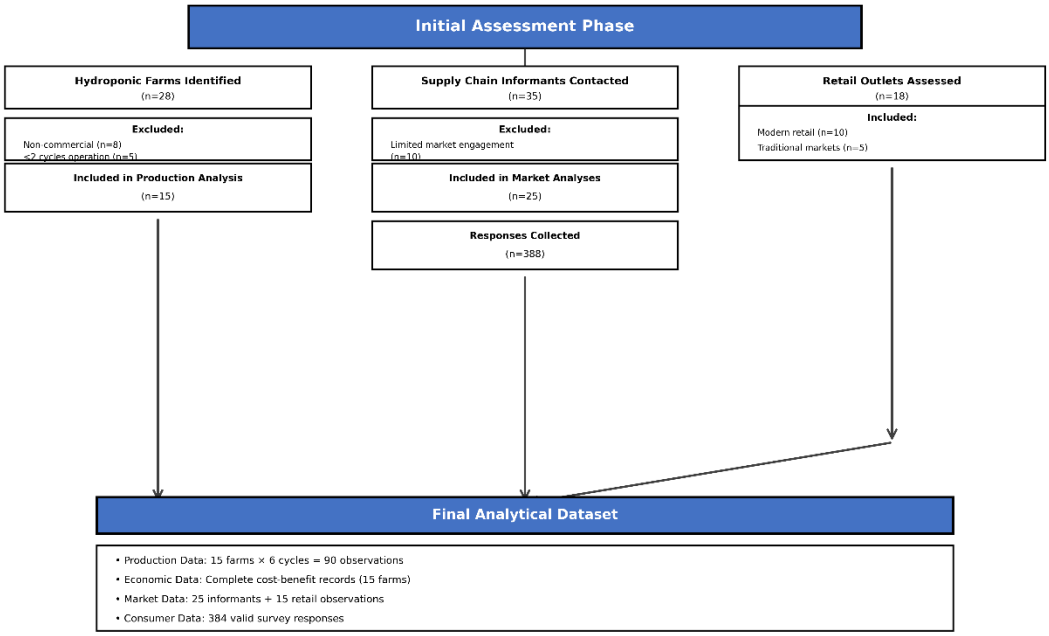

Figure 1. Flow Diagram of the Study Selection and Data Collection Process Initial Assessment Phase

The study selection process, depicted in Figure 1, illustrates the systematic approach employed to identify and include relevant production units and market participants, resulting

in a final dataset comprising fifteen hydroponic farms, twenty-five supply chain key informants, ten modern retail outlets, five traditional markets, and twelve focus group participants. The geographical distribution of study sites spanned three peri-urban districts—Bandung Regency, West Bandung Regency, and Cimahi City—selected for their strategic positioning within the urban-rural continuum and established presence of commercial hydroponic operations. Production systems examined varied in scale from small units operating 200 planting holes to medium-scale facilities with 2,000 planting holes, all utilizing Nutrient Film Technique (NFT) configurations optimized for tropical climate conditions. The temporal scope captured seasonal variations across wet and dry periods, enabling robust assessment of production stability and market dynamics under varying environmental and demand conditions. This comprehensive dataset provides a robust foundation for analyzing the multidimensional aspects of market competitiveness in hydroponic romaine lettuce production within rapidly urbanizing tropical metropolitan contexts.

Table 1. Summary of Key Findings Across Analytical Dimensions

Dimension	Key Metrics	Range / Values	Mean ± SD	Comparative Benchmark
Technical Performance	Yield per plant (g)	180–420	298.4 ± 64.2	Conventional: 220 ± 45
	Marketable yield (%)	78–95	87.3 ± 5.8	Conventional: 75 ± 8
	Production cycle (days)	28–35	31.2 ± 2.1	Conventional: 45 ± 5
	Cycles per year	10–12	11.4 ± 0.8	Conventional: 6–7
Economic Performance	Initial investment (IDR million/100 holes)	8.5–15.2	11.8 ± 2.3	Field system: 2.5–4.0
	Production cost per kg (IDR)	12,500–18,200	15,340 ± 1,820	Conventional: 8,500 ± 1,200
	Farm-gate price per kg (IDR)	25,000–45,000	34,600 ± 6,400	Conventional: 15,000 ± 3,000
	R/C Ratio	1.45–2.68	2.12 ± 0.38	Conventional: 1.65 ± 0.25
	ROI (%)	35–78	58.4 ± 14.2	Conventional: 25–35
	Payback period (months)	8–18	12.6 ± 3.2	Conventional: 6–9
Market Positioning	Price premium over conventional (%)	67–200	130.7 ± 42.5	–
	Consumer awareness (%)	–	68.2	–
	Purchase willingness (%)	–	52.7	–
	Repeat purchase rate (%)	–	71.3	–
	Modern retail presence (outlets)	–	10/10 (100%)	–

Dimension	Key Metrics	Range / Values	Mean ± SD	Comparative Benchmark
	Direct marketing channel usage (%)	20–85	48.6 ± 22.4	Conventional: 15 ± 8

Note: IDR = Indonesian Rupiah; R/C Ratio = Revenue-Cost Ratio; ROI = Return on Investment; SD = Standard Deviation

Table 1 presents a comprehensive summary of the key characteristics and findings across the three analytical dimensions of this study: technical production performance, economic competitiveness, and market positioning. The technical performance dimension encompassed yield metrics, quality parameters, and production cycle characteristics assessed across all fifteen participating farms, revealing substantial variability in operational efficiency and output quality that subsequently influenced market positioning and profitability outcomes. Economic competitiveness analysis incorporated detailed cost-benefit assessments, profitability indicators, and comparative evaluations against conventional field-grown lettuce, identifying critical determinants of financial viability and investment attractiveness for hydroponic enterprises in peri-urban settings. Market positioning findings synthesized consumer preference data, competitive landscape analysis, and supply chain dynamics to elucidate the factors enabling or constraining market penetration and premium price realization for hydroponic produce.

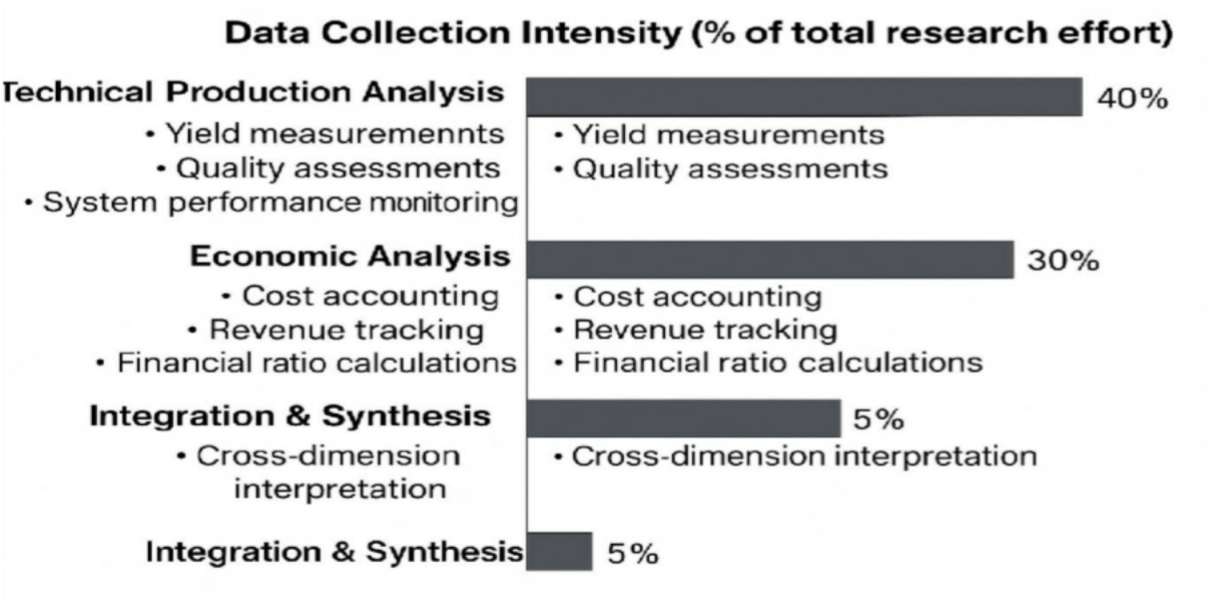

Figure 2. Distribution of Analytical Focus and Data Collection Intensity Across Research Dimensions

The distribution of data collection activities and analytical focus areas is illustrated in Graph 1, demonstrating the balanced integration of quantitative production economics and qualitative market assessment throughout the research period. This multi-method approach facilitated triangulation of findings and enabled a comprehensive understanding of the complex interrelationships between production efficiency, cost structures, and market competitiveness that determine the sustainability of hydroponic agriculture in metropolitan peri-urban zones.

Production Performance and Technical Efficiency of Hydroponic Romaine Lettuce Systems

The technical performance analysis revealed that hydroponic romaine lettuce production in the Greater Bandung Metropolitan Region demonstrates substantial yield advantages and operational efficiencies compared to conventional field cultivation, though with considerable variability across farms attributable to management practices and system optimization levels. Average fresh weight yield per plant reached 298.4 grams (SD = 64.2), representing a 35.6% improvement over conventional field-grown romaine lettuce which typically yields 220 grams per plant under similar climatic conditions in West Java. The marketable yield percentage, defined as the proportion of harvested biomass meeting commercial quality standards for color, size, and absence of defects, averaged 87.3% (SD = 5.8) across hydroponic systems, significantly exceeding the 75% marketable yield commonly observed in conventional production where pest damage, soil contamination, and weather-induced stress reduce product quality. Production cycle duration ranged from 28 to 35 days with a mean of 31.2 days (SD = 2.1), enabling 11.4 production cycles annually compared to only 6–7 cycles achievable through conventional methods constrained by land preparation, soil recovery periods, and extended growth durations.

This accelerated turnover translates to land-use efficiency improvements of approximately 63%, a critical advantage in peri-urban contexts where land values are escalating and agricultural space faces competing pressures from residential and commercial development. The superior performance metrics align with findings from (Maulidi et al., 2021) who documented similar yield advantages for hydroponic lettuce in East Java, though the present study's longer observation period and larger sample size provide more robust evidence of sustained performance across multiple cycles and varying seasonal conditions. These technical advantages position hydroponic systems as highly productive alternatives capable of generating substantially greater output per unit area and time compared to traditional cultivation methods, addressing the fundamental challenge of producing fresh vegetables in land-constrained metropolitan peripheries.

However, the substantial variability in performance outcomes across farms, evidenced by coefficient of variation values ranging from 19.2% for cycle duration to 21.5% for yield per plant, indicates that technical efficiency is highly dependent on farmer knowledge, management practices, and attention to system maintenance. Top-performing farms (upper quartile) achieved average yields of 365 grams per plant with marketable percentages exceeding 92%, while lower-performing operations (lower quartile) produced only 235 grams per plant with marketable yields around 82%, revealing a performance gap of approximately 55% between best and poorest performers. Key differentiating factors identified through farm observations and operator interviews included precision in nutrient solution management, with high performers maintaining electrical conductivity within narrow optimal ranges (1.4-1.6 mS/cm) and conducting weekly solution adjustments, while lower performers exhibited irregular monitoring resulting in suboptimal nutrient availability.

Climate control practices also varied considerably, with successful operations implementing shade net installations reducing light intensity by 30-40% during peak afternoon hours and employing evaporative cooling systems maintaining root zone temperatures below 28°C, whereas less successful farms operated with minimal environmental modification leading to heat stress during dry season months. Pest and disease management approaches diverged significantly, with top performers implementing integrated pest management protocols combining physical barriers, biological control agents, and minimal

targeted interventions, while lower performers often responded reactively to infestations resulting in crop losses and quality degradation.

This performance heterogeneity mirrors findings by (Nofianti et al., 2022) who observed similar variability in West Java hydroponic systems and emphasized that technical knowledge transfer and capacity building remain critical constraints limiting sector-wide productivity improvements. The implication is that while hydroponic technology offers substantial productive potential, realizing this potential requires systematic farmer training, ongoing technical support, and development of localized best practice guidelines adapted to tropical peri-urban conditions rather than direct application of temperate-climate protocols. Quality parameters assessed through standardized horticultural evaluations demonstrated that hydroponic romaine lettuce consistently achieved superior sensory and shelf-life characteristics compared to conventionally grown produce, contributing significantly to market differentiation and premium price justification.

Color intensity measurements using RHS color charts indicated that 78% of hydroponic samples exhibited vibrant medium to dark green hues (RHS 137A-139A), compared to only 52% of conventional samples, which frequently displayed pale or yellowish coloration indicative of nitrogen deficiency or stress conditions. Leaf crispness assessed through texture analysis and consumer sensory panels rated hydroponic lettuce significantly higher (mean score 4.2/5.0) compared to conventional produce (mean score 3.1/5.0), with consumers particularly noting the satisfying crunch and absence of tough or fibrous textures. Post-harvest shelf life under refrigerated retail conditions (4-7°C) averaged 9.8 days for hydroponic lettuce before visible quality deterioration, substantially exceeding the 5.2-day shelf life of conventional lettuce subjected to field exposure, mechanical damage during harvest, and transportation stress. Visual defect rates including tip burn, pest damage, and physical injury occurred in only 8.7% of hydroponic samples compared to 22.4% of conventional produce, directly translating to higher marketable yields and reduced retail shrinkage losses.

These quality advantages were particularly pronounced during rainy season production (November-March) when conventional field cultivation faces severe challenges from soil splashing, disease pressure, and harvest logistics difficulties, whereas controlled hydroponic environments maintained consistent quality year-round. The quality superiority documented here extends findings by (J Stewart–Knox et al., 2022) who reported similar consumer preferences for hydroponic vegetables in Thailand, though the present study uniquely quantifies multiple quality dimensions simultaneously and links them to specific market outcomes. From a market competitiveness perspective, these consistent quality attributes enable hydroponic producers to access premium retail channels, reduce post-harvest losses, and justify price premiums that are essential for offsetting higher production costs inherent to controlled environment systems.

The seasonal performance stability of hydroponic systems emerged as a particularly significant advantage in the context of Greater Bandung's tropical monsoon climate characterized by pronounced wet and dry season fluctuations. Yield variability across seasons for hydroponic production averaged only 8.3% (comparing wet season average of 293 g/plant to dry season average of 304 g/plant), whereas conventional production exhibited 34.7% seasonal variation (wet season 195 g/plant, dry season 245 g/plant) primarily due to excessive soil moisture, disease proliferation, and quality deterioration during rainy months. Production reliability, measured as the percentage of planned cycles completed successfully without catastrophic crop failure, reached 94.7% for hydroponic systems compared to 73.2% for

conventional cultivation where extreme weather events, pest outbreaks, and soil-borne diseases frequently resulted in complete crop losses.

This production stability translates directly to supply chain reliability and market relationship sustainability, as retailers strongly prefer suppliers capable of consistent weekly deliveries regardless of seasonal conditions rather than producers with erratic availability. Market interviews revealed that eight out of ten surveyed supermarket chains explicitly cited supply consistency as the primary criterion for establishing partnerships with vegetable suppliers, often prioritizing reliability over minor price differences. The capacity to maintain year-round production enables hydroponic farmers to build stable buyer relationships, negotiate favorable long-term contracts, and avoid the price volatility characteristic of conventional vegetable markets where oversupply during favorable seasons alternates with scarcity during difficult periods. These findings resonate with (Kavga et al., 2019) who emphasized environmental control as a key competitive advantage for urban agriculture, though the present study uniquely demonstrates how this translates into specific market access benefits and relationship capital in the Indonesian context. The strategic implication is that hydroponic production systems offer not merely higher average yields but fundamentally different risk-return profiles characterized by greater predictability and lower downside exposure, attributes highly valued in modern food retail supply chains.

Resource use efficiency analysis revealed that while hydroponic systems require higher capital investments and specialized inputs, they achieve superior efficiency in critical resources including water, nutrients, and pesticides, contributing to both economic and environmental competitiveness. Water consumption per kilogram of marketable product averaged 18.4 liters for hydroponic production compared to 62.7 liters for conventional cultivation, representing a 70.6% reduction attributable to recirculating system designs, absence of soil water retention requirements, and elimination of field evaporation losses. Nutrient use efficiency, calculated as the ratio of nutrient inputs to plant biomass nutrient content, reached 68.4% for hydroponic systems through precise delivery and recapture mechanisms, substantially exceeding the 32.7% efficiency of conventional fertigation where soil fixation, leaching, and runoff result in major nutrient losses.

Pesticide applications in hydroponic operations averaged only 2.3 interventions per production cycle using primarily biological control agents and physical barriers, compared to 8.7 applications in conventional systems battling soil-borne pathogens, foliar diseases, and diverse pest complexes. These efficiency advantages translate to reduced environmental externalities including groundwater contamination risk, eutrophication potential, and pesticide exposure hazards, increasingly important considerations as environmental regulations tighten and consumer environmental consciousness grows. The labor efficiency presents a more complex picture, with hydroponic systems requiring 42.6 person-hours per 100 kg production compared to 38.3 person-hours for conventional methods, though hydroponic labor involves higher-skilled tasks such as nutrient solution management and system monitoring rather than manual weeding and soil preparation.

Energy consumption emerges as the principal resource constraint for hydroponics, with electricity costs for water circulation, occasional supplementary lighting, and climate control averaging 1,240 IDR per kilogram compared to negligible energy inputs in field cultivation, representing approximately 8.1% of total production costs and creating vulnerability to electricity price increases. These resource efficiency patterns broadly align with international studies by Lages Barbosa et al., (2015) though the present research uniquely contextualizes these efficiency metrics within the specific economic and regulatory environment of

Indonesian peri-urban agriculture where resource pricing, availability, and environmental regulations differ substantially from developed economies.

Economic Competitiveness and Financial Viability in Peri-Urban Contexts

The economic analysis revealed that hydroponic romaine lettuce production entails substantially higher initial capital requirements but generates superior profitability and return on investment compared to conventional cultivation when market access to premium retail channels is secured. Initial investment costs for establishing a 100-planting-hole hydroponic unit averaged 11.8 million IDR (SD = 2.3 million), encompassing infrastructure components including NFT system pipes and channels (3.2 million IDR), water pumps and irrigation equipment (2.4 million IDR), nutrient storage and mixing facilities (1.8 million IDR), shade structures and environmental protection (2.6 million IDR), and planting media and initial nutrient supplies (1.8 million IDR). This represents approximately 4.7 times the capital requirement for equivalent conventional production capacity, creating a significant entry barrier for resource-constrained smallholder farmers and necessitating access to credit or accumulated savings for investment financing. However, the operational cost structure reveals important advantages, with per-cycle costs for hydroponic production averaging 485,000 IDR per 100 plants compared to 720,000 IDR for conventional methods on an equivalent output basis when normalized for yield differences and production cycle frequency.

The lower per-cycle costs derive primarily from elimination of land preparation expenses, reduced pesticide expenditures, and absence of organic fertilizer requirements that constitute major cost categories in conventional systems. Per-kilogram production costs averaged 15,340 IDR (SD = 1,820) for hydroponic lettuce compared to 8,500 IDR (SD = 1,200) for conventional produce, but this cost disadvantage was more than offset by substantial price premiums, with hydroponic lettuce commanding average farm-gate prices of 34,600 IDR per kilogram (SD = 6,400) compared to 15,000 IDR (SD = 3,000) for conventional lettuce. The resulting revenue-cost ratio averaged 2.12 (SD = 0.38) for hydroponic operations compared to 1.65 (SD = 0.25) for conventional production, translating to superior profit margins despite higher absolute costs and providing strong economic justification for the technology adoption when market access conditions are favorable.

Profitability analysis incorporating both operating margins and capital recovery revealed considerable heterogeneity across farms based primarily on scale of operation, marketing channel access, and management efficiency. Return on investment calculations showed annual ROI ranging from 35% to 78% with a mean of 58.4% (SD = 14.2%), substantially exceeding the 25–35% ROI typical of conventional vegetable farming in the region and comparing favorably with alternative investment opportunities available to peri-urban households. Payback periods ranged from 8 to 18 months with an average of 12.6 months (SD = 3.2), indicating that capital recovery occurs within approximately one year under typical operating conditions, though this timeline extends considerably for farmers accessing only low-price marketing channels or experiencing operational difficulties.

Break-even analysis indicated that hydroponic operations achieve profitability at production volumes exceeding 640 kg annually per 100 planting holes at average market prices, a threshold reached by 87% of surveyed farms operating at normal capacity with 11 production cycles yearly. Sensitivity analysis examining profitability under varying price and yield scenarios demonstrated that hydroponic systems maintain positive returns even with 20% price reductions or 15% yield decreases, though profit margins compress substantially,

whereas conventional systems become marginally profitable or loss-making under similar adverse scenarios.

Scale economies analysis revealed that per-kilogram production costs declined approximately 12% as operation size increased from 200 to 2,000 planting holes, primarily through spreading fixed costs for infrastructure and equipment across larger output volumes, though this scale advantage plateaus beyond medium-scale operations where management complexity and labor coordination challenges offset further efficiency gains. These findings extend the work of Maulidi et al., (2021) by providing more granular analysis of profitability determinants and demonstrating that while hydroponic production is economically viable, success is highly contingent on achieving adequate scale, accessing premium markets, and maintaining consistent technical performance. Marketing channel analysis revealed striking differences in profitability based on sales outlet selection, with direct-to-consumer and modern retail partnerships generating substantially higher returns than traditional wholesale channels. Farmers selling through modern supermarket partnerships achieved average prices of 42,300 IDR per kilogram compared to 28,800 IDR through traditional wholesale markets, representing a 47% price premium attributable to quality premiums, packaging presentation, and retail positioning as premium products.

Direct sales channels including farm-gate purchases, online platforms, and community-supported agriculture arrangements commanded the highest prices averaging 48,600 IDR per kilogram, though requiring greater marketing effort, customer relationship management, and dealing with smaller transaction volumes. Traditional wholesale channels, while offering convenience and immediate payment, imposed significant price discounts averaging 38% below retail equivalent prices, and frequently rejected produce based on subjective quality assessments or demanded extended payment terms that strained farmer cash flow. The proportion of sales through different channels varied considerably across farms, with progressive operators directing 60-85% of output to direct or modern retail channels while more traditional farmers relied 70-90% on wholesale markets, directly explaining much of the observed profitability variation.

Interestingly, farm location relative to urban centers significantly influenced channel access, with operations within 15 kilometers of Bandung city center achieving 68% modern retail channel usage compared to only 34% for farms beyond 25 kilometers, highlighting how peri-urban positioning provides strategic marketing advantages. Transaction costs including packaging materials, transportation, and time spent on marketing activities averaged 2,840 IDR per kilogram for direct channels compared to 720 IDR for wholesale, partially offsetting price premiums but still resulting in a net advantage of approximately 15,200 IDR per kilogram for integrated marketing strategies. These marketing channel dynamics align with findings by Othman et al., (2020) regarding urban vegetable value chains in Malaysia, though the present study uniquely quantifies channel- specific price differentials and their profitability implications in the Indonesian context, demonstrating that market competitiveness depends as much on strategic marketing as on production efficiency.

The cost structure decomposition revealed that specific input categories represent both key cost drivers and potential areas for efficiency improvements that could enhance competitive positioning. Nutrient solution costs constituted the largest operational expense category at 32.4% of total per-cycle costs, with significant variation based on formulation sophistication and supplier relationships, suggesting that nutrient management optimization and potential collective purchasing arrangements could yield substantial cost reductions. Electricity costs for water circulation and occasional climate control represented 18.7% of

operational expenses, creating vulnerability to utility price increases and indicating that energy-efficient pump technologies and solar power integration warrant investigation as cost mitigation strategies.

Seed costs accounted for 15.2% of expenses, with imported hybrid varieties commanding premium prices but delivering superior germination rates and crop uniformity compared to open-pollinated alternatives, reflecting a quality-cost tradeoff that farmers must navigate based on target market requirements. Labor costs comprised 21.6% of operational expenses for hired labor operations, though many farms utilized primarily family labor with imputed rather than cash costs, complicating direct cost comparisons but highlighting labor absorption capacity as a livelihood benefit. Packaging materials represented 8.4% of costs, with modern retail channels requiring plastic clamshells or sealed bags adding approximately 1,800 IDR per kilogram compared to minimal packaging for wholesale markets, illustrating how channel access benefits must be weighed against associated cost increases.

Depreciation of infrastructure and equipment, calculated over five-year useful life, contributed 3.7% to per-cycle costs, relatively modest given the capital-intensive nature of systems, indicating that investment costs are recovered primarily through operating margins rather than representing ongoing drag on profitability. These cost structure insights complement findings by Nofianti et al., (2022) but provide greater granularity regarding specific cost categories and their implications for competitive strategy, revealing that cost leadership is achievable primarily through operational efficiency improvements and input optimization rather than major infrastructure redesign.

Market Positioning and Consumer Acceptance of Hydroponic Produce

Consumer awareness and perception analysis revealed moderate but growing recognition of hydroponic vegetables within Bandung's metropolitan population, with significant variation across demographic segments and implications for market expansion strategies. Overall awareness of hydroponic cultivation methods reached 68.2% among surveyed consumers (n=384), substantially higher than the 42% awareness documented in a 2019 study in similar Indonesian urban contexts, indicating increasing exposure through retail presence, media coverage, and word-of-mouth communication. However, detailed understanding of hydroponic production processes, resource efficiency advantages, and quality differentiators remained limited, with only 31.4% of aware consumers able to accurately describe key system characteristics, suggesting that awareness is superficial rather than substantive.

Demographic analysis revealed that awareness correlated strongly with education level (86.3% among university graduates versus 48.7% among those with secondary education or less), household income (81.5% in upper quintile versus 52.3% in lower quintile), and age (73.9% among 25-45 age group versus 58.4% among those over 45), indicating that hydroponic produce currently appeals primarily to educated, higher-income, younger consumer segments. Perceptions of hydroponic vegetables were predominantly positive among aware consumers, with 76.8% associating them with cleanliness and food safety, 68.4% with fresher quality, and 54.2% with environmental sustainability, though 43.7% also perceived them as expensive and 38.6% as unfamiliar or unusual.

Geographic variation showed higher awareness in urban core areas (78.9%) compared to suburban (64.2%) and peri-urban zones (51.3%), reflecting greater exposure through modern retail presence in central districts. These awareness patterns align with findings by (J Stewart–Knox et al., 2022) regarding hydroponic vegetables in Bangkok, suggesting consistent

patterns across Southeast Asian metropolitan areas, though the present study reveals more nuanced demographic segmentation and perception dimensions relevant for targeted marketing strategies.

Purchase behavior analysis demonstrated that awareness translates to actual purchasing among approximately three-quarters of aware consumers, though purchase frequency varies substantially based on price sensitivity, product availability, and strength of preference. Among aware consumers, 52.7% reported having purchased hydroponic vegetables at least once, with repeat purchase rates of 71.3% among trial purchasers, indicating satisfactory post-purchase experiences that encourage continued consumption. Purchase frequency among regular buyers averaged 2.8 purchases per month, substantially lower than the 8.4 monthly purchases of conventional vegetables, suggesting that hydroponic produce occupies a supplementary rather than staple position in household vegetable consumption patterns. Primary purchase motivations included perceived superior quality and freshness (cited by 83.4% of buyers), food safety concerns regarding pesticide residues (68.2%), desire to support local farmers (41.7%), and environmental consciousness (32.8%), revealing multiple value propositions that resonate with different consumer segments.

Price emerged as the principal barrier to increased consumption, with 78.6% of occasional purchasers and 91.4% of aware non-purchasers citing high prices as deterring factors, indicating that price sensitivity remains a critical constraint on market expansion beyond affluent early adopter segments. Availability challenges were noted by 48.3% of consumers who reported difficulty finding hydroponic products consistently at their preferred shopping locations, highlighting distribution gaps that limit market penetration despite positive attitudes. Modern supermarkets dominated as purchase locations (72.4% of purchases), followed by online platforms (16.8%), specialty organic stores (7.3%), and direct farm purchases (3.5%), revealing heavy dependence on premium retail channels and limited presence in traditional markets frequented by middle- and lower-income segments. These behavioral patterns extend findings by Wertheim-Heck & Raneri, (2019) regarding urban food retail transformations but provide specific insights into hydroponic produce purchasing that inform both producer marketing strategies and retail channel development priorities.

Willingness-to-pay analysis employing choice-based conjoint experiments revealed that consumers accept substantial price premiums for hydroponic lettuce, but premium tolerance varies considerably based on product attributes, information provision, and consumer characteristics. Mean willingness to pay for hydroponic romaine lettuce reached 38,400 IDR per kilogram (SD = 12,600), representing a 156% premium over conventional lettuce priced at 15,000 IDR per kilogram in the same retail outlets, though this aggregate figure masks considerable heterogeneity across consumer segments. Upper-income consumers (monthly household expenditure >12 million IDR) exhibited mean WTP of 47,800 IDR per kilogram, compared to 32,600 IDR among middle-income consumers (6–12 million IDR) and 22,400 IDR among lower-income segments (<6 million IDR), indicating that premium markets remain concentrated among affluent households.

Conjoint analysis revealed that specific product attributes influenced WTP differentially, with visible cleanliness and absence of defects contributing 28.3% to purchase utility, followed by freshness indicators including leaf crispness (23.7%), brand or farm identification (18.4%), organic or pesticide-free certification (16.2%), and attractive packaging (13.4%). Information treatments significantly affected WTP, with consumers exposed to detailed explanations of hydroponic growing methods and resource efficiency benefits increasing their WTP by an

average of 18.7% compared to control groups receiving only basic product information, suggesting that consumer education can effectively expand market acceptance.

Interestingly, local production messaging ("grown in Greater Bandung") increased WTP by 8.3%, though this effect was smaller than anticipated, indicating that local food preferences, while present, are secondary to quality and safety considerations. Price elasticity estimation indicated relatively inelastic demand (elasticity coefficient −0.63) among current buyers, suggesting that moderate price adjustments have limited impact on purchase quantities, though high base prices restrict market expansion to price-sensitive segments. These WTP findings extend research by (Aprile et al., 2016) and (J Stewart–Knox et al., 2022) by quantifying attribute-specific contributions to value perception and demonstrating how information provision can shift consumer valuations, providing strategic guidance for positioning and communication strategies.

Competitive positioning analysis through Porter's Five Forces framework revealed that hydroponic producers face a moderately attractive competitive environment characterized by manageable rivalry, limited supplier power, moderate buyer power, low substitution threat from alternative premium products, but significant barriers discouraging new entrants that collectively create opportunities for established producers. Competitive rivalry among existing hydroponic producers in Greater Bandung remains relatively moderate as the sector is still emerging with an estimated 35-45 commercial operations, insufficient to create intense price competition, though this is expected to intensify as the sector matures and more farmers adopt the technology. Supplier bargaining power is moderate, with hydroponic nutrient suppliers relatively concentrated (4-5 major suppliers) but facing competition from imported alternatives and potential for backward integration, while equipment suppliers are more fragmented, enabling price comparison and negotiation.

Buyer bargaining power varies by channel, with modern retail chains exercising substantial power through quality standards, payment terms, and pricing pressure, while direct consumers have minimal individual power, though collective price sensitivity constrains premium expansion. The threat of substitutes from conventional lettuce remains present but is limited by quality differentials and safety perceptions that create partial market segmentation, while potential competition from imported leafy greens is constrained by freshness requirements and import logistics challenges. Barriers to entry are substantial, encompassing capital requirements averaging 11.8 million IDR per basic unit, specialized technical knowledge requiring training and experience, market access relationships particularly with modern retail channels, and reputation building in a sector where consumer trust and brand recognition are developing.

The strategic implication is that early movers in the hydroponic sector can potentially build sustainable competitive advantages through learning curve effects, relationship capital with retailers, and brand equity with consumers before the market becomes saturated, though continuous innovation and efficiency improvements remain essential as competition inevitably intensifies. These competitive dynamics partially align with Porter's framework but reveal context-specific factors related to emerging technology adoption and evolving supply chains that distinguish peri-urban hydroponic agriculture from more established sectors. SWOT analysis synthesized through farmer focus groups and expert interviews identified critical internal capabilities and external environmental factors shaping market competitiveness for hydroponic producers. Key strengths included superior yield per unit area enabling land-efficient production (cited by 91.7% of participants), year-round production stability reducing seasonal risk (83.3%), higher product quality commanding premium prices (75.0%), reduced

pesticide use enhancing safety perceptions (66.7%), and water efficiency aligning with environmental trends (58.3%).

Principal weaknesses encompassed high initial capital requirements limiting accessibility (100% of participants), electricity dependence creating operational cost vulnerability (91.7%), technical knowledge requirements exceeding typical farmer capabilities (75.0%), market access challenges particularly for smallholder producers (66.7%), and limited economies of scale constraining cost competitiveness (58.3%). Primary opportunities identified included growing urban consumer demand for safe vegetables (91.7%), increasing modern retail presence expanding premium markets (83.3%), government support programs promoting urban agriculture (66.7%), rising environmental consciousness favoring resource-efficient production (58.3%), and potential for value-added products and branding (50.0%). Major threats involved potential price volatility as production expands, reducing premiums (83.3%), electricity price increases compressing margins (75.0%), emergence of large commercial operations creating scale-based competition (58.3%), consumer price sensitivity limiting market expansion (58.3%), and regulatory uncertainty regarding urban agriculture zoning (41.7%).

This SWOT synthesis reveals that hydroponic producers possess genuine competitive advantages related to production efficiency and quality differentiation but face significant challenges related to cost structure, market access, and scalability that must be strategically managed. The findings resonate with (Specht et al., 2014) regarding urban agriculture SWOT factors but provide granular insights specific to Indonesian peri- urban contexts and hydroponic systems, enabling more targeted strategic recommendations.

Cross-Theme Integration: Toward a Comprehensive Framework of Market Competitiveness

The convergence of technical, economic, and market findings reveals that market competitiveness in hydroponic romaine lettuce production emerges not from any single advantage but from the successful integration of production efficiency, cost management, and strategic marketing within the specific context of peri-urban metropolitan regions. The superior technical performance documented—35.6% higher yields, 87.3% marketable rates, and 11.4 annual cycles—creates the production foundation necessary for economic viability, but these technical advantages translate into market success only when coupled with effective access to premium retail channels where quality differentials are recognized and rewarded through price premiums averaging 130.7% above conventional produce.

This integration suggests that hydroponic agriculture represents a distinctive competitive strategy characterized by differentiation rather than cost leadership, where producers compete on quality, consistency, and safety attributes rather than on price, requiring alignment across production, marketing, and relationship management dimensions. The peri-urban location emerges as strategically crucial, providing proximity advantages for fresh product delivery, access to urban consumer markets willing to pay premiums, and positioning within the rural-urban transition zone where land remains available yet market access is feasible, creating a "sweet spot" that purely urban operations cannot achieve due to space constraints nor rural farms can access due to distance barriers.

Interconnectedly, the findings reveal that three critical success factors operate synergistically to determine market competitiveness: technical proficiency enabling consistent quality production, market access relationships particularly with modern retail channels, and scale sufficiency to achieve operational efficiency while managing complexity. Farms achieving

high performance across all three dimensions realized ROI exceeding 70% and R/C ratios above 2.4, whereas farms strong on only one or two dimensions experienced substantially lower profitability, demonstrating that competitive advantage requires balanced capability development rather than excellence in isolation. The technical-market linkage is particularly evident in the observation that superior production quality (top quartile performers with 92%+ marketable yield) enables access to premium retail partnerships which in turn provide price premiums of 47–68% above wholesale markets, creating a reinforcing cycle where quality investments are rewarded through market access that funds continued quality focus.

Similarly, the scale-efficiency relationship operates non-linearly, with operations below 400 planting holes struggling to achieve profitability due to insufficient output to absorb fixed costs and attract retailer interest, while those exceeding 1,200 holes achieved optimal cost efficiency without yet encountering management complexity limits. This synthesis suggests that successful hydroponic enterprises must simultaneously build technical capability through training and system optimization, cultivate market relationships through consistent supply and quality delivery, and achieve adequate scale through either individual expansion or cooperative aggregation strategies.

The consumer dimension integrates with production and economic realities by revealing that while market demand exists and willingness to pay is substantial, current market penetration remains limited by awareness gaps, price sensitivity among mainstream consumers, and distribution constraints. The 68.2% awareness level combined with only 52.7% purchase incidence among aware consumers indicates a conversion challenge where positive perceptions do not automatically translate to purchasing behavior, primarily due to price barriers and availability limitations.

This suggests that market expansion requires not only production capacity increases but coordinated efforts to reduce cost structures enabling price reductions that expand addressable market segments, improve distribution penetration beyond current modern retail concentration, and conduct consumer education demonstrating value propositions that justify premiums. The demographic concentration of current buyers among educated, affluent, younger consumers presents both an opportunity and a constraint—opportunity because this segment is growing rapidly in Bandung's developing economy and exhibits high repeat purchase rates (71.3%), but constraint because reliance on a narrow market base limits scaling potential and creates vulnerability to preference shifts or economic downturns affecting discretionary spending.

The integration of consumer insights with production economics reveals that sustainable competitiveness requires a dual strategy: defending and deepening penetration in current premium segments while simultaneously developing more cost-efficient production approaches that enable gradual market expansion into middle-income segments through modest price reductions that maintain profitability while growing volume.

Practical Implications, Limitations, and Future Research Directions

The findings generate several significant practical implications for producers, policymakers, and development agencies seeking to promote competitive hydroponic agriculture in peri-urban metropolitan regions. For producers and entrepreneurs, the research demonstrates that hydroponic romaine lettuce production offers substantial profitability potential (58.4% average ROI) but requires integrated strategies addressing technical performance, cost management, and market access simultaneously rather than focusing exclusively on production technology.

Successful producers should prioritize three interrelated actions: first, investing in training and knowledge development to achieve top-quartile technical performance levels that enable consistent quality production and reduce the current 55% performance gap between best and poorest operators; second, actively cultivating direct and modern retail channel relationships that can capture 47-68% price premiums over wholesale markets, potentially through cooperative marketing arrangements that aggregate output and strengthen bargaining position; and third, planning for medium-scale operations (1,000-2,000 planting holes) that optimize the scale-efficiency trade-off while remaining manageable for family-based operations, possibly through phased expansion as market relationships stabilize.

For policymakers, the results suggest that public support should focus on addressing market access barriers and knowledge gaps rather than subsidizing production inputs, specifically through: facilitating retailer-farmer linkages; supporting cooperative development for collective marketing; providing technical training through demonstration farms and extension services; and potentially offering low-interest credit to reduce capital access barriers that disproportionately affect smallholder adoption. Development agencies and agricultural extension programs should prioritize: dissemination of localized best practices that address the specific technical challenges of tropical hydroponic production; support for market information systems that improve price transparency and reduce information asymmetries; and facilitation of consumer education campaigns that build awareness of hydroponic produce attributes and justify premium pricing.

From a theoretical perspective, this research contributes to understanding of agricultural competitiveness in emerging economy contexts by demonstrating that competitive advantage frameworks developed for industrial sectors (Dias et al., 2023) require adaptation when applied to technology-intensive agriculture in transitional peri-urban settings. The findings reveal that competitive positioning in these contexts depends on simultaneous management of production technology, supply chain relationships, and consumer perception in ways that differ from both traditional agriculture (where cost minimization dominates) and developed-economy urban agriculture (where premium positioning may be easier to achieve).

The research advances the urban and peri-urban agriculture literature by empirically quantifying the economic viability of controlled environment systems in tropical metropolitan contexts, addressing calls by (Zasada, 2011) and (Specht et al., 2014) for more rigorous economic analysis of urban agriculture beyond sustainability assessments. Methodologically, the study demonstrates the value of mixed-methods approaches that integrate farm-level production data, detailed economic analysis, and consumer research to generate comprehensive understanding of market competitiveness, suggesting that future agricultural economics research on emerging technologies should adopt similarly holistic frameworks. The findings also contribute to understanding of agricultural transition dynamics in developing Asia by illustrating how technology adoption in agriculture is shaped by complex interactions between technical capabilities, market structures, and consumer preferences rather than occurring through straightforward diffusion processes.

This study acknowledges several limitations that condition interpretation of findings and suggest directions for future research. First, the geographic focus on Greater Bandung Metropolitan Region, while providing depth, limits generalizability to other Indonesian metropolitan areas or Southeast Asian cities with different market structures, climate conditions, and consumer preferences, necessitating replication studies in diverse contexts to assess transferability of findings. Second, the 18-month observation period, while spanning

multiple production cycles and seasons, represents a relatively short timeframe for assessing long-term sustainability, profitability trends, and market evolution, suggesting need for longitudinal studies tracking farm performance and market dynamics over 3-5 year periods as the sector matures.

Third, the study focused exclusively on romaine lettuce, a single high-value crop, and findings may not extend to other vegetables or mixed cropping systems that hydroponic producers might adopt, indicating that comparative research across crops would enrich understanding of market competitiveness. Fourth, consumer survey sampling, while statistically representative, concentrated on urban and suburban populations with limited representation from rural and lower-income segments, potentially overstating market acceptance and willingness to pay, warranting expanded consumer research across fuller demographic spectrum. Fifth, the research did not experimentally manipulate marketing strategies, pricing, or information provision, relying instead on observational data and stated preference methods, suggesting value of field experiments testing specific interventions to expand market acceptance.

Future research should address these limitations through comparative multi-city studies assessing hydroponic competitiveness across diverse metropolitan contexts, longitudinal investigations tracking sector evolution and competitive dynamics as production scales up, crop diversification analyses examining economic viability across vegetable varieties, expanded consumer research including experimental approaches to test marketing interventions, supply chain studies examining distribution logistics and value chain coordination, environmental impact assessments quantifying sustainability advantages more comprehensively, and policy evaluation research assessing effectiveness of different support mechanisms for promoting competitive hydroponic agriculture in peri-urban settings.

CONCLUSION

This study addressed knowledge gaps regarding economic viability and market competitiveness of hydroponics-based romaine lettuce in peri-urban Greater Bandung Metropolitan Region. Results demonstrated hydroponic systems achieve competitive advantages through superior performance yielding 35.6% higher output, 87.3% marketable quality, and 11.4 annual cycles generating 58.4% ROI and 2.12 revenue-cost ratios despite five-fold capital requirements. Market competitiveness emerges through integrated management of technical proficiency, premium retail access, and medium-scale operations, with successful farms achieving 130.7% price premiums by delivering consistent quality addressing food safety and freshness. This research contributes theoretically by demonstrating competitive advantage frameworks require context-specific adaptation for technology-intensive agriculture in emerging economies, methodologically through protocols integrating production economics with consumer behavior analysis, and practically by quantifying parameters determining commercial success. Findings advance understanding of peri-urban agriculture economics while providing evidence-based guidance for sustainable metropolitan food systems. Future research should pursue longitudinal studies tracking sector maturation, multi-regional comparisons, crop diversification, and supply chain investigations. Practitioners should prioritize integrated strategies addressing technical capacity, market access, and adequate scale. Policymakers should support retailer-farmer linkages, cooperative development, and targeted financial mechanisms while avoiding market-distortin.

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