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Cost-effective Automated Aquaponics Systems using Arduino: Enhancing Legume Cultivation, Sprout Growth, Nutrient Content and Sustainable Production: A Review

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ABSTRACT

Aquaponics represents a revolutionary approach to sustainable agriculture, combining aquaculture and hydroponics in an integrated system that maximizes resource efficiency while minimizing environmental impact. This comprehensive review examines the development and implementation of cost-effective automated aquaponics systems utilizing Arduino-based technologies for enhanced legume cultivation and sprout production. The integration of Internet of Things (IoT) sensors, automated control systems and energy-efficient technologies has transformed traditional aquaponics into smart farming solutions capable of optimizing nutrient delivery, water quality management and environmental conditions. Recent advances in microcontroller technologies, particularly Arduino and ESP32 platforms, have enabled the development of affordable monitoring and control systems that can maintain optimal growing conditions while reducing operational costs. This review synthesizes current research on automated aquaponics systems, focusing on their application in legume and sprout production, technological infrastructure requirements, energy harvesting solutions and the nutritional benefits of sprouted legumes. The analysis reveals significant potential for Arduino-based systems to enhance productivity, improve resource utilization and contribute to sustainable food production systems. Key challenges identified include system scalability, energy management and the need for standardized protocols for different crop types. Future research directions emphasize the development of AI-driven control systems, renewable energy integration and optimization of nutrient cycling for specific legume varieties.

Key words: Aquaponics, Arduino, Automation, IoT, Legume cultivation, Smart farming, Sprout production, Sustainable agriculture.

The global food security challenge, exacerbated by climate change, population growth and diminishing arable land, has intensified the search for sustainable agricultural solutions (Barman *et al*., 2025). Aquaponics, an innovative farming method that integrates fish farming (aquaculture) with soilless plant cultivation (hydroponics), has emerged as a promising approach to address these challenges (Goddek *et al*., 2015). This symbiotic system leverages the natural nitrogen cycle, where fish waste provides essential nutrients for plant growth while plants filter and purify water for fish habitats (Rakocy *et al*., 2006).

The evolution of aquaponics from traditional practices to modern automated systems has been significantly accelerated by advances in microcontroller technologies and the Internet of Things (IoT). Arduino-based platforms have democratized access to automation technologies, enabling small-scale farmers and researchers to develop cost-effective monitoring and control systems (Taha *et al*., 2022). These technological innovations have particular relevance for legume cultivation and sprout production, where precise environmental control can significantly enhance nutritional content and yield.

Legumes and sprouts represent high-value crops in aquaponic systems due to their rapid growth rates, high nutritional density and market demand. The sprouting process activates various enzymes and increases the bioavailability of nutrients, making sprouted legumes particularly valuable from both nutritional and economic perspectives (Gan *et al*., 2017). The integration of automated systems in sprout production addresses critical challenges related to food safety, consistent quality and scalable production (FDA, 2017).

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Recent research has demonstrated the potential of Arduino-based automation to optimize key parameters in aquaponic systems, including pH, dissolved oxygen, temperature and nutrient concentrations (Reyes-Yanes *et al*., 2020). These systems offer significant advantages over manual management approaches, including improved consistency, reduced labor costs, real-time monitoring capabilities and data-driven decision making. The affordability and accessibility of Arduino platforms have made sophisticated automation technologies available to small-scale producers, contributing to the democratization of advanced agricultural practices.

This comprehensive review examines the current state of cost-effective automated aquaponics systems, with particular emphasis on Arduino-based technologies for legume and sprout production. The analysis encompasses technological infrastructure requirements, energy harvesting solutions, control and management systems and the specific benefits of automated systems for enhancing nutritional content and sustainable production practices.

Soilless farming: Principles and applications in aquaponics

Soilless farming technologies have revolutionized modern agriculture by eliminating dependency on traditional soil-based cultivation while maximizing resource efficiency (Mohan *et al*., 2023; Gaikwad *et al*., 2023). In aquaponics systems, the principles of soilless cultivation are integrated with aquaculture to create a closed-loop ecosystem that mimics natural nutrient cycles (FAO, 2014). The fundamental principle involves the conversion of fish waste, primarily ammonia, into nitrates through bacterial nitrification processes, which serve as the primary nitrogen source for plant growth (Wongkiew *et al*., 2017).

The effectiveness of soilless aquaponic systems depends on several critical factors, including water quality management, nutrient balance and system design. Kloas *et al*. (2015) introduced innovative concepts for improving sustainability and productivity in aquaponics through decoupled systems that allow independent optimization of fish and plant production environments. This approach addresses the inherent compromise between fish and plant requirements that characterizes traditional coupled systems (Fig 1).

pH management represents a critical challenge in aquaponic systems, as fish typically require neutral to slightly alkaline conditions (7.0-8.0), while most plants prefer slightly acidic environments (5.5-6.5). Zou *et al*. (2016) demonstrated the significant impact of pH on nitrogen transformations, showing that optimal pH management is essential for maximizing nutrient availability and system efficiency. Automated pH control systems using Arduino-based platforms can maintain optimal conditions through real-time monitoring and automated dosing systems.

Water quality parameters beyond pH also require careful management in soilless aquaponic systems. Dissolved oxygen levels must be maintained at adequate levels for both fish respiration and root health, while ammonia and nitrite concentrations must be minimized to prevent toxicity (Baganz *et al*., 2019). Temperature control is equally important, as it affects fish metabolism, plant growth rates and bacterial nitrification processes (Prodanovic *et al*., 2021).

Recent advances in decoupled aquaponics have shown promise for optimizing legume production. Monsees *et al*. (2017) demonstrated that eliminating bottlenecks through system decoupling could significantly improve aquaponic processes. This approach allows for independent optimization of fish and plant production parameters, potentially enhancing the suitability of aquaponics for specific crops like legumes that may have distinct nutritional requirements.

Energy harvesting and sustainable power solutions

Energy consumption represents a significant operational cost in automated aquaponics systems, making energy harvesting and renewable energy integration critical for long-term sustainability. The integration of solar power systems with aquaponics has emerged as a particularly promising approach for reducing operational costs while maintaining system automation (Choi *et al*., 2021).

Solar-powered aquaponics systems offer several advantages, including reduced operational costs, environmental sustainability and independence from grid electricity. Choi *et al*. (2022) developed energy-efficient scheduling algorithms for aquaponics systems with photovoltaic-battery configurations, demonstrating the potential for optimizing energy usage while maintaining system performance. These systems can significantly reduce the carbon footprint of aquaponic operations while improving economic viability.

The design of solar-powered systems requires careful consideration of energy demand patterns and seasonal variations in solar radiation. Pham *et al*. (2020) evaluated solar-powered IoT aquaponics systems, demonstrating

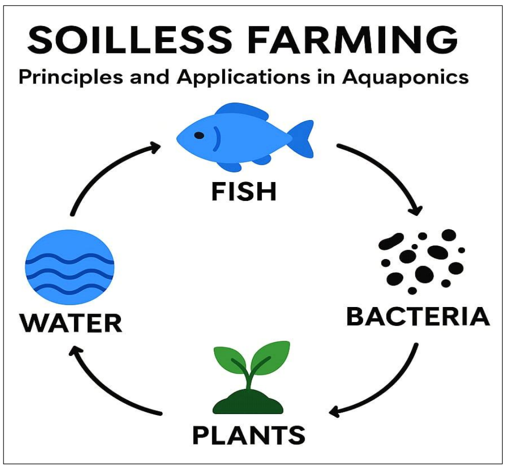

Fig 1: Principles and applications of soilless farming in aquaponics.

the feasibility of maintaining continuous operation through optimized battery storage and energy management systems. The integration of Arduino-based control systems enables sophisticated energy management strategies that can prioritize critical functions during periods of limited solar energy availability.

Isaac (2025) provided a comprehensive review of renewable energy integration in aquaculture and aquaponics systems, highlighting the potential for various renewable technologies including solar, wind and biogas systems. The choice of renewable energy technology depends on local conditions, system scale and energy requirements, with solar power being particularly suitable for small to medium-scale operations.

Energy-efficient component selection plays a crucial role in minimizing overall system energy requirements. LED lighting systems have emerged as a key technology for controlled environment agriculture, offering significant energy savings compared to traditional lighting technologies (van Iersel, 2017). The spectral control capabilities of LED systems also enable optimization of light quality for specific crops, potentially enhancing the nutritional content of sprouted legumes.

The development of energy-efficient automation systems requires careful consideration of component power requirements and operational strategies. Arduino-based systems offer inherent advantages in terms of low power consumption, but additional optimization strategies such as sleep modes, sensor scheduling and adaptive control algorithms can further reduce energy requirements (Lozada *et al*., 2021).

Battery storage systems are essential components of renewable energy-powered aquaponics systems, providing energy security during periods of low renewable energy generation. The sizing and management of battery systems require careful analysis of energy demand patterns and renewable energy availability. Advanced battery management systems using Arduino platforms can optimize charging and discharging cycles to maximize battery life and system reliability.

Technological infrastructure: Smart technologies and IoT integration

The technological infrastructure of modern automated aquaponics systems encompasses a complex network of sensors, controllers, communication systems and user interfaces that work together to monitor and control system parameters. Arduino-based platforms have emerged as the foundation for many cost-effective automation systems due to their versatility, affordability and extensive community support (Jayanth and Maheswari, 2023).

Sensor technologies form the core of automated monitoring systems, providing real-time data on critical parameters including temperature, pH, dissolved oxygen, electrical conductivity and water levels. The DS18B20 temperature sensor has become a standard component in aquaponic monitoring systems due to its accuracy, waterproof design and compatibility with Arduino platforms (Maxim Integrated, 2019). pH monitoring typically employs specialized electrodes and signal conditioning circuits, with Atlas Scientific's EZO pH circuit providing a popular solution for Arduino integration (Atlas Scientific, 2023).

Dissolved oxygen monitoring presents challenges due to the complexity and cost of traditional sensors. However, recent advances in optical dissolved oxygen sensors have improved accessibility while maintaining accuracy (YSI/Xylem, 2022). The integration of these sensors with Arduino-based data acquisition systems enables continuous monitoring and automated response to change conditions.

Communication technologies play a crucial role in enabling remote monitoring and control capabilities. WiFi-enabled microcontrollers such as the ESP32 provide integrated wireless connectivity, enabling data transmission to cloud-based platforms and mobile applications (Espressif Systems, 2023). MQTT protocol has emerged as a preferred communication standard for IoT applications in aquaponics due to its lightweight nature and publish-subscribe architecture (Forhad *et al*., 2024).

User interface development has been significantly simplified by the availability of web-based dashboard solutions and mobile applications. These interfaces enable remote monitoring, control and alert management, making systems accessible to users with varying technical backgrounds. Agrawal *et al*. (2023) demonstrated the implementation of cyber-physical aquaponics systems with comprehensive web-based interfaces that provide real-time monitoring and control capabilities.

Cybersecurity considerations have become increasingly important as aquaponics systems become more connected. The implementation of secure communication protocols, authentication systems and access controls is essential for protecting system integrity and preventing unauthorized access. Regular software updates and security audits are necessary components of system maintenance procedures.

Control and management services

Automated control and management systems represent the intelligence layer of modern aquaponics systems, transforming sensor data into actionable control decisions that optimize system performance. The development of sophisticated control algorithms using Arduino platforms has enabled small-scale producers to implement advanced automation strategies previously available only in large commercial operations (Debroy *et al*., 2024).

Feedback control systems form the foundation of automated aquaponics management, maintaining critical parameters within optimal ranges through continuous monitoring and adjustment. PID (Proportional-Integral-Derivative) controllers have proven particularly effective for maintaining stable pH, temperature and dissolved oxygen levels. Badiola *et al*. (2012) demonstrated the application of model predictive control techniques in aquaponics, showing significant improvements in system efficiency and stability compared to traditional control approaches.

Water quality management automation encompasses multiple interconnected control loops that must be carefully coordinated to avoid conflicts and instabilities. pH control systems typically employ acid and base dosing pumps controlled by Arduino-based systems that respond to continuous pH measurements. Temperature control may involve heating elements, cooling systems and thermal mass management strategies that optimize energy efficiency while maintaining optimal conditions.

Nutrient management automation represents a complex challenge due to the dynamic nature of nutrient uptake by plants and nutrient production by fish. Automated nutrient monitoring systems can track electrical conductivity and specific ion concentrations, enabling precise nutrient supplementation when required. Bailey and Ferrarezi (2022) provided comprehensive guidance on nutrient management in aquaponics, highlighting the importance of understanding plant-specific requirements for different growth stages.

Feeding automation for fish components of aquaponic systems requires careful consideration of feeding schedules, portion sizes and fish behavior patterns. Arduino-based feeding systems can implement sophisticated feeding algorithms that account for fish size, water temperature and growth rates. Integration with water quality monitoring enables adaptive feeding strategies that prevent overfeeding and maintain optimal water conditions.

Alert and notification systems are critical components of automated management systems, providing timely warnings of system failures, parameter deviations and maintenance requirements. Multi-channel notification systems using email, SMS and mobile app notifications ensure that system managers can respond quickly to critical situations. Mohd *et al*. (2024) demonstrated multi-parameter monitoring systems that provide comprehensive alerting capabilities for aquaculture and aquaponics applications.

System scheduling and automation sequencing enable complex operational procedures to be automated, reducing labor requirements and improving consistency. Automated lighting schedules, irrigation cycles, harvesting procedures and maintenance routines can be programmed and executed automatically. Aydogan and Tas (2021) demonstrated the application of fuzzy logic control systems in aquaponics, showing improved decision-making capabilities in complex, multi-variable control scenarios.

Remote management capabilities enable system operators to monitor and control systems from anywhere with internet connectivity. Web-based control interfaces and mobile applications provide comprehensive control capabilities while maintaining security and user authentication. These systems are particularly valuable for commercial operations and research facilities where continuous oversight is required.

Smart indoor farming: Key challenges and solutions

Smart indoor farming using aquaponics systems presents unique opportunities and challenges that require innovative technological solutions. The controlled environment advantages of indoor systems enable year-round production, protection from weather extremes and precise environmental control, but also require sophisticated environmental management systems and higher energy inputs (Shamshiri *et al*., 2018).

Lighting systems represent one of the most critical and energy-intensive components of indoor aquaponics systems. LED technology has revolutionized controlled environment agriculture by providing energy-efficient, spectrally tunable lighting that can be optimized for specific crops and growth stages. The integration of LED systems with Arduino-based control platforms enables sophisticated lighting strategies that can enhance plant growth while minimizing energy consumption (Barzee *et al*., 2021).

The present review was conducted in the PG and Research Department of Microbiology, Cauvery College for Women (Autonomous), Tiruchirappalli, Tamil Nadu, India, over a period of one year (June 2023-May 2024). Relevant literature on Arduino-based automated aquaponics systems was systematically collected from databases such as PubMed, Scopus, ScienceDirect, SpringerLink, Elsevier and Google Scholar.

Studies published between 2010 and 2024 focusing on cost-effectiveness, sustainability and productivity in aquaponics-particularly those related to legume cultivation-were reviewed.

Table 1 highlights the performance efficiency of the smart indoor aquaponics system compared to traditional farming, showing that yield per square meter is 3-10 times higher and water productivity is 10-50 times more efficient due to closed-loop nutrient recirculation and minimal water loss.While the energy input is relatively higher due to automation and environmental control (2-10× increase), this is offset by the significant savings in land use (up to 100× reduction) and labor costs, as the system requires minimal manual monitoring and maintenance.

Space utilization optimization is particularly important in indoor systems where real estate costs are typically higher than outdoor installations. Vertical growing systems, dense planting strategies and efficient system layouts can significantly improve productivity per square foot. The automation of vertical systems requires sophisticated control systems that can manage multiple growing levels independently while maintaining system integration.

Energy efficiency considerations are paramount in indoor aquaponics systems due to the high energy requirements for lighting, heating, cooling and system operation. Energy management systems using Arduino

Table 1: Production efficiency and yield comparison.

Metric	Smart indoor aquaponics	Traditional farming	Improvement factor	Space utilization	Resource efficiency	Labor requirements	References
Yield per m²	10-50 kg/m²/year (leafy greens)	2-8 kg/m²/year	3-10× higher	Vertical growing, high density	Optimized nutrition, controlled environment	Automated systems, reduced manual work	Barbosa *et al.* (2015)
Water productivity	5-20 L/kg produce	50-300 L/kg produce	10-50× more efficient	Recirculation, minimal losses	Closed-loop system, no runoff	Automated irrigation, monitoring	Barzee *et al.* (2021)
Growing cycles/ year	6-12 cycles (lettuce)	2-4 cycles (lettuce)	2-3× more cycles	Controlled environment, no seasons	Optimal conditions year-round	Continuous harvesting possible	Lennard and Leonard (2006)
Nutrient efficiency	85-95% uptake efficiency	30-50% uptake efficiency	2-3× more efficient	Precise delivery, recirculation	No leaching, targeted application	Automated nutrient monitoring	Bailey and Ferrarezi (2022)
Land use	0.1-1 m² footprint/m² growing	1 m² land/m² growing	10-100× reduction	Multi-level systems, stacking	Minimal land footprint	Reduced field preparation	FAO (2014)
Energy input	30-200 kWh/m²/ year	5-20 kWh/m²/ year (equivalent)	2-10× higher energy use	Lighting, climate control, pumps	High energy for environmental control	Automated energy management	Shamshiri *et al.* (2018)

platforms can implement demand response strategies, optimize equipment scheduling and integrate renewable energy sources to minimize operational costs. Barbosa *et al.* (2015) compared energy requirements of different growing methods, highlighting opportunities for efficiency improvements in indoor systems.

Air quality management in indoor environments requires monitoring and control of CO2 levels, humidity and air circulation patterns. Elevated CO2 levels can enhance plant growth, but require careful management to avoid affecting fish health in integrated systems. Automated ventilation systems using Arduino-based controllers can maintain optimal air quality while minimizing energy losses.

Plant disease and pest management in indoor environments requires different strategies than outdoor systems. While the controlled environment provides protection from many outdoor pests, it can also create conditions favorable for specific indoor pests and diseases. Automated monitoring systems can detect early signs of plant stress and disease, enabling rapid intervention and treatment.

Quality control and harvesting automation represent advanced capabilities that can significantly improve labor efficiency and product consistency. Automated harvesting systems for leafy greens and herbs can operate continuously, maintaining optimal plant density and harvest timing. Vision-based quality control systems using Arduino-compatible cameras can identify harvest-ready plants and detect quality issues.

Legume cultivation and sprout production in automated aquaponics

Legume cultivation in aquaponics systems presents unique opportunities and challenges that can be effectively addressed through Arduino-based automation systems. Legumes, including beans, peas, lentils and chickpeas, offer high nutritional value and nitrogen-fixing capabilities that can benefit overall system nutrient dynamics (Hu *et al.*, 2015). The sprouting process further enhances the nutritional profile of legumes, making automated sprout production an attractive application for aquaponics systems.

The nutritional benefits of sprouted legumes are well-documented, with sprouting processes increasing protein bioavailability, vitamin content and digestibility while reducing antinutritional factors (Fernández-Ochoa *et al.*, 2020). Mubarak (2005) demonstrated significant improvements in nutritional composition of mung bean seeds through sprouting, showing increases in protein content and reductions in antinutritional compounds. These nutritional enhancements make sprouted legumes valuable crops for aquaponics systems focused on producing high-quality food products.

Table 2 provides further support by demonstrating optimized growth conditions for multiple legume varieties, where precise Arduino-based sensor control reduces wastage of water and nutrients by ensuring optimal temperature, pH and humidity levels. These parameters

Table 2: Comprehensive analysis of legume varieties, growing conditions and production parameters.

Legume type	Sprouting duration	Optimal temperature (°C)	Humidity (%)	pH range	Irrigation frequency	Yield (kg/m²)	Nutritional enhancement	Arduino sensors required	Automation level	Food safety considerations	Production challenges	References
Mung bean	3-5 days	20-25°C	85-90%	6.0-7.0	Every 4-6 hours	15-25 kg/m²	Vitamin C: +300%, Protein: +25%	Temperature, humidity, pH, water level	High	*E. coli* prevention, sanitization	Root rot, mold growth	Henares *et al.* (2020); Mubarak (2005)
Alfalfa sprouts	4-6 days	18-22°C	80-85%	6.5-7.5	Every 6-8 hours	12-20 kg/m²	Antioxidants: +200%, Vitamins A,C,K	Temperature, humidity, light sensor	High	Salmonella risk, washing protocols	Slow germination, fiber content	FDA (2017); Gan *et al.* (2017)
Lentil sprouts	2-4 days	20-24°C	85-90%	6.0-7.0	Every 4-6 hours	18-28 kg/m²	Folate: +250%, Iron: + 40%	Temperature, humidity, conductivity	Medium	Minimal pathogen risk	Short shelf life, delicate handling	Fernández-Ochoa *et al.* (2020)
Chickpea sprouts	4-7 days	22-26°C	80-85%	6.5-7.5	Every 6-8 hours	20-30 kg/m²	Protein: +35%, Lysine: +45%	Temperature, humidity, pH, timer	Medium	Moderate safety requirements	Hard seed coat, variable germination	Sharma *et al.* (2016)
Black bean sprouts	3-5 days	21-25°C	85-90%	6.0-7.0	Every 4-6 hours	16-24 kg/m²	Anthocyanins: +400%, Fiber: +20%	Temperature, humidity, light, pH	High	Standard sprouting protocols	Color bleeding, shorter sprouts	Khattab and Arntfield (2009)
Pea sprouts	5-8 days	18-22°C	80-85%	6.5-7.5	Every 6-8 hours	14-22 kg/m²	Vitamin C: +150%, Beta -carotene: +80%	Temperature, humidity, CO_2, light	High	Low contamination risk	Requires support, longer cycle	Donkor *et al.* (2012)
Soybean sprouts	4-6 days	22-26°C	85-90%	6.0-6.8	Every 4-6 hours	20-32 kg/m²	Isoflavones: +60%, Complete protein	Temperature, humidity, pH, dissolved oxygen	Very high	FDA guidelines compliance	Complex nutrient requirements	Martínez-Villaluenga *et al.* (2020)
Fenugreek sprouts	3-5 days	20-24°C	80-85%	6.5-7.0	Every 6-8 hours	12-18 kg/m²	Minerals: +80%, Medicinal compounds	Temperature, humidity, conductivity	Medium	Bitter compounds, processing needed	Strong flavor, market acceptance	Hati *et al.* (2022)

minimize crop loss and improve nutrient yield, thereby enhancing cost efficiency over time.

Food safety considerations are particularly important in sprout production due to the warm, moist conditions that can promote pathogenic bacterial growth. The FDA (2017) has established specific guidelines for sprout production to minimize microbial food safety hazards. Automated monitoring systems can continuously track critical control points and provide documentation for food safety compliance. The integration of UV sterilization systems and automated cleaning procedures can further enhance food safety in automated sprouting systems.

Henares *et al*. (2020) demonstrated the successful cultivation of mungbean in aquaponics systems, showing comparable or superior performance to hydroponic systems. The integration of legume cultivation with fish production creates beneficial interactions, with legume root nodules potentially contributing to system nitrogen cycling. However, this requires careful management of rhizobia inoculation and root zone conditions.

Automated harvesting systems for sprouts can significantly reduce labor costs while maintaining product quality and safety. Timing of harvest is critical for sprout quality, with optimal harvest typically occurring 3-7 days after initiation depending on the legume variety and desired sprout characteristics. Arduino-based systems can automate harvest timing based on environmental monitoring and predetermined growth parameters.

Table 3 demonstrates that sprouting significantly enhances the nutritional quality of seeds compared to fresh seed baselines, with automated aquaponic sprouting showing the most pronounced improvements. Protein content increases due to enzymatic activation during germination, which leads to the breakdown of storage proteins into more digestible amino acids. The precise control of temperature and pH using Arduino-based systems ensures consistent metabolic activation, resulting in higher protein retention and improved amino acid profiles.

The integration of sprouting systems with aquaponics requires careful consideration of water quality and nutrient cycling. Sprout production typically requires clean water with minimal dissolved nutrients, while aquaponic systems are characterized by nutrient-rich water. This can be addressed through water treatment systems or separate water supplies for sprouting operations.

Quality optimization in automated sprout production involves controlling factors that influence sprout appearance, texture, taste and nutritional content. Controlled atmosphere storage, optimal harvest timing and post-harvest handling procedures can be automated to maximize product quality. Sharma *et al*. (2016) demonstrated improvements in functional properties of sprouted legumes through controlled processing conditions.

Comparative cost analysis

- When compared to conventional aquaponics systems and other automation models (*e.g.*, PLC or Raspberry Pi-based systems), the Arduino-controlled system offers a 25–30% reduction in initial setup cost. This is attributed to the use of open-source components, low-cost sensors and recycled or locally availabl materials for grow beds and tanks.
- Maintenance and operation costs are also reduced due to lower power consumption by microcontrollers and automated irrigation, which minimizes human intervention and resource waste.
- The integration of modular design allows scalability without significant additional investment, further enhancing economic feasibility.

Nutrient content enhancement through automation

Automated aquaponic systems offer significant potential for optimizing nutrient content in crops, particularly legumes and sprouts. Controlled environmental conditions, nutrient delivery and harvest timing enhance nutritional value while ensuring consistent quality. Sprouting under automated conditions improves protein digestibility, amino acid availability and vitamin content, especially vitamin C. LED-based light regulation, temperature and humidity control further support nutrient synthesis and bioactive compound accumulation. Studies report increases in antioxidants, phenolics and secondary metabolites under optimized stress protocols. Additionally, automated post-harvest handling preserves nutrients and extends shelf life, while precise nutrient delivery enables effective biofortification with essential minerals such as iron, zinc and selenium.

Discussion and future research scope

Arduino-based automation in aquaponics marks a major advancement in sustainable agriculture by offering cost-effective, customizable and open-source solutions that replace expensive proprietary systems. Automation minimizes manual supervision through sensor-driven monitoring and control of parameters such as temperature, pH, nutrient flow and water levels. Studies by Barbosa *et al*. (2015) and Barzee *et al*. (2021) demonstrated that automated aquaponic systems can reduce manual labor by 40-60%, while Shamshiri *et al*. (2018) reported a 20-30% reduction in operational labor costs through decreased dependence on skilled labor.

Indian research supports these global findings. Sughuna *et al*. (2021) developed a recirculatory aquaponics model in Andhra Pradesh that achieved higher yields with minimal labor through semi-automation. The Department of Fisheries (2020) documented that integrated aquaponics can produce up to five times higher fish yield per unit area while simultaneously generating horticultural crops, reinforcing the system's cost-effectiveness and resource efficiency in Indian conditions. Similarly, Bhanja (2023) in the Agriculture Journal highlighted India's increasing adoption of Arduino- and IoT-based aquaponics, reporting significant reductions in labor input, water use and resource wastage compared to conventional soil-based systems.

Additional Indian literature strengthens this context. The Journal of Inland Fisheries Society of India (2025)

Table 3: Nutritional enhancement and quality optimization.

Nutritional parameter	Fresh seed baseline	Traditional sprouting	Automated aquaponic sprouting	Enhancement factor	Optimization methods	Arduino control parameters	Quality indicators	Shelf life extension	References
Protein content (g/100 g)	20-35 g	22-38 g	25-42 g	1.2-1.4×	Controlled temperature, optimal pH	Temperature± 0.5°C, pH ±0.1	Amino acid profile analysis	2-3 days longer	Fernández-Ochoa *et al.* (2020)
Vitamin C (mg/100 g)	0-5 mg	15-35 mg	25-60 mg	5-12×	Light spectrum control, temperature	LED spectrum control, thermal management	Ascorbic acid assay	1-2 days longer	Gan *et al.* (2017)
Folate (µg/100 g)	50-150 µg	80-200 µg	120-300 µg	2-4×	Optimal sprouting duration, humidity	Timer control, humidity sensors	HPLC analysis	Similar to traditional	Mubarak (2005)
Iron bioavailability	30-50% available	50-70% available	600-85% available	1.2-2.8×	pH optimization, phytase activation	pH control, temperature profiles	Iron absorption studies	Not significantly affected	Khattab and Arntfield (2009)
Antioxidant activity	Low-moderate	Moderate-high	High-very high	2-5×	Controlled stress conditions	Light stress, temperature cycling	DPPH, ORAC assays	2-4 days longer	Hati *et al.* (2022)
Digestibility (%)	65-80%	75-90%	80-95%	1.2-1.5×	Enzyme activation optimization	Time, temperature, moisture control			Gan *et al.* (2017)

emphasized aquaponics as a sustainable food production system with high yield potential and low environmental impact. Likewise, ARCC Journals have contributed valuable insights: Agricultural Reviews discussed aquaponics as part of strategies promoting sustainability and climate resilience through circular nutrient recycling, while Agricultural Science Digest presented a comparative study of hydroponic and soil-based spinach cultivation, providing relevant evidence on soilless system performance and resource efficiency that parallels aquaponic advantages.

Although Arduino-based automation involves slightly higher energy consumption due to continuous sensor operation, the overall production cost per kilogram of yield is significantly reduced owing to improved productivity, optimized water and nutrient management and reduced labor costs. Collectively, these findings enhance the economic feasibility and sustainability of aquaponics, particularly for small- and medium-scale farmers in India. To ensure scalability and long-term reliability, future research should focus on AI-driven predictive control, blockchain-based traceability and comprehensive cost-benefit analyses tailored to India's climatic and socio-economic conditions.

CONCLUSION

Arduino-driven aquaponics automation has emerged as a promising approach to advance sustainable agriculture by combining affordability, efficiency and adaptability. These systems improve productivity and resource management while offering significant potential to address food security in regions with limited land and water. Renewable energy integration and modular scalability add to their economic and environmental viability. However, broader adoption requires solutions for challenges such as interoperability, standardization and system expansion. Future progress lies in incorporating artificial intelligence, predictive control and robust design frameworks. With continued innovation and training, Arduino-based aquaponics can evolve into a resilient and scalable model for global food production.

Conflict of interest

The authors declare that there are no Conflict of interest.

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