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Original Article

Aquaponics Production of Indian Catfish *Clarias magur* (Hamilton, 1822) Integrated with Lettuce (*Lactuca sativa* L.): Comparison with Controlled and Conventional Production Systems

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Abstract

The integration of aquaculture and hydroponics through aquaponics has emerged as a promising strategy to address the increasing demand for sustainable food production under conditions of limited land and freshwater resources. Fish performance was compared among aquaponic, recirculating aquaculture, and conventional tank systems, while lettuce productivity was assessed under aquaponic, hydroponic, and conventional soil-based cultivation across five consecutive 42-day crop cycles (CC1–CC5). Aquaponics significantly improved water quality by reducing residual ammonia, nitrite, phosphate, electrical conductivity, and total dissolved solids while maintaining dissolved oxygen and pH within favourable ranges for fish growth ($p < 0.05$). Consequently, *C. magur* reared in AQPS1 exhibited superior growth performance, achieving the highest final weight (143.05 ± 13.04 g), specific growth rate (2.43 ± 0.11% day^{-1}), thermal growth coefficient (0.78 ± 0.01), survival rate (95.83 ± 2.89%), and net biomass yield (5448.96 ± 98.53 g), together with the lowest feed conversion ratio (2.21 ± 0.03) ($p < 0.05$). For lettuce production, aquaponics progressively outperformed hydroponic and soil-based systems as the system matured, recording the highest plant biomass (58.43 ± 9.66 g) and maximum yield of 1168.77 ± 63.05 g m^{-2} during the third crop cycle. These findings demonstrate that NFT-based aquaponics effectively couples fish and vegetable production while enhancing nutrient recycling, improving water quality, increasing productivity, and reducing environmental losses compared with conventional systems. The integration of *C. magur* and lettuce therefore represents a viable and climate-resilient food production model with considerable potential for adoption in resource-constrained regions of developing countries.

Keywords: *Aquaponics; Clarias magur; Lactuca sativa; Nutrient Recycling; Sustainable Aquaculture*

Introduction

The sustainability of traditional agriculture is increasingly pressured by declining productivity of the soils, long-term decreases in soil fertility due to continuous cropping, and a decreasing amount of land available for agriculture per person (Lambin, 2012; Lehman *et al*., 2015; Majid *et al*., 2020). Climate change and its negative effects, such as increased temperatures, increased frequency of droughts and increased unpredictability of weather, as well as unsustainable practices in watersheds and irrigation, are leading to excessive water use, contamination of surface waters and a decreased groundwater table (Bhanja *et al*., 2018). These interconnected factors will together reduce the reliability and productivity of traditional agricultural systems and contribute to the greater challenges in food production (Majid *et al*., 2020).

Therefore, there is an evident need to supplement traditional agriculture practices with more productive and ecologically sustainable ways of food production (Lambin & Meyfroidt, 2011). In response to the pressures facing traditional agriculture, intensive urban and controlled environment techniques such as

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recirculating aquaculture systems (RAS) and hydroponics are being researched (Texier, 2020; Oladimeji *et al*., 2020; Majid *et al*., 2020). Both these closed-loop systems recycle water and hence reduce the need for fresh water and their environmental footprint (Timmons *et al*., 2002; Verdegem, 2013). However, both systems have practical limitations, as RAS require periodic water changes to avoid accumulation of nitrogen-based wastes in excessive concentrations that could be harmful to fish (Yildiz *et al*., 2017; Oladimeji *et al*., 2020) and hydroponics rely on continuous replenishment of nutrients to satisfy crop demands (Sonneveld & Voogt, 2009; Pantanella *et al*., 2012; Love *et al*., 2015). On the other side, the tank culture of fish suffers from many challenges, including rapid degradation of water quality, rapid increase of toxic nitrogenous wastes and high-water consumption. All of these factors create risks to health as well as the survivability of the fish, and higher operating costs (Hashmi *et al*., 2025).

There is potential for improvements in sustainability and productivity when using these technologies together, integrating RAS with hydroponics to create an aquaponic system. Aquaponics system capitalizes on the natural symbiosis between fish and plants, where fish waste provides an organic nutrient source for the plants, and the plants, in turn, purify the water for the fish (Shafahi & Woolston, 2014; Mandal *et al*., 2023; Bhanja *et al*., 2024). Plants rely on nitrogen and phosphates from fish excretion for cellular growth and development in aquaculture systems (Lucas *et al*., 2019). A distinguishing feature of aquaponic systems is their efficient use of space, which has spurred the growth of urban aquaponics. This trend is transforming how we view agriculture, leading to innovative applications such as urban farming, urban gardening, terrace gardening, vertical gardening, and even indoor office farms. These practices are revolutionizing food production in densely populated areas (Eigenbrod & Gruda, 2015).

McMurtry *et al*. (1990) were among the first to design an aquaponic system that integrated fish, plants, and microbial units, conducting studies on blue tilapia (*Sarotherodon aureus* L.) alongside plants such as bush beans (*Phaseolus vulgaris* L.), cucumbers (*Cucumis sativus* L.), and tomatoes (*Lycopersicon esculentum* Mill.) in a greenhouse environment. Several tropical and temperate fish species, such as tilapia, catfish, sea bass perch, etc. have been identified as optimal candidates for integration into fish-plant integrated culture facilities worldwide (Mchunu *et al*., 2017). Similarly, various leafy vegetables and other plants, including lettuce, spinach, money plant, tomato, capsicum, cucumber, cabbage, carrots, mint, etc., are commonly cultivated within aquaponics systems (Effendi *et al*., 2017). Numerous studies have evaluated various fish–plant pairings within aquaponic systems to optimize both biological and economic outcomes. For instance, *Oreochromis niloticus* (tilapia) has been integrated with *Solanum lycopersicum* (tomato) (Watten & Busch,1984; McMurtry *et al*.,1997) and nile tilapia with *Lactuca sativa* (lettuce) (Ani *et al*., 2022). Co-cultivation of *Abelmoschus esculentus* (okra) and *Ocimum basilicum* with tilapia (Rakocy *et al*., 2004), and *Lactuca sativa* paired with *Maccullochella peelii* (Murray cod) (Lennard & Leonard, 2006).

The selection of species for aquaponics systems is crucial to optimizing their productivity and sustainability (Bambhaniya *et al*., 2023). This study focused on the Indian catfish (*Clarias magur*) and Lettuce (*Lactuca sativa*) due to their high nutritional value, significant market demand, and proven compatibility with aquaponic environments. *Clarias* species are known for their rapid growth rate and adaptability, serves as an ideal aquaculture candidate species (Haymer & Khedkar, 2022). At the same time, Lettuce (*Lactuca sativa*), a popular leafy vegetable, thrives in hydroponics and is a staple in diverse diets worldwide (Mulabagal *et al*., 2010; Kumar *et al*., 2010). Lettuce plants are recognized for their efficient absorption of nutrients from water, capable of reducing up to 90.1% and 23.3% ammonia and nitrate, respectively, in aquaponics systems (Effendi *et al*., 2015). It has been commercialised globally and can command higher market prices due to its nutritional value (Abu-Rayyan *et al*., 2004). Lettuce cultivation with protected conditions has been promoted in recent years, but the crop production techniques for lettuce have not yet been standardised (Abdullah *et al*., 2004; Spehia *et al*., 2018). In the latest studies, lettuce growth has only been measured in aquaponic and hydroponic systems (Delaide *et al*., 2016). Lettuce is one of the most studied crops around the world using different hydroponic models, especially deep-water culture and nutrient film technique (Safaei *et al*., 2015). The

NFT system provides high oxygen to the plant roots that facilitates high yield of vegetables (Wongkiew *et al*., 2017).

This study evaluated the specific growth rate (SGR) of *Clarias magur* and the survival rates in different aquaponics treatments, along with the lettuce yields. The concept of aquaponics remains relatively uncommon in many underdeveloped and developing countries worldwide (Oladimeji *et al*., 2020). That's why the findings of this study are expected to underscore the efficiency of the aquaponics system compared to hydroponics, traditional soil culture of planting, RAS, and control tank culture of fish rearing.

Materials and Methods

Study Area and Period

The study was conducted at an experimental aquaponics research facility located in Barsolemanpur, Ramnagar, Purba Medinipur, West Bengal 721441, India. The fish-plant culture experiment was conducted over a seven-month period (30 weeks), from June to December 2023, with each experimental treatment maintained in triplicate. The study site lies between the coordinates of 21°40'34.6"N and 87°34'14.6"E.

Experimental Design

The experiment was conducted to compare the growth performance of magur (*Clarias magur*) and lettuce (*Lactuca sativa*) in integrated aquaponics and conventional culture systems for the assessment of the efficiency of the aquaponics configuration. Three treatments of magur were established: Aquaponics fish tank (AQPS1), recirculatory aquaculture system (RASS1) and control tank system (CTRLTS1). Each treatment was maintained in triplicate using three independent experimental units (n = 3). Simultaneously, three lettuce plant treatments were carried out: aquaponics plant channel (AQPP1), hydroponics (HYDP1) and conventional soil culture (CONVP1), with three independent replicates for each treatment (n = 3).

The aquaponics system (AQP) was set up using a Nutrient Film Technique (NFT) comprising a fish rearing tank (200 L), a mechanical filter (50 L) and a biological filter (50 L) for nitrification. Water for rearing fish was continuously circulated through the NFT plant channels and returned to the fish tank to make a closed-loop recirculation (Figure 1 and Figure 2). The loading rate remained constant at 2.88 m day-1 throughout the experiment. The structural dimensions and component specifications of the AQP unit are shown in Table 1. AQPS1 and RASS1 were added daily to the tank at a rate of 5% of the total water volume to account for evaporation and losses caused by plant transpiration (Maucieri *et al*., 2018). Partial water changes (30-40% of total volume) were made three times weekly in CTRLTS1. For static or conventional tank systems, water changes are important to maintain water quality, fish growth and limit accumulation of nitrogenous wastes (Okomoda *et al*., 2016).

Forty randomly selected magur (*Clarias magur*) fingerlings with a mean initial body weight of 0.92 ± 0.10 g were stocked in each 200 litre (0.2 m^3) tank of aquaponics (AQP), Recirculatory Aquaculture System (RAS) and Control tank (CTRLT) treatments. The same stocking density was maintained across all triplicate systems to ensure comparable initial stocking densities. The stocking density was within the range reported for aquaponics and intensive catfish culture systems (Suprapto & Samtafsir, 2013; Pamula, 2019; Oladimeji *et al*., 2020; Knaus *et al*., 2020; Yeşiltaş *et al*., 2021; Rahman *et al*., 2021; Sabwa *et al*., 2022; Wiyoto *et al*., 2023).

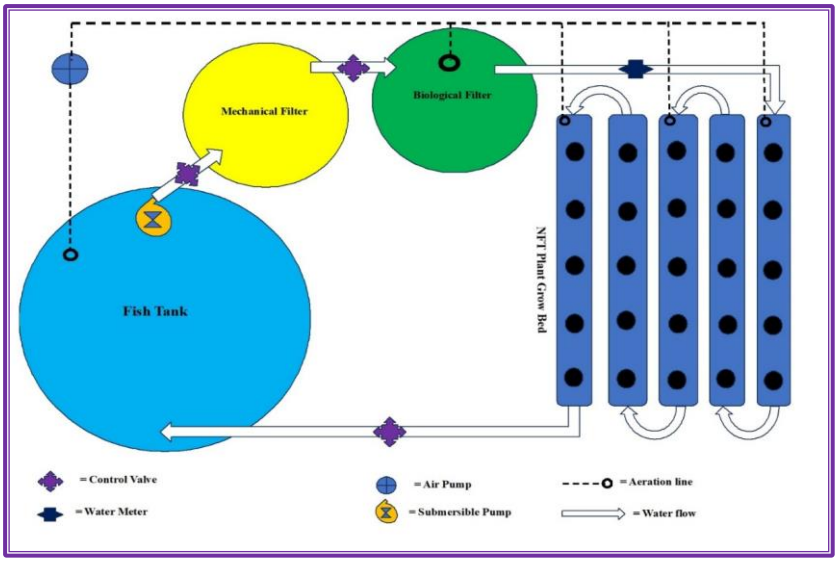


Figure 1: *Layout of the Aquaponics System*



Figure 2: *Integration of Clarias magur with Lactuca sativa in NFT Aquaponics System*

Table 1: *Structural Design and Dimension Specifications of the Aquaponics System*

Sl. No.	Tanks	Dimensions
1	Fish rearing tanks	200 L (0.2 m^3)
2	Mechanical filter tank	50 L (0.05 m^3)
3	Biofilter tank	50 L (0.05 m^3)
4	Volume of water in the system	370 L (0.37 m^3)
5	Hydraulic Loading Rate (HLR)	2.88 $m.day^{-1}$
6	Hydraulic Retention Time (HRT)	34.56 min
7	Land area occupied by the rearing tank, including filtration systems	20 ft^2
8	Land area occupied by the hydroponics system	18 ft^2

Fish were provided with a commercial pelleted feed (Growel Growfin®) with graded crude-protein levels appropriate for the growth stage (30%, 32%, 38% and 40% CP). Proximate composition of the commercial feed is shown in Table 2. The feeding rate was varied between 2% and 10% of the body weight. The feeding regime was adjusted periodically based on observations of feed acceptance and fish growth.

Table 2: *Proximate Composition of the Commercial Diet Used to Fed C. magur in This Study*

Die Size (mm)	Crude Protein (%)	Crude Fat (%)	Crude Fibre (%)	Moisture (%)
0.6	40.0	6.0	3.0	12.0
0.8	40.0	6.0	3.0	12.0
1.2	38.0	6.0	3.0	12.0
1.8	30.0	5.0	5.5	12.0

Lettuce seeds were obtained from 'All That Grows' farm and germinated using cocopeat as the nursery medium. Following 20 days of germination, twenty healthy and uniform seedlings were selected for each treatment, AQPP1, HYDP1 and CONVP1, at a planting density of 20 plants m^{-2}. The seedlings were then carefully transferred to the net pots supported with clay balls and placed in the NFT channels. The conventional soil-culture treatment (CONVP1) was maintained adjacent to the shade-net aquaponics research facility. The soil of the experiment site was characterized as sandy loam. Periodic irrigation was applied to maintain optimum soil moisture conditions for lettuce growth. Throughout the study period, plants were monitored for pest infestations and nutrient deficiencies. Eco sticky traps were also used to manage pests safely without risking water contamination or harming aquatic biomass.

Measurement of Water and Soil Quality Parameters

Water quality parameters were regularly monitored to ensure optimal conditions for the aquaponics system. Temperature was measured using the SKADIOO digital water temperature meter (range: -50~ 110°C and ±1°C accuracy). TDS (Total Dissolved Solids) was measured with the A1 Portable TDS Meter (range: 1~9990ppm and ± 2% accuracy); Electrical Conductivity (EC) Meter (Range: 1~9990us/cm and Resolution: 1ppm and 1us/cm). Water pH was tracked using a Digital pH meter [PH-009(I)A]. DO, NH_3, NO_3^-, NO_2^-, Phosphate, and Alkalinity were measured following the American Public Health Association (APHA) 1926 standard methods and tested at the general laboratory of the Department of Fishery Sciences, Vidyasagar University.

The soil pH and electrical conductivity (EC) were determined by the method of Jackson *et al*. (1973). Total Nitrogen (N) content was estimated by the alkaline permanganate method as given by Subbiah and Asija (1956). The available phosphorus (P) was obtained by the Olsen method (Olsen, 1954), and the available potassium (K) was determined by the method of Metson (1956). Gravimetric moisture content (w), soil bulk density (Bd), particle density (Pd), and soil porosity (Sp) were analysed using the standard protocols (Bilskie, 2001; Rai *et al*., 2017; Schwyter & Vaughan, 2020; Food and Agriculture Organization (FAO), 2023; Ahmad *et al*., 2025).

Fish and Plant Growth & Production Determination

A Vernier caliper (111022 Plain Vernier; accuracy of ±0.01 mm), a plastic ruler scale closest to 0.1cm, and ImageJ software (v1.54) were used in different length measurements of magur and lettuce. The weight was recorded using a digital weighing scale (V 600-W) with an accuracy of ±0.01 g. Leaf area of lettuce (cm^2) was measured using ImageJ software (v1.54) and a centimetre graph.

The key parameters observed in this study were the survival rate and growth rate of *Clarias magur*. The growth performance and related indices were assessed following the methods adopted by Jhingran (1982), Ridha and Cruz (2001); Kordi (2009), Mizanur & Bai (2014), Okomoda *et al*. (2017); Maranga *et al*. (2023):

$$SGR(\%) = \left(ln\left(W_f(g)\right) - ln\left(W_i(g)\right)\right)/D_e \times 100$$

Where SGR = Specific Growth Rate (%/day), Wf = mean final weight (g) at the end of the experiment, Wi = initial weight (g) at the time of stocking, and De = Days of the experiment.

$$DGR\ (\%) = \frac{W_f}{D_e} \times 100$$

Where DGR = Daily Growth Rate (%), Wf= Final weight (g) at the end of the experiment, De = Days of the experiment.

$$SR(\%) = F_e/F_i \times 100$$

Where SR = Survival Rate (%), F_e = final number of fish at the end of the rearing period, and F_i = initial number of fish stocked for this experiment.

$$FCR = \frac{Total\ feed\ intake(g)}{W_f - W_i(g)}$$

Where FCR = Feed Conversion Ratio, (Wf -Wi) = Total weight gain (g)

$$PER = \frac{(W_f - W_i)\ (g)}{\text{Total protein intake (g)}}$$

Where PER = Protein Efficiency Ratio, (Wf -Wi) = Weight gain (g)

$$\text{TGC} = \frac{\frac{1}{3}(W_f - W_i)}{MWT \times D_e} \times 1000$$

Where TGC = Thermal Growth Coefficient, Wf = Final weight (g) at the end of the experiment, Wi = initial weight (g) at the time of stocking, MWT = Mean water Temperature (oC), De = Days of the experiment.

$$\text{Fold Increase (x)} = \frac{Final\ Weight}{Initial\ weight}$$

Where Fold Increase (x) means Times/Fold

Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistics Version 27.0 for Windows. Mean values for fish weight and length, lettuce length, and water quality parameters across the treatments were compared using a one-way analysis of variance (ANOVA) model to determine significant differences. Where ANOVA indicated significance, post-hoc comparisons were made using Tukey's test. Graphical representation of the results was performed using Microsoft Excel 2021 and OriginPro (version 2024b) software. The confidence interval was set at 95%, and all results are expressed as mean ± standard deviation (SD). Statistical significance was determined at $p < 0.05$.

Results

Water Quality Parameters

The analysis of physicochemical parameters of water in the fish rearing tanks showed differences between the three treatments (AQPS1, RASS1, CTRLTS1) during the thirty-week culture period (Table 3). Water quality parameters in AQPS1 and RASS1 were in the acceptable range for sustainable aquaculture (Ajani *et al*., 2011).

Table 3: *Physico-Chemical Parameters of Water from Different Fish Culture Systems*

Sl. No.	Water Quality Parameters	Aquaponic System (AQPS1)	Recirculatory Aquaculture System (RASS1)	Control Tank System (CTRLTS1)	*p*-value	Significance
1	Temperature (°C)	26.06 ± 2.62^a	26.2 ± 2.59^a	27.07 ± 2.35^a	0.868	ns
2	pH	7.45 ± 0.09^a	7.51 ± 0.1^a	6.88 ± 0.28^b	0.009	**
3	DO (mg L^{-1})	6.08 ± 0.3^a	6.15 ± 0.29^a	4.89 ± 0.17^b	0.001	***
4	EC (µS/cm)	661.35 ± 41.49^c	711.45 ± 47.78^b	779.19 ± 37.87^a	0.02	*
5	TDS (mg L^{-1})	329.16 ± 24.96^c	370.32 ± 28.21^b	422.48 ± 22.37^a	0.01	*
6	NH_3 (mg L^{-1})	0.11 ± 0.06^c	0.4 ± 0.16^b	1.79 ± 0.88^a	<0.001	***
7	NO_3^- (mg L^{-1})	5.61 ± 2.28^b	7.07 ± 2.38^a	3.13 ± 1.03^c	0.001	***
8	NO_2^- (mg L^{-1})	0.21 ± 0.06^b	0.44 ± 0.1^b	1.22 ± 0.29^a	<0.001	***
9	Phosphate (mg L^{-1})	0.24 ± 0.08^c	0.33 ± 0.09^b	0.42 ± 0.1^a	0.03	*
10	Alkalinity (mg L^{-1})	116.65 ± 10.38^a	121.13 ± 9.32^a	96.29 ± 9.1^b	0.01	*

*Note: Values are presented as mean ± SD. Different superscripts within the same row indicate significant differences among different cultures at p<0.05. Significant levels are denoted as *p<0.05, **p<0.01, ***p<0.001, and ns = non-significant.*

Soil Characters

The field soil used for conventional soil cultivation of lettuce (CONVP1) exhibited favourable characteristics for leafy vegetable production (Table 4).

Table 4: *Physico-Chemical Properties of Soil Used for the Conventional Culture of Lettuce (CONVP1)*

Sl. No.	Soil Properties	Unit	Value (Mean ± SD)
1	Texture classification	ISSCS	Sandy loam
2	pH	-	6.8 ± 0.26
3	Electrical Conductivity (EC)	dS/m	0.70 ± 0.016
4	Total Nitrogen (TN)	%	0.15 ± 0.03
5	Available Phosphorus (P)	Kg/ha	32.29 ± 3.81
6	Available Potassium (K)	Kg/ha	196.45 ± 9.36
7	Gravimetric moisture content (w)	%	18.04 ± 0.43
8	Soil bulk density (Bd)	g/cm^3	1.3 ± 0.06
9	Particle Density (Pd)	g/cm^3	2.67 ± 0.1
10	Soil Porosity (Sp)	%	51.31 ± 1.25

Growth of Magur

At the beginning of the seven-month experimental period, magur in the AQP system had a mean initial length of 4.84 ± 0.25 cm and mean initial weight of 0.88 ± 0.19 g, which increased to a mean final length of 25.73 ± 0.65 cm and mean final weight of 143.05 ± 13.04 g at the end of the seven-month experimental period. Relatively, in RAS, magur grew from a mean initial length of 5.08 ± 0.17 cm and mean initial weight of 1.04 ± 0.12 g to a final mean length of 24.49 ± 0.51 cm and final mean weight of 118.98±9.75 g. Lastly magur grew from mean initial length 4.85 ± 0.2 cm and 0.85 ± 0.14 g initial weight to 22.74 ± 1.56 cm final mean length and 96.84 ± 19.58 g final mean weight in CTRLT system at the end of the seven-month experimental period (Table 5). The weekly growth trend is significantly different ($p < 0.01$) among the three treatments (Figures 3 and 4). Under AQP rearing, survival was higher (95.83 ± 2.89) than in the RAS system (90.83 ± 1.44) and in the CTRLT system (79.17 ± 5.20) at the end of the 210-day experimental period (Figure 5). However, the superior performance of AQP and RAS over the Conventional culture system (CTRLT) also indicates that an optimal environmental matrix can serve as a sustainable and efficient production system for fish and support enhanced growth performance (Figure 6).

Table 5: *Growth Parameters of Magur Reared in Three Different Culture Systems*

Magur Growth Parameters	Aquaponic System (AQPS1)	Recirculatory Aquaculture System (RASS1)	Control Tank System (CTRLTS1)	*p*-value	Significance
Initial Length (cm)	4.84 ± 0.25^{a}	5.08 ± 0.17^{a}	4.85 ± 0.2^{a}	0.362	ns
Final Length (cm)	25.73 ± 0.65^{a}	24.49 ± 0.51^{ab}	22.74 ± 1.56^{b}	0.031	*
Initial weight (g)	0.88 ± 0.19^{a}	1.04 ± 0.12^{a}	0.85 ± 0.14^{a}	0.330	ns
Final weight (g)	143.05 ± 13.04^{a}	118.98 ± 9.75^{b}	96.84 ± 19.58^{c}	0.001	***
Absolute Weight Gain (AWG) (g)	142.16 ± 13.06^{a}	117.83 ± 9.74^{b}	95.98 ± 19.60^{c}	0.001	***
Daily Weight gain (g/day)	0.68 ± 0.01^{a}	0.56 ± 0.01^{b}	0.45 ± 0.04^{c}	<0.001	***
FCR	2.21 ± 0.03^{c}	2.69 ± 0.07^{b}	3.21 ± 0.23^{a}	<0.001	***
PER	1.48 ± 0.02^{a}	1.21 ± 0.03^{b}	1.02 ± 0.06^{c}	<0.001	***
SGR (%)	2.43 ± 0.11^{a}	2.25 ± 0.09^{b}	2.12 ± 0.03^{b}	0.003	**
Survival rate (%)	95.83 ± 2.89^{a}	90.83 ± 1.44^{ab}	79.17 ± 5.20^{b}	0.014	*
Gross biomass yield (g)	5483.44 ± 107.05^{a}	4319.19 ± 166.88^{b}	3163.46 ± 230.98^{c}	<0.001	***
Net biomass yield (g)	5448.96 ± 98.53^{a}	4277.27 ± 166.43^{b}	3129.4 ± 231.57^{c}	<0.001	***
TGC	0.78 ± 0.01^{a}	0.71 ± 0.01^{b}	0.64 ± 0.02^{c}	<0.001	***
Fold Increase (x)	170.63 ± 9.6^{a}	119.05 ± 2.21^{b}	112.06 ± 9.30^{b}	<0.001	***

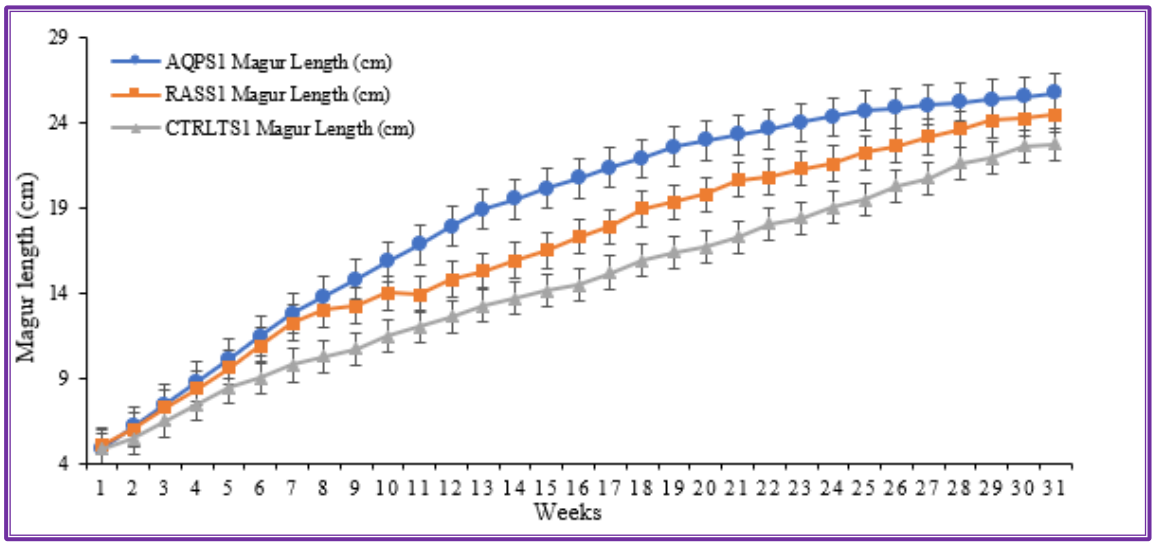


Figure 3: *Weekly Length Changes (Cm) of Magur in Different Culture Systems Over 30 Weeks from The Initial Measurement*

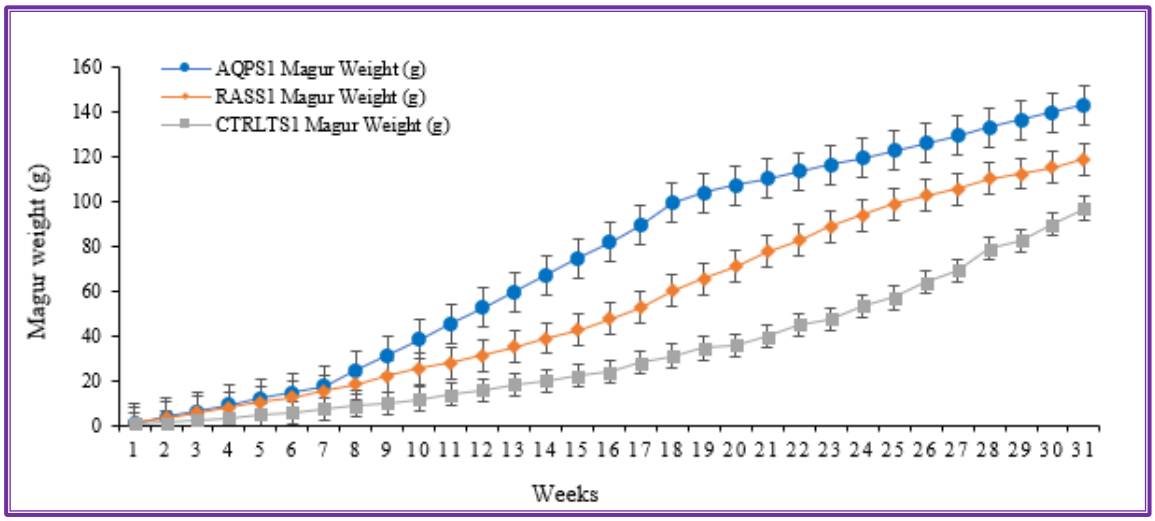


Figure 4: *Weekly Weight Changes (G) of Magur in Different Culture Systems Over 30 Weeks from the Initial Measurement*

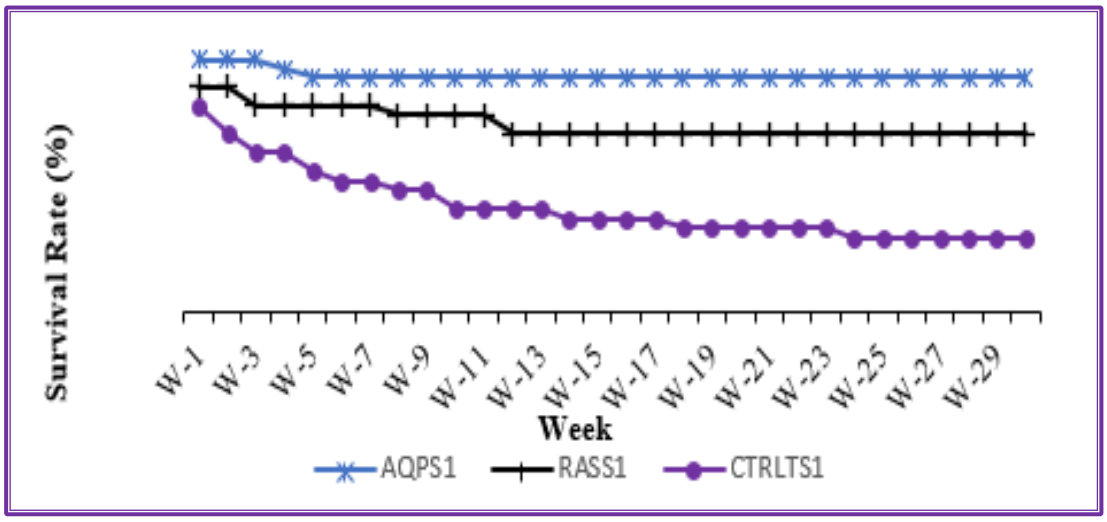


Figure 5: *Weekly Survival Rate (%) of Magur in Different Rearing Systems*

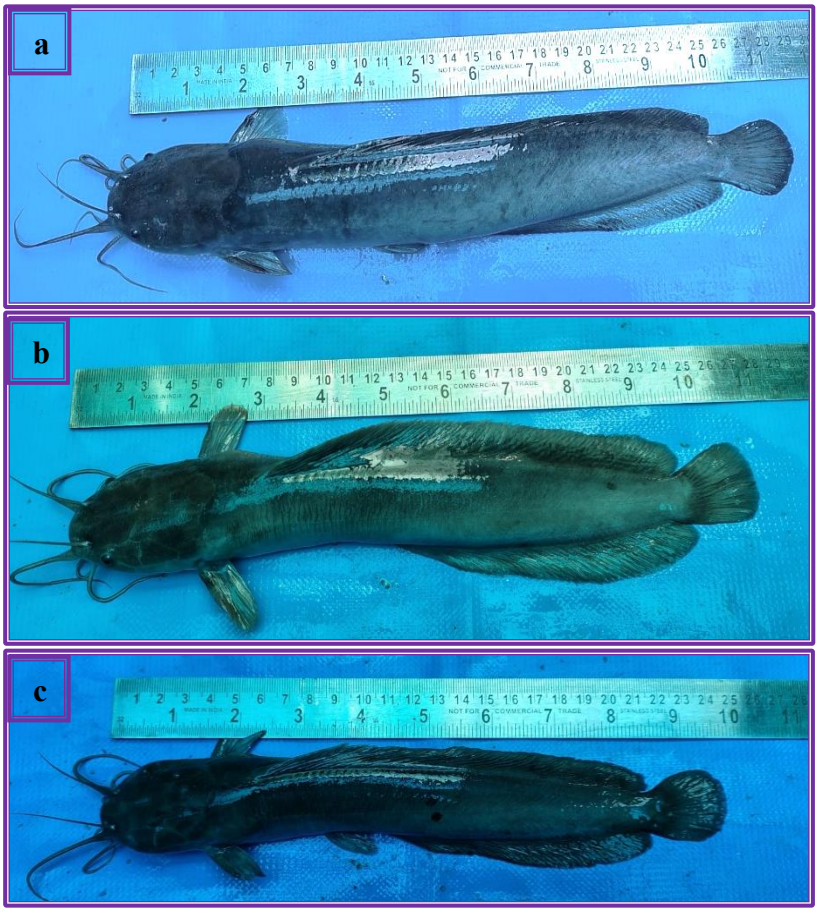


Figure 6: *Magur Reared in Three Different Culture Systems: (A) Aquaponics Magur (AQPS1), (B) Recirculatory Aquaculture System Magur (RASS1) And (C) Control Tank Culture Magur (CTRLTS1)*

Lettuce Growth

Lettuce growth revealed significant differences in growth parameters between the plants grown in the three different systems. However, the highest plant biomass was recorded from the AQPP1 system (max biomass = 83.04 g), followed by HYDP1 (max biomass = 68.3 g) and lower in CONVP1 (max biomass = 57.0 g) (Table 6). The highest lettuce yields in AQPP1 (1168.77 ± 63.05 g) and HYDP1 (961.18 ± 11.66 g) were recorded during CC3, whereas CONVP1 (732.46 ± 11.95 g) achieved its highest yield during CC4 (Figure 7). A significant difference was observed in the final leaf area of lettuce, where AQPP1 achieved the highest value compared to HYDP1 and CONVP1 during CC3 (Figure 8). The log-transformed regression analysis revealed distinct growth patterns among the three different culture systems, with AQPP1 exhibiting the highest shoot and plant height, followed by HYDP1 and CONVP1 (Figure 9). A significant observation was also noted in terms of shoot-root geometry (Figure 10).

Table 6: *Growth Performance of Lettuce Reared in Three Different Culture Systems*

Lettuce Growth Parameters	**Culture System**	**Crop Cycle (42 days each)**				
		CC1	**CC2**	**CC3**	**CC4**	**CC5**
Initial height of plant with root (cm)	AQPP1	9.14 ± 0.43^{a}	9.05 ± 0.41^{a}	8.36 ± 0.4^{a}	8.24 ± 0.45^{a}	8.53 ± 0.47^{ab}
	HYDP1	9.11 ± 0.46^{a}	8.96 ± 0.34^{a}	8.3 ± 0.36^{ab}	8.16 ± 0.44^{ab}	8.24 ± 0.51^{b}
	CONVP1	9.01 ± 0.42^{a}	8.99 ± 0.45^{a}	8.07 ± 0.46^{b}	9.2 ± 0.65^{b}	8.64 ± 0.48^{a}
p-value		**0.2381**	**0.8255**	**0.04**	**0.003**	**0.0033**
Significance		**ns**	**ns**	*	**	**
Initial height of shoot (cm)	AQPP1	5.17 ± 0.21^{a}	5.22 ± 0.19^{a}	4.94 ± 0.18^{a}	4.85 ± 0.2^{a}	5.16 ± 0.23^{a}
	HYDP1	5.14 ± 0.25^{a}	5.19 ± 0.16^{a}	4.9 ± 0.26^{a}	4.87 ± 0.21^{a}	5.06 ± 0.24^{a}
	CONVP1	5.08 ± 0.27^{a}	5.26 ± 0.22^{a}	4.68 ± 0.2^{a}	5.48 ± 0.36^{a}	5.21 ± 0.24^{a}
***p*-value**		**0.2167**	**0.7203**	**0.2074**	**0.157**	**0.095**
Significance		**ns**	**ns**	**ns**	**ns**	**ns**
Final height of plant with root (cm)	AQPP1	37.85 ± 2.63^{b}	50.09 ± 2.47^{a}	53.76 ± 2.19^{a}	52.15 ± 2.14^{a}	48.39 ± 2.77^{a}
	HYDP1	48.76 ± 3.08^{a}	49.31 ± 2.39^{a}	52.42 ± 1.98^{a}	43.01 ± 1.94^{b}	44.68 ± 2.64^{ab}
	CONVP1	24.38 ± 1.97^{c}	24.65 ± 1.64^{b}	25.67 ± 1.87^{b}	27.9 ± 1.34^{c}	26.92 ± 1.22^{c}
p-value		**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Significance		***	***	***	***	***
Final height of shoot (cm)	AQPP1	18.52 ± 1.64^{b}	23.38 ± 0.91^{a}	24.1 ± 1.17^{a}	23.35 ± 1.36^{a}	22.32 ± 1.22^{a}
	HYDP1	22.92 ± 1.59^{a}	21.82 ± 0.94^{a}	22.78 ± 0.92^{ab}	19.15 ± 1.17^{b}	20.25 ± 0.97^{ab}
	CONVP1	15.5 ± 2.03^{c}	15.82 ± 1.53^{b}	16.38 ± 1.46^{b}	18.8 ± 1.32^{b}	17.2 ± 1.19^{b}
***p*-value**		**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Significance		***	***	***	***	***
Initial plant biomass (g)	AQPP1	0.51 ± 0.07^{a}	0.49 ± 0.05^{a}	0.44 ± 0.05^{a}	0.48 ± 0.06^{a}	0.49 ± 0.06^{a}
	HYDP1	0.54 ± 0.06^{a}	0.48 ± 0.04^{a}	0.47 ± 0.06^{a}	0.46 ± 0.05^{a}	0.48 ± 0.07^{a}
	CONVP1	0.52 ± 0.08^{a}	0.46 ± 0.04^{a}	0.49 ± 0.08^{a}	0.52 ± 0.07^{a}	0.52 ± 0.08^{a}
***p*-value**		**0.266**	**0.164**	**0.299**	**0.09**	**0.0698**
Significance		**ns**	**ns**	**ns**	**ns**	**ns**
Final plant biomass (g)	AQPP1	32.61 ± 4.61^{b}	49.48 ± 4.5^{a}	58.43 ± 9.66^{a}	50.16 ± 6.1^{a}	48.71 ± 5.73^{a}
	HYDP1	40.08 ± 5.68^{ab}	43.1 ± 4.87^{ab}	48.06 ± 5.6^{ab}	42.27 ± 6.07^{ab}	38.58 ± 3.44^{b}
	CONVP1	18.94 ± 2.77^{c}	20.35 ± 3.29^{c}	27.9 ± 3.73^{c}	37.24 ± 7.38^{b}	32.83 ± 3.84^{b}
p-value		**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Significance		***	***	***	***	***
Initial leaf number (measurable)	AQPP1	2.74 ± 0.72^{a}	2.75 ± 0.67^{a}	2.75 ± 0.7^{a}	2.7 ± 0.8^{a}	2.88 ± 0.69^{a}
	HYDP1	2.68 ± 0.69^{a}	2.73 ± 0.7^{a}	2.98 ± 0.64^{a}	2.86 ± 0.82^{a}	2.91 ± 0.83^{a}
	CONVP1	3.05 ± 0.87^{a}	3.0 ± 0.65^{a}	2.77 ± 0.69^{a}	3.76 ± 0.61^{b}	3.03 ± 0.84^{a}
***p*-value**		**0.068**	**0.0883**	**0.3265**	**0.0445**	**0.0783**
Significance		**ns**	**ns**	**ns**	*	**ns**
Final leaf number (measurable)	AQPP1	16.28 ± 1.04^{ab}	14.1 ± 0.98^{b}	14.91 ± 1.75^{b}	13.91 ± 1.31^{b}	13.68 ± 0.96^{b}
	HYDP1	16.0 ± 1.57^{ab}	16.1 ± 1.95^{ab}	15.16 ± 2.25^{ab}	15.75 ± 1.53^{ab}	17.0 ± 1.45^{a}
	CONVP1	18.92 ± 1.72^{a}	19.16 ± 1.47^{a}	17.45 ± 1.68^{a}	16.63 ± 1.84^{a}	17.08 ± 1.74^{a}
p-value		**<0.001**	**<0.001**	**0.0058**	**<0.001**	**0.001**
Significance		***	***	**	***	**
Initial fresh leaf weight (g)	AQPP1	0.17 ± 0.03^{a}	0.18 ± 0.03^{a}	0.2 ± 0.04^{a}	0.18 ± 0.03^{ab}	0.16 ± 0.03^{ab}
	HYDP1	0.14 ± 0.03^{a}	0.16 ± 0.02^{a}	0.18 ± 0.03^{a}	0.16 ± 0.04^{b}	0.14 ± 0.02^{b}
	CONVP1	0.17 ± 0.05^{a}	0.13 ± 0.04^{a}	0.17 ± 0.04^{a}	0.21 ± 0.06^{a}	0.19 ± 0.05^{a}

***p*-value**		**0.114**	**0.215**	**0.108**	**0.054**	**0.043**
Significance		**ns**	**ns**	**ns**	*	*
Final fresh leaf weight (g)	AQPP1	2.77 ± 0.45^{ab}	3.45 ± 0.55^{a}	4.87 ± 0.92^{a}	4.54 ± 0.97^{a}	4.04 ± 0.65^{a}
	HYDP1	2.86 ± 0.77^{a}	3.06 ± 0.79^{ab}	3.7 ± 0.81^{ab}	3.55 ± 1.05^{ab}	3.05 ± 0.62^{ab}
	CONVP1	1.34 ± 0.63^{b}	1.39 ± 0.5^{b}	2.04 ± 0.44^{b}	2.85 ± 0.94^{b}	2.5 ± 0.63^{b}
***p*-value**		**<0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**
Significance		***	***	**	***	***
Initial leaf area of plant (cm^2)	AQPP1	10.12 ± 1.48^{a}	10.74 ± 1.53^{a}	11.81 ± 2.03^{a}	10.56 ± 1.63^{a}	10.5 ± 1.67^{a}
	HYDP1	10.09 ± 1.57^{a}	10.67 ± 2.01^{a}	11.65 ± 2.2^{a}	10.3 ± 1.98^{a}	9.57 ± 1.59^{a}
	CONVP1	10.17 ± 1.46^{a}	9.33 ± 1.83^{a}	10.8 ± 2.13^{a}	12.64 ± 1.87^{a}	11.53 ± 1.9^{a}
***p*-value**		**0.8643**	**0.1284**	**0.2887**	**0.0859**	**0.0632**
Significance		**ns**	**ns**	**ns**	**ns**	**ns**
Final leaf area of plant (cm^2)	AQPP1	93.44 ± 8.94^{ab}	106.07 ± 11.41^{a}	130.64 ± 19.38^{a}	123.49 ± 20.09^{a}	113.88 ± 16.93^{a}
	HYDP1	95.01 ± 14.09^{a}	96.28 ± 13.1^{ab}	109.18 ± 15.65^{ab}	106.8 ± 18.11^{ab}	99.02 ± 12.55^{ab}
	CONVP1	70.47 ± 11.92^{b}	71.35 ± 10.48^{b}	81.6 ± 9.07^{b}	96.01 ± 16.46^{b}	89.17 ± 11.82^{b}
***p*-value**		**<0.001**	**<0.001**	**0.003**	**<0.001**	**<0.001**
Significance		***	***	**	***	***
Specific leaf fresh weight (g/dm^2)	AQPP1	2.95 ± 0.23^{a}	3.23 ± 0.27^{a}	3.68 ± 0.26^{a}	3.66 ± 0.3^{a}	3.57 ± 0.36^{a}
	HYDP1	2.96 ± 0.44^{a}	3.13 ± 0.46^{a}	3.35 ± 0.34^{ab}	3.27 ± 0.4^{ab}	3.06 ± 0.29^{ab}
	CONVP1	1.82 ± 051^{b}	1.89 ± 0.43^{b}	2.47 ± 0.3^{b}	2.9 ± 0.45^{b}	2.78 ± 0.33^{b}
***p*-value**		**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Significance		***	***	***	***	***
Final yield (g/m^2)	AQPP1	630.47 ± 23.96^{b}	989.71 ± 25.6^{a}	1168.77 ± 63.05^{a}	1003.26 ± 48.67^{a}	974.27 ± 31.87^{a}
	HYDP1	794.07 ± 21.25^{a}	861.94 ± 15.63^{b}	961.18 ± 11.66^{b}	845.46 ± 15.3^{b}	771.6 ± 28.11^{b}
	CONVP1	334.65 ± 9.38^{c}	406.91 ± 18.37^{c}	557.98 ± 30.05^{c}	732.46 ± 11.95^{c}	659.91 ± 10.49^{c}
***p*-value**		**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Significance		***	***	***	***	***

AQPP1 = Aquaponics Culture of Lettuce, HYDP1 = Hydroponics Culture of Lettuce, CONVP1 = Conventional Soil Culture of Lettuce

*Note: Data are presented as mean ± SD. Within each row, means followed by the same superscript are not significantly different, while means followed by different superscript letters are significantly different at p< 0.05. Significance is denoted as ns = not significant, * = p < 0.05, ** = < 0.01, and *** = p< 0.001*

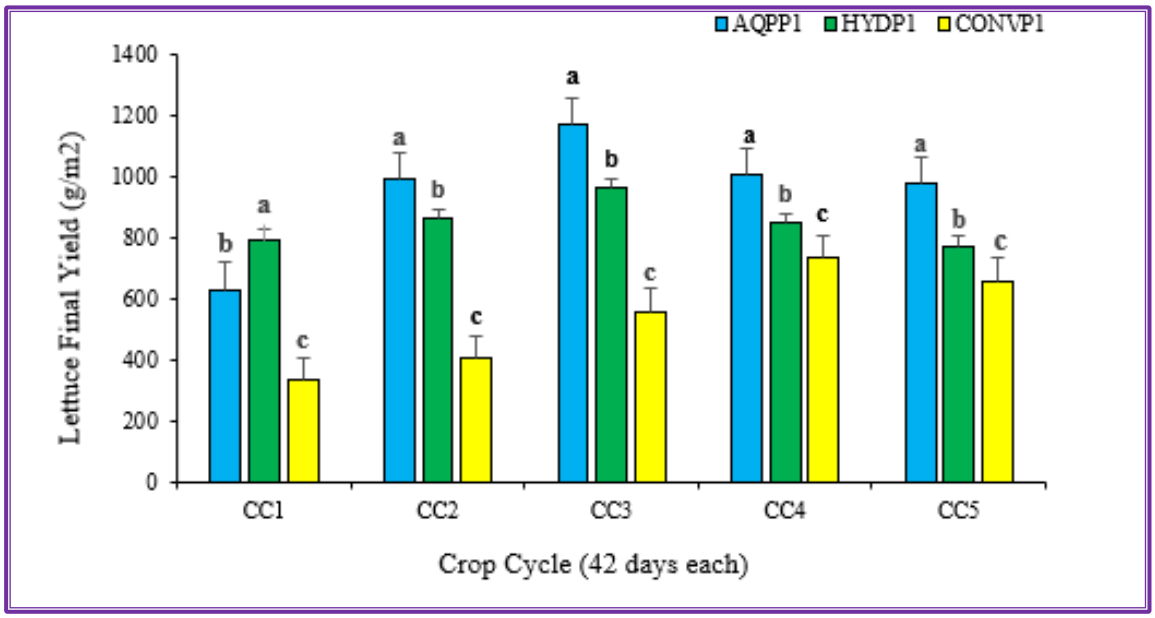


Figure 7: *Lettuce Final Yield (g/m²) from Different Culture Systems Over Five Crop Cycles (42 Days Each). Bars with Different Letters are Significantly Different at p < 0.05*

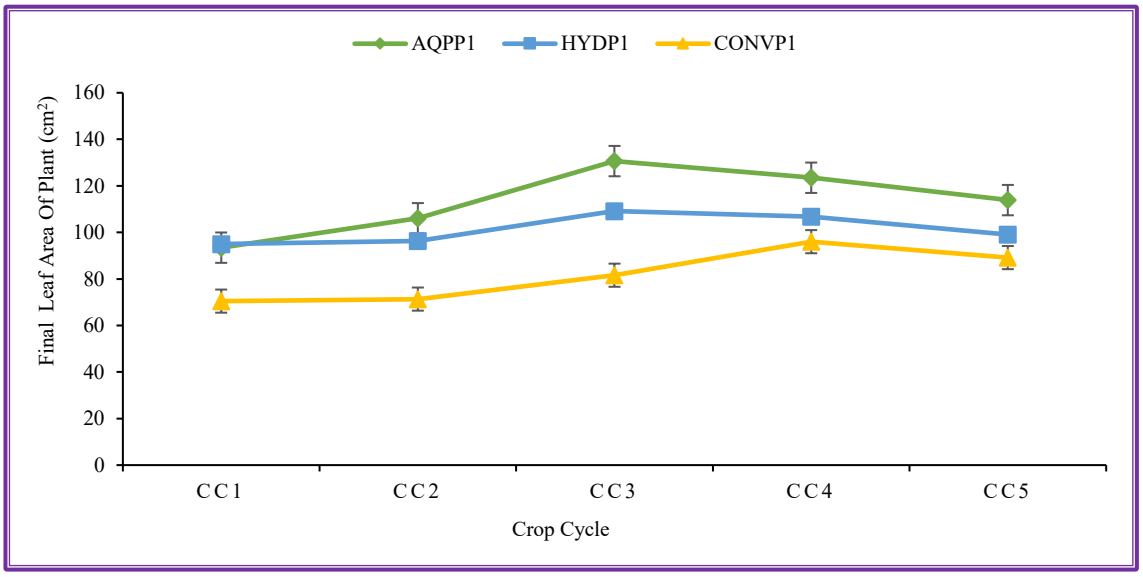


Figure 8: *Final Mean Leaf Area of Lettuce (Cm²) During the Five-Crop Cycle Period in Different Culture Systems*

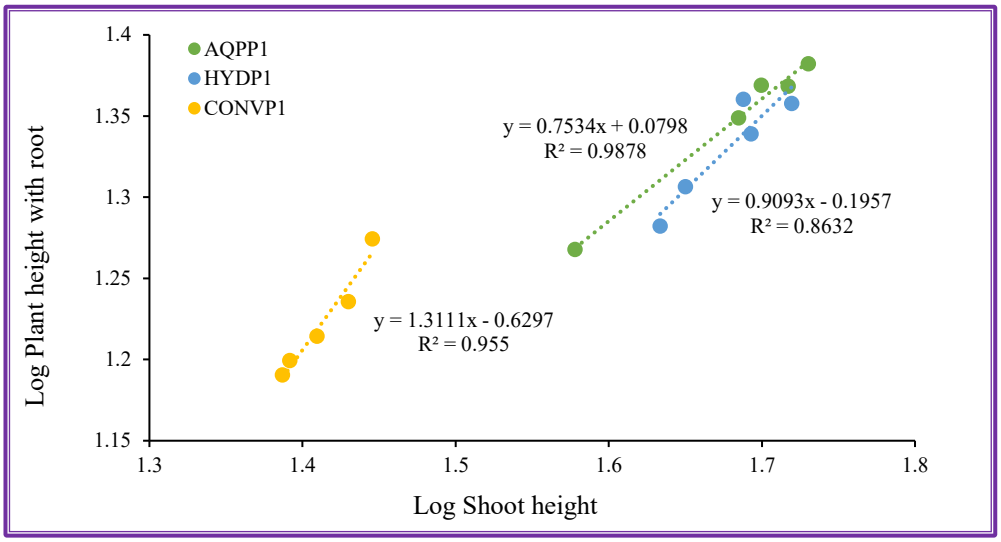


Figure 9: *Relationship Between Log-Transformed Shoot Height and Plant Height with The Root of Lettuce Grown in Different Culture Systems Over Five Crop Cycles*



Figure 10: *Lettuce Yield from Three Different Culture Systems: (A) Aquaponics Lettuce (Aqpp1), (B) Hydroponics Lettuce (Hydp1), And (C) Conventional Soil Culture Lettuce (Convp1)*

Discussion

Water Quality Parameters

Water temperature is one of the important factors responsible for optimum fish and plant growth (Khater *et al*., 2023). Water temperature did not show any significant variation throughout the study period among the three different treatments. The temperature was not significantly different (p = 0.868) for AQPS1, RASS1 and CTRLTS1, ranging narrowly from 26.06±2.62°C to 27.07±2.35°C. The comparatively low DO concentration (4.89±0.17 ppm), together with increased nitrogenous waste levels, may have contributed to the reduced growth performance of magur in CTRLTS1. A significant difference was observed in DO level (p = 0.001) among the three treatments. According to Boyd (1982), dissolved oxygen level should be above 5 ppm to sustain the aquatic organisms in the environment. In AQPS1 and RASS1, the pH was recorded as 7.45 ± 0.09and 7.51±0.1 respectively, which is similar to the result by Kifufu *et al*. (2024), who found a neutral pH (7.22 - 7.75) in different stocking densities of tilapia in an aquaponics system. In the present study, the recorded pH level (6.88 ± 0.28) was slightly lower than the other two treatments. The nitrification process is more efficient at higher pH levels (> 7) and often ceases at <6 pH level. A pH <6 affects nutrient solubility, which impacts plant growth and overall yields (Rakocy, 2007).

Ammonia is a result of fish excretion via the gills and decomposition of uneaten feed in an aquaponics system (Eck *et al*., 2019). High ammonia levels slow down the fish growth, increase mortality rate and cause different physiological functional issues in fish (Yildiz *et al*., 2017; Anantharaja *et al*., 2017). According to Knepp & Arkin (1973), levels of ammonia above 0.2 ppm are toxic to fish, while a level of less than 1 ppm is recommended by Somerville *et al*. (2014). The highest concentration of ammonia (3.21 ppm) was observed in the control tank culture system (CTRLTS1). The cause may be attributed to the high stocking density and lack of water recirculation, as seen in AQP and RAS systems. In CTRLTS1, high ammonia levels may negatively impact fish growth and physiological function. Nitrite is toxic as it can lead to increased fish mortality (Oladimeji *et al*., 2020). According to Bernstein (2013), nitrite toxic levels prevent the spread of oxygen within the bloodstream of fish. Throughout the study, the NO_2 range was lower (0.01 - 0.58 ppm) in AQPS1 and RASS1 than the recommended level (<1 ppm by Somerville *et al*., 2014). The highest nitrite value (1.58 ppm) was recorded from the CTRLTS1. The surpass level of nitrite was also obtained by Oladimeji *et al*. (2020). The removal of ammonia and nitrite was more pronounced in aquaponics compared to the other systems, probably due to the activity of microorganisms and plant absorption (Somerville *et al*., 2014; Zarantoniello *et al*., 2021). However, the nitrate level is higher in RASS1 (12.34 ppm) because of the build-up of nitrate by nitrifying bacteria present without any uptake (Britto *et al*., 2002). Microorganisms present in the aquaponics system assimilate the nitrate in the water, and plants utilize the nitrates for growth (Azam & Ifzal, 2006). Therefore, we found a lower level of nitrate value in the AQPS1 system (5.61±2.28 ppm) than in RASS1. Significant difference ($p \leq 0.001$) was observed in the levels of NH_3, NO_3^-, and NO_2^- among the three treatments. According to a study by Wahyuingsih *et al*. (2015) leafy vegetables significantly reduced nitrogen waste by up to 90% (NH_3) and 50 % (NO_3) from the aquaponics system. Nitrate was also found to be lower in the CTRLTS1 likely due to the limited nitrification within CTRLTS1 compared to other two closed-loop systems (AQP and RAS) (Oladimeji *et al*., 2020).

TDS ranged from 247 ppm (AQPS1) to 451 ppm (CTRLTS1) in the present study. Somerville *et al*. (2014) recommended that TDS below 800 ppm maintain the suitability of aquaponics system. The range of EC was between 600µs/cm and 727 µs/cm in AQPS1, 650 µs/cm and 780 µs/cm in RASS1 and 726 µs/cm and 844 µs/cm in CTRLTS1. These present findings are consistent with those reported by Rocha *et al*. (2025), who observed significantly lower EC and TDS concentrations in aquaflocponics system compared with hydroponics ($p < 0.05$). Kifufu *et al*. (2024) recorded an EC range of 523.9 to 786.7 µS/cm in aquaponics culture of Nile Tilapia and Roselle plant. A statistically significant ($p = 0.01$) difference in alkaline level was noted across treatment groups. The highest level of alkalinity was noted in RASS1 (121.13 ± 9.32 ppm), followed by AQPS1 (116.65 ± 10.38 ppm) and CTRLTS1 (96.29 ± 9.10 ppm). Alkalinity greater than 75 ppm raise the water pH (Singh & Dunn, 2016).

According to Somerville *et al*. (2014), the alkalinity level in aquaponics should remain between 121 and 180 ppm. A similar observation was found in the present study. Significant differences in phosphate levels were observed among the three treatment groups ($p < 0.05$). The control tank culture system (CTRLTS1) exhibited the highest phosphate concentration at 0.81 ppm, followed by the recirculating aquaculture system (RASS1) at 0.57 ppm. In contrast, the aquaponic system (AQPS1) recorded the lowest residual phosphate concentration at 0.49 ppm. The lower residual phosphate level in AQPS1 may be attributed to the uptake of phosphorus by plants and microbial assimilation within the aquaponic unit. In contrast, the absence of plant-mediated nutrient removal in RASS1 and CTRLTS1 likely contributed to the higher phosphate accumulation observed in these systems. Nuswantoro *et al*. (2023) reported baseline phosphate fluctuations averaging 0.72 ± 0.58 ppm in a polyculture system comprising Nile tilapia and freshwater prawn under unmodified nutrition conditions.

Soil Characters

As presented in Table 4, the soil was classified as sandy loam texture, with a pH of 6.8 ± 0.26, EC of 0.70 ± 0.016 dS/m. The soil characteristics from this present study are aligned with the findings of Biswas & Das (2014), Bisai *et al*. (2016), Ojha & Chakrabarty (2018). Kreutz *et al*. (2021) demonstrated that butterhead and romaine lettuce exhibit superior initial head development and lower heat stress in sandy loam soils compared to high-organic muck or dense clay profiles. The recorded soil bulk density

(1.3 ± 0.06 g/cm^3) aligns perfectly with normal agricultural ranges. Soil porosity (Sp) of this soil was found to be 51.31 ± 1.25%. According to Neumann *et al*. (2014), the porous loam structure of soil optimises the gas exchange required by lettuce roots, preventing localised anoxia and promoting uniform root exudation profiles. Nitrogen acts as the primary limiting driver for vegetative leaf area index development in lettuce (Hong *et al*., 2022). A total nitrogen content of 0.15 ± 0.03% is typical for productive sub-tropical upland soils. The available soil phosphorus was found to be 32.29 ± 3.81 kg/ha. In cold-season vegetable production, a bicarbonate-extractable phosphorus level of 30-40 mg/kg is often heavily supplemented through synthetic inputs (Hoque *et al*., 2010). The recorded phosphorus level denoted a moderate baseline supply, ensuring that the early-stage root branching and energy transfer transformations were sufficiently supported in the control group.

Growth of Magur

Significant differences ($p < 0.05$) were observed in the final length and weight of magur among the three treatments.According to Ferosekhan *et al*. (2021), magur can grow up to 100-120 g in earthen ponds, stone-pitched ponds or cemented tanks during a one-year culture period. The final biomass of magur in AQP was 26.95% and 73.34% higher than that of the RAS and CTRLT systems. Sahoo *et al*. (2018) compared the growth characteristics of *Clarias magur* among stocks collected from Godavari, Mahanadi, and Hooghly river systems and reported mean total lengths of 14.8 ± 0.22 cm, 21.7 ± 0.71 cm, and 15.9 ± 0.27 cm, respectively, with corresponding body weights of 24.7 ± 1.17 g, 70.0 ± 4.73 g, and 26.8 ± 1.35 g. From week one to week ten, a higher mortality trend was observed in CTRLT than in RAS and AQP, which may be attributed to the progressive accumulation of nitrogenous wastes in CTRLTS1. Higher SGR (%) was recorded in AQP (2.43 ± 0.11), followed by RAS (2.25 ± 0.09) and CTRLT (2.12 ± 0.03). Maranga *et al*. (2022) found an SGR range of 2.17 to 2.50 for *C. gariepinus* under different dietary treatments. In this present study, the feed conversion ratio (FCR) was highest in CTRLT (FCR = 3.39), while the lowest value was observed in AQP (FCR = 2.19), and the PER value ranged from 0.97 (CTRLT) to 1.50 (AQP). Faturoti (1989) reported an FCR range of 1.26-3.34 in the conventional culture of *C. gariepinus*. Naeem *et al*. (2024) found an FCR ranged from 1.90 to 5.24, varying across different feeding treatments for *C. batrachus*, with the lowest FCR value (1.90 ± 0.02) noted in fish provided with 40% CP, while PER ranged from 0.6 to 1.32. Results of the present study also revealed that the highest daily weight gain (0.68 ± 0.01 g/day) was in AQPSI, followed by RASS1 (0.56 ± 0.01 g/day), and the lowest in CTRLTS1 (0.45 ± 0.04 g/day). Differences between the systems (AQPS1, RASS1, CTRLTS1) were statistically significant ($p < 0.001$) for growth rates of magur, suggesting how the aquaculture environment and nutrient availability play critical roles in the growth performance. The higher amount of growth produced from aquaponics demonstrates its production efficiency compared to the other two systems. Overall, the growth rate of *C. magur* observed during this study is closely similar to the findings of Naeem *et al*. (2024) for Tadesse (2019) for *C. gariepinus*. In terms of thermal growth coefficient (TGC), AQPS1 was the highest growth efficiency (0.78 ± 0.01), followed by RASS1 (0.71 ± 0.01), while the CTRLTS1 treatment was the least efficient at 0.64 ± 0.02. The significantly higher TGC values observed in AQPS1 and RASS1 relative to CTRLTS1 underscore the highly managed culture environments played crucial role in enhancing fish growth performance in AQP and RAS. Similar observations were reported by Al-Dubakel *et al*. (2011), who noted that recirculatory systems maintain stable water quality parameters within an optimal tolerance limit, thus reducing the metabolic stress experienced by fish, allowing more energy to be utilized for somatic growth.

Lettuce Growth

The main advantage of an aquaponics system is the diversification of two different yields (fish and plants), which are considered the healthiest for the human diet according to nutritional science (Somerville *et al*., 2014). The presence of nitrogen compounds resulted from nitrification; these compounds serve as essential nutrients for lettuce growth (Goddek *et al*., 2015). Lettuce yields an average of 630.47 ± 23.96 g/m^2 in CC1 of AQPP1 system, and the highest yield reached to 1168.77 ± 63.05 g/m^2 in CC3. In CC1 HYDP1, grown lettuce showed greater biomass accumulation (40.08 ± 5.68 g) than that observed in the AQPP1 system (32.61 ± 4.61 g). The enhanced growth in HYDP1 may be

associated with a more stable nutrient supply, while comparatively lower growth in AQPP1 could be due to nutrient availability arising from smaller fish biomass and lower faecal output, which may have limited nutrient inputs to the plants. The comparable superior performance of AQPP1 in the later crop cycle indicates that the system provides sufficient nutrient availability for optimal lettuce growth (Delaide *et al*., 2016; Sabwa *et al*., 2022); Pantanella *et al*. (2012), demonstrated that a mature aquaponic system can match or exceed hydroponic yields for different leafy vegetables due to the multi-nutrient richness of organic fish effluents. Notably, despite the lower biomass in AQPP1 in CC1, both AQPP1 and HYDP1 consistently outperformed CONVP1 in all CC. Findings by Suhl *et al*. (2016) showed similar growth performance of aquaponic and hydroponic systems without a significant advantage in production. The highest growth in terms of plant height with root was observed in AQPP1 (53.76 ± 2.19 cm), followed by HYDP1 (52.42 ± 1.98 cm) during CC3, while in CONVP1, the highest plant height with root was in CC4 (27.9 ± 1.34 cm). The present findings are in agreement with those of Majid *et al*. (2020), who reported that soilless plant culture systems promote higher plant growth compared with the conventional soil-based culture system. The final leaf area and final leaf weight were significantly shifted in favour of AQPP1 and HYDP1 ($P < 0.01$). The highest final leaf area for AQPP1 (130.64 ± 19.38 cm^2) and HYDP1 (109.18 ± 15.65 cm^2) were recorded in CC3, substantially exceeding the maximum leaf area of CONVP1 (96.01 ± 16.46 cm^2), which was recorded in CC4. This trend was mirrored in the final fresh leaf weight, where AQPP1 achieved a maximum of 6.69 g compared to 5.26 g in CONVP1. The higher yields during the winter crop cycles may be associated with favourable seasonal conditions for lettuce growth. October-February is considered a suitable growth period for lettuce in eastern India (AllThatGrows, n.d.), while recommended growth periods are September-October for North India and October-December for South India (Singh *et al*., 2021). In this present study, lettuce growth across all three systems (AQPP1, HYDP1, CONVP1) was comparatively higher during CC3 and CC4, corresponding to September through early November reflects the favourable seasonal conditions for the suitable growth of this crop.

AQPP1 ($m = 0.7534$) and HYDP1 ($m = 0.9093$), both soilless systems, show a suppressed scaling exponent ($m < 1,0$). Because nutrients are dissolved directly in the water layer and delivered seamlessly to the root zone of the plant. Instead, it prioritises aerial shoot growth, which maximises light interception and vegetative yield. In CONVP1 ($m = 1.3111$), lettuce exhibits a steep slope. These align with the findings of Delaide *et al*. (2016) and Goddek and Vermeulen (2018), who demonstrated that lettuce grown in nutrient-supplemented aquaponics often outperforms conventional hydroponic systems by up to 30-40 %. Furthermore, Maxwell *et al*. (2023) evaluated DWC aquaponics, which yielded significantly higher leafy biomass and superior shoot-to-root geometry (4.9 vs 4.6) compared to the hydroponic system due to optimized organic nutrient cycling and microbial activity.

Limitations

Despite the promising findings, some limitations need to be addressed. The experiment was conducted at single location under controlled environmental conditions, which may limit the extent to which may limit the generalization of the results to other climatic regions and production settings. This present study has considered only one fish species (*Clarias magur*) and one vegetable crop (*Lactuca sativa*); consequently, the reported results may not necessarily be representative of the performance of other fish-plant integrations. The experimental system was conducted at a relatively small research scale, and the results may differ under commercial-scale aquaponic production, where management complexity, operational costs and environmental conditions are more variable.

Future Scope

Future studies must assess the long-term efficacy and economic feasibility of aquaponic systems in commercial-scale production environments, which would yield significant insights for farmers and enterprises contemplating large-scale implementation. Advanced technologies, including Internet of Things (IoT) monitoring, artificial intelligence management systems, and renewable energy integration, focused on microbial activity may enhance operational efficiency and sustainability.

Conclusion

This study provides a comprehensive, comparative evaluation of an integrated Nutrient Film Technique (NFT) aquaponic system against conventional monoculture variations for the co-cultivation of Indian catfish (*Clarias magur*) and lettuce (*Lactuca sativa*). The findings demonstrate that the integrated aquaponic system effectively supported both fish and plant production while improving water quality through continuous recirculation, mechanical and biological filtration, and plant nutrient uptake. *Clarias magur* reared in the aquaponic system (AQPS1) showed significantly better growth and production performance than fish maintained in the RAS and conventional tank systems. The plant component further demonstrated the productive potential of the integrated system. Lettuce cultivated in the aquaponic system showed progressive improvement across the successive crop cycles, with the highest plant biomass. Although hydroponic lettuce showed comparatively higher biomass during the initial crop cycle, aquaponic production improved as the system matured and subsequently performed favourably relative to both hydroponic and conventional soil-based cultivation. Overall, the results indicate that NFT-based aquaponics can simultaneously enhance fish production, lettuce productivity, water-quality management, and nutrient recycling compared with separate production systems. The study therefore demonstrates the technical and biological potential of integrating *C. magur* with *L. sativa* in a recirculating aquaponic system and provides a useful basis for further research on system optimization, economic feasibility, and commercial-scale production.

Conflict of Interest

The authors do not have any conflict of interest

Ethical Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Conflict of Interest

The authors declare that they have no competing interests.

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