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Performance Evaluation of Hydroponic Grow-Outs in An Innovative Coldwater Aquaponic System Featuring Rainbow Trout and Lettuce

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Abstract

A 45-day trial was carried out to assess the production performance of different hydroponic media in a novel do-it-yourself (DIY) low-tech re-circulating aquaponic system for temperate regions with rainbow trout (*Oncorhynchus mykiss*) and lettuce (*Lactuca sativa*). Rainbow trout juveniles (average weight of 35.59 g) were stocked in the experimental units at 2.8 $kg.m^{-3}$ and fed with commercial floating pelleted feed at 8 % of their body weight in three treatments and a control. The lettuce saplings were randomly planted in the river stone bed (T_1), crushed stone bed (T_2), raft/deep water culture (DWC) unit (T_3) and control (C) soil bed (fortified with NPK fertiliser) with equivalent planting intervals of 42 $saplings.m^{-2}$. The system, designed with low-tech simplicity, was managed without alkalinity correction and depended entirely on plant growth and metabolism for biofiltration. The water quality parameters such as temperature, pH, dissolved oxygen (DO), dissolved free CO_2, hardness, total alkalinity, ammonium, nitrite, and nitrate varied significantly ($P < 0.05$) among the treatments compared to the control. The final individual weight, biomass gain, specific growth rate (SGR), and feed conversion ratio (FCR) of rainbow trout were significantly better ($P < 0.05$) in media beds (crushed stone and river stone) compared to control and DWC systems. The final mean weights of rainbow trout in river stone (12.33 ± 0.002 g and crushed stone (12.39 ± 0.054 g) treatments were significantly higher ($P < 0.05$) than in DWC (12.1 ± 0.023 g) and control (12.09 ± 0.002 g) treatments. The production of lettuce was significantly greater ($P < 0.05$) in all three treatments (river stone: 4.33 ± 0.123 g, crushed stone: 4.53 ± 0.09 g and DWC: 4.31 ± 0.163 g) compared to the control (3.31 ± 0.172 g). The DWC including the media bed systems facilitates the improved performance of lettuce saplings in terms of final height and leaf number. These results show that a low-tech media bed system without a supplementary biofiltration unit can achieve sustainable production of both fish and vegetables in temperate hilly terrains.

Keywords: temperate systems, river stone, crushed stone, deep water culture/raft

Introduction

Due to the rapid increase in world population, the food demand is projected to rise by 60 % by 2050 (Alexandratos and Bruinsma, 2012). Global water demand has increased by 600 % over the past 100 years (Wada et al., 2016). Fish farming in open systems bears the demerits of huge water loss and effluent discharge, causing oxygen depletion and eutrophication in the receiving environment (Martins et al., 2010). On the other hand, aquaponic cultivation in open systems is purely based on the waste-to-input mechanism where the effluent in the outflow is transformed by microbes into a nutrient form suitable for utilisation by hydroponic plants (Bosma et al., 2017). The nutrient-stripped water with an improved water quality is then returned to the aquaculture unit (Buzby and Lin 2014; Goddek et al., 2015; Espinosa Moya et al., 2017). So as to feed the population with chemical free nutritionally balanced diet at one end and optimal use of the water at other end, the self-sustained one-loop recirculating aquaponic system or integrated agriculture and aquaculture (IAA) system is one of the most promising precision farming tools for growers (Endut et al., 2016; Schmautz et al., 2016; Yogev et al., 2016; Knaus and Palm 2017) as it satisfies the motto of zero-emission circular economy (EU, 2018). Unlike conventional agriculture in soil, the aquaponic system does not need the supplementation of chemical fertilisers and also requires only about 10 % of the water needed by conventional agriculture (Duarte et al., 2015). The water is replenished only to compensate for the plant-mediated evapotranspiration loss (Lennard and Leonard, 2006; Timmons and Ebeling, 2007).

For the growth and well-being of plants, the majority of the nutrients are derived from the effluents produced by fish under cultivation (Palm et al., 2018). The proportion of waste to water in the fish farm effluent discharge is very low and, hence difficult to treat (Adler et al., 1996a; Heinen et al., 1996). There are several methods to lessen nutrient discharge of aquaculture effluents such as the reduction of excess phosphorus in fish diets (Ketola and Harland, 1993; Jacobsen and Børresen, 1995; Heinen et al., 1996), reduction of leftover feed (Summerfelt et al., 1995), fast removal of excess feed and faecal matter from the unit (Summerfelt, 1996), application of various nutrient stripping techniques (Metcalf and Eddy Inc., 1991; Adler et al., 2000) and plant-based mechanisms for the removal of nutrients (Rakocy and Hargreaves 1993; Adler et al., 1996b,c; Adler, 1998). Among the above-mentioned tools, a plant-based integrated system strips nutrients from the medium without any extra cost and provides additional benefits to the grower as well (Adler et al., 2000). The system follows the concept of 'waste to wealth' by utilising discarded byproducts for a sustainable economy and environment in the long run (Adler et al., 1996a).

In aquaponics farming, the most commonly used plant grow-out units are substrate loaded media beds, nutrient film technique (NFT) and floating raft or deep water culture (DWC) systems (Delaide et al., 2017). The media bed substrates may be of gravels, pebbles, clay balls and perlite (Endut et al., 2010; Sikawa and Yakupitiyage, 2010; Shete et al., 2014; Hussain et al., 2015; Nuwansi et al., 2015), which can act as plant support system, solid filter and biofilter media (Rakocy and Hargreaves, 1993; McMurtry et al., 1997; Seawright et al., 1998) so that additional biofilters may not be necessary (McMurtry et al., 1997; Seawright et al., 1998; Dontje and Clanton, 1999). The competency of other kinds of media bed substrates such as peat moss and coconut fibre are also well validated by several researchers (Bhatnagar et al., 2010; Yaghi and Hartikainen, 2013; Boxman et al., 2017). On the other hand, efficient water flow across root boundaries, lightweight, no clogging, and cost-effective are the properties that attract aquaponic growers towards a floating raft system (Lennard and Leonard, 2006). In NFT, the plant roots are exposed to a thin layer of water and hence, have significantly less efficiency for removing nutrients and less buffering capacity than media beds and DWC systems (Graves, 1993; Lennard and Leonard, 2006). However, in cold water aquaponics, the potential of floating raft and gravel bed systems without supplementary biofilter units still needs to be evaluated. Several researchers have cited the efficiency of different kinds of media bed substrates but the locally available ones with similar competency may be targeted for making the do-it-yourself (DIY) system economically feasible. Therefore, to test the efficiency of aquaponic systems in cold thermal Indian upland, locally available low-cost hydroponic components such as gravel-based media beds and floating raft systems were used for evaluating the integrated aquaculture of rainbow trout (*Oncorhynchus mykiss*) and lettuce (*Lactuca sativa*) in the present study.

Materials and Methods

Ethical approval

The ARRIVE (Animals in research: Reporting in vivo experiments) guidelines as outlined in Kilkenny et al. (2010) are being followed for undertaking research. The experiment was conducted with the approval of the Institutional Animal Care and Use Committee (IACUC) of ICAR-Directorate of Coldwater Fisheries Research, Bhimtal, India (DCFR/IACUC/07.09.2021/3), and no animals were sacrificed during this study.

Experimental fish and plants

The fish and plants used for the experimental trial were rainbow trout (*Oncorhynchus mykiss*) and lettuce (*Lactuca sativa*) respectively. The rainbow trout eyed ova weighing more than 60 mg and diameter 4.2–5.1 mm were reared separately (quarantined) under flow-through condition at the Directorate of Coldwater Fisheries Research experimental farm, located at Champawat, Uttarakhand, where there was no signs and symptoms of any disease. Eggs were transported at eyed ova stage from the Champawat farm followed by disinfection with boric acid at 500 ppm and grown to juvenile stage in the wet laboratory of Bhimtal. The lettuce (*Lactuca sativa*) seeds were procured online and planted in peat loaded egg and plastic trays and grown to sapling stage. Saplings were thoroughly washed and randomly transplanted into the control and treatment units.

System design

An indigenously designed low-tech aquaponics setup was installed at Indian Council of Agricultural Research - Directorate of Coldwater Fisheries Research, Bhimtal, Uttarakhand, India (Fig. 1). The experimental trial was conducted under polyhouse covered DIY system for a period of 45-day, which is the general time taken for the lettuce to reach harvesting size. The experimental setup consists of control and treatments with three randomly assigned replicates. Fish were grown in tanks with normal feeding and the flow through tank without aquaponic unit, served as control.

The lettuce plantlets planted in rectangular troughs with

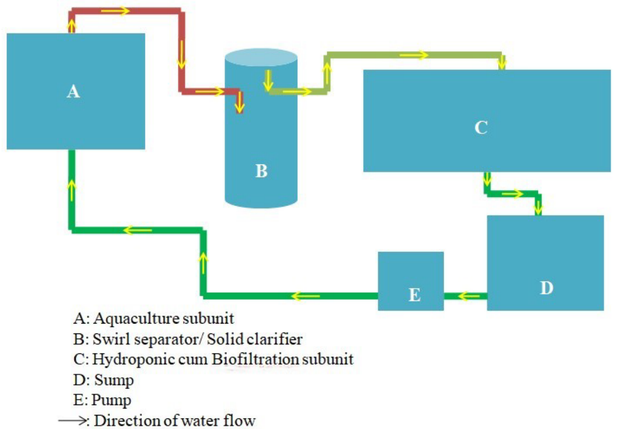

Fig. 1. Schematic diagram of experimental aquaponic system.

soil base were the control unit. These plantlets were fertilised once during the experiment with one teaspoon of 16N:16P:16K fertiliser. The growing plants were watered regularly, and the control bed was provided with sufficient drainage to avoid water logging. For plant grow-out, different hydroponic units such as river stone bed, crushed stone bed and deep water culture (DWC)/raft systems were allocated as three treatments i.e. T_1, T_2 and T_3, respectively whereas the soil bed was represented as control (C) unit. The size range of river stones and crushed stones were 5–9 mm and 3–8 mm with porosities of 0.40 and 0.42, respectively. The hydroponic units were filled to 30 cm depth with gravel substrates and water for media bed systems and DWC, respectively. The DWC systems were made with thermocol sheets and disposable plastic glasses as net pots. The plantlets were planted in net pots with gravel base (support plant roots) and then fitted into the holes in the thermocol sheets. The control plant grow-out unit was filled with soil up to a depth of 30 cm. The system was operated with one swirl separator for sludge removal but without any additional biofilter. The media bed substrates and the plant roots, including the walls of hydroponic tanks, acted as biofilters.

The experimental aquaponic system comprised of square fish tank, cylindrical sludge removal tank, rectangular hydroponic tank and square sump with capacities of 1000 L, 200 L, 300 L (1.5 m^2 surface area) and 500 L, respectively. The swirl separator or sludge removal tank was made of cylindrical plastic drum with inlet and outlet pipes. The inlet receives water from the fish tank and was angled towards the inner side whereas the outlet was angled towards the outer side and directs the outflow of water to the hydroponic component. The inlet and outlet were positioned at lower and upper section of the unit, respectively with a direction opposite to each other. The hydroponic units were also made of cylindrical plastic drum by dividing them into two equal parts through its longitudinal section. The flow of water from fish tank to sump was driven by an external 0.5 hp water pump, while the water flow from fish tank to sump was through a swirl separator and the hydroponic component was gravity driven. A standard water level was maintained by the addition of fresh water two times per week to compensate for water lost due to sludge removal, evaporation and transpiration. The average initial size of fish and plants used for the experiment were 35.59 g and 0.2 g (3.1 cm height), respectively. The planting rate was maintained at 42 saplings.m^{-2} while the stocking density of fish was 80 fish.m^{-3} (2.8 kg.m^{-3}). Rainbow trout in experimental tanks were fed with commercially available floating pelleted feed (Table 1) at 8 % of their body weight twice each day at 10 am and 4 pm, while the plant growth was fully subsistent on the intrinsic nutrients, generated from the effluents of the fish culture unit. This low-tech system was managed with no alkalinity correction, no management through remote control, no probe for continuous evaluation of water quality parameters and no specific tool for water sanitation.

Growth indices of fish and plants

Growth parameters (total length and weight) of fish and plants (height and number of leaves) were estimated every 15-day. The weight of plants was assessed at the end of the experimental trial i.e. after 45-day. The fish and plant growth parameters such as biomass gain (BG), percentage weight gain (WG %), specific growth rate (SGR), feed conversion ratio (FCR), feed efficiency ratio (FER), amount of protein fed (g), protein efficiency ratio (PER) and survival % were evaluated using the following formulae:

$$\text{Biomass gain (BG)} \\ = \text{Mean final biomass} - \text{Mean initial biomass}$$

$$\text{Weight gain percentage (WG \%)} \\ = \frac{\text{Mean final weight} - \text{Mean initial weight}}{\text{Mean initial weight}} \times 100$$

$$\text{Specific growth rate (SGR: \%/day)} \\ = \frac{\ln \text{mean final weight} - \ln \text{mean initial weight}}{\text{Experimental period in days}} \times 100$$

$$\text{Feed conversion ratio (FCR)} \\ = \frac{\text{Dry weight of feed given during experimental period (g)}}{\text{Mean final wet weight gain (g)}}$$

$$\text{Feed efficiency ratio (FER)} \\ = \frac{\text{Mean final wet weight gain (g)}}{\text{Dry weight of feed given during experimental period (g)}}$$

$$\text{Protein fed (g)} = \text{Crude protein \%} \times \text{Total feed given (g)}$$

$$\text{Protein efficiency ratio (PER)} \\ = \frac{\text{Mean final wet weight gain (g)}}{\text{Crude protein intake (g)}}$$

$$\text{Survival (\%)} \\ = \frac{\text{Final no. (fish or plants) surviving at end of the experiment}}{\text{Initial no. (fish or plants) stocked at start of the experiment}} \\ \times 100$$

Table 1. Proximate composition of rainbow trout *Oncorhynchus mykiss* experimental diet (g.100 g^{-1}).

Moisture (%)	Crude protein (%)	Ether extract (%)	Ash (%)	Digestible carbohydrate (%)	Dry matter (%)	Fibre (%)	Organic matter (%)	Digestible energy (Kcal.100 g^{-1})
4.26	45.87	18.67	10.49	19.89	95.74	0.83	89.51	434.4

Water quality parameters

The water temperature, pH, dissolved oxygen (DO), dissolved free carbon dioxide and conductivity in each experimental unit were recorded daily with the help of the portable multiparameter water quality meter (ProQuatro, YSI, USA). The standard protocols mentioned in APHA (2005) were followed to estimate the parameters such as water hardness and total alkalinity on weekly basis. The ammonium, nitrite, nitrate and phosphate content of water of different experimental units were analysed weekly by Spectroquant Multy (Merck).

Data analyses

The data for each treatment are summarised as means ± SD using SPSS v20 and GraphPad Prism 8 was used to prepare the graphs. One-way ANOVA and post-hoc Tukey's multiple range test were used to test for significant differences among the control and treatment groups at 95 % confidence level ($P < 0.05$).

Results

Water quality parameters

The estimated water quality parameters of fish and plant grow-out units at the start (Table 2) and end (Table 3) were well within the recommended range for pisciculture (Boyd, 1982; Ajani et al., 2011). The conductivity of water did not show any significant difference ($P < 0.05$) among the experimental groups. The dissolved oxygen (DO) was significantly higher ($P < 0.05$) in all treatments (7.1 mg.L^{-1}) than the control (6.61 mg.L^{-1}) and the free CO$_2$ concentration in control (5.1 mg.L^{-1}) was significantly higher than all the treatment groups (4.81–4.86 mg.L^{-1})(Table 3). Total alkalinity in the control (126.73 mg.L^{-1}) was significantly lower than in all treatments (150.0–150.96 mg.L^{-1}). The mean ammonium concentration was significantly lower in the control unit (0.34 mg.L^{-}) than the treatment groups (0.43–0.61 mg.L^{-1}) as was the case for phosphate (C = 2.097 mg.L^{-1} and 2.42–2.59 mg.L^{-1} in the treatments) (Table 4). Mean concentrations of nitrite (mg.L^{-1}) (T$_1$: 0.16, T$_2$: 0.15 and T$_3$: 0.14) and nitrate (mg.L^{-1})(T$_1$: 58.57, T$_2$: 62.63 and T$_3$: 64.27) were significantly higher in treatments than the control (0.34 mg.L^{-1} for nitrite and 4.12 mg.L^{-1} for nitrate).

Growth indices of rainbow trout

At the end of the 45-day experimental period, the final average body weight (g)(T$_1$: 154.13, T$_2$: 154.81) and biomass gain (kg.m^{-3}) (T$_1$: 9.48, T$_2$: 9.54) of rainbow trout were significantly higher ($P < 0.05$) in gravel media-based treatments compared to the T$_3$ (DWC) and control (Table 5). The specific growth rate (% body weight day^{-1}) of trout followed a similar trend as that of final body weight and biomass gain i.e. it was significantly faster in gravel media-based treatments than DWC and the control (Table 5). Feed conversion ratios varied significantly among the experimental groups with lower FCR in T$_1$(1.08) and T$_2$ (1.07). No mortality was observed during the experimental period thus ensuring 100 % survivability of rainbow trout in all the experimental units.

Growth parameters of lettuce

All lettuce survived throughout the 45-day trial, with an absolute 100 % survival rate observed in both the control and treatment units (Table 6). The final height (24.44 cm) and number of leaves (15.53) were significantly higher ($P < 0.05$) in T$_2$ (crushed stone) than all other groups (Table 6). The final plant weight and biomass gain varied significantly among the experimental groups, and these were all greater than in the Control unit (final weight = 78.85 g and biomass gain = 3.3 kg.m^{-2}). Weight gain (%) did not show any significant difference ($P < 0.05$) among the treatment and control units. The specific growth rate varied significantly among all the groups with maximum value in T$_1$, the river stone treatment (13.59 % weight.day^{-1}, Table 6).

Discussion

For making any production unit economically viable,

Table 2. Physical and chemical composition of source water.

Parameters	Value	Parameters	Value
Temperature (°C)	16.2–16.4	Ammonium (mg.L^{-1})	0.25–0.32
pH	7.61–7.63	Nitrite (mg.L^{-1})	0.05–0.06
DO (mg.L^{-1})	6.65–6.67	Nitrate (mg.L^{-1})	2.28–2.69
Dissolved free CO$_2$ (mg.L^{-1})	5.1–5.13	Phosphate (mg. L^{-1})	1.25–1.69
Hardness (mg.L^{-1})	87.1–87.9		
Total alkalinity (mg.L^{-1})	126.8–128.9		
Conductivity (μS.cm^{-1})	232.6–240.7		

Table 3. Water quality parameters of experimental units.

Parameters	Experimental units			
	T_1 (n = 3) (River stone)	T_2 (n = 3) (Crushed stone)	T_3 (n = 3) (Deep water culture/raft)	C (n = 3) (Control)
Temperature (°C)	17.2 ± 0.1^b	17.13 ± 0.055^b	17.03 ± 0.057^b	16.63 ± 0.056^a
pH	7.17 ± 0.051^a	7.13 ± 0.057^a	7.18 ± 0.015^a	7.68 ± 0.0^b
DO ($mg.L^{-1}$)	7.13 ± 0.055^a	7.12 ± 0.153^a	7.15 ± 0.026^a	6.61 ± 0.01^b
Dissolved free CO_2 ($mg.L^{-1}$)	4.86 ± 0.036^a	4.82 ± 0.03^a	4.81 ± 0.025^a	5.1 ± 0.015^b
Hardness ($mg.L^{-1}$)	77.89 ± 0.337^a	79.29 ± 0.991^{ab}	80.07 ± 0.938^b	85.17 ± 0.321^c
Total alkalinity ($mg.L^{-1}$)	150.43 ± 1.069^b	150.0 ± 1.609^b	150.97 ± 1.457^b	126.73 ± 0.665^a
Conductivity ($\mu S.cm^{-1}$)	241.03 ± 4.443^a	239.4 ± 2.605^a	236.17 ± 2.247^a	236.03 ± 4.724^a

The reported values are presented as mean ± standard deviation. n = number of replicates. Mean values with different superscripts across the rows varied significantly ($P < 0.05$).

Table 4. Water quality parameters for various hydroponic systems.

Hydroponic system	Water quality parameters ($mg.L^{-1}$)			
	Ammonium	Nitrite	Nitrate	Phosphate
River stone	0.51 ± 0.02^{bc}	0.16 ± 0.02^a	58.57 ± 4.29^b	2.42 ± 0.45^b
Crushed stone	0.43 ± 0.05^{ab}	0.15 ± 0.04^{bc}	62.63 ± 5.07^b	2.52 ± 0.06^b
(Deep water culture/raft)	0.61 ± 0.04^c	0.14 ± 0.03^{bc}	64.27 ± 6.35^b	2.59 ± 0.09^b
Control	0.34 ± 0.05^a	0.07 ± 0.02	4.12 ± 0.45^a	2.06 ± 0.12^a

The reported values are presented as mean ± standard deviation. n = number of replicates. Mean values with different superscripts across columns varied significantly ($P < 0.05$).

Table 5. Rainbow trout *Oncorhynchus mykiss* growth indices during the experimental trial.

Parameters	Experimental units			
	T_1 (n = 3) (River stone)	T_2 (n = 3) (Crushed stone)	T_3 (n = 3) (Deep water culture/raft)	C (n = 3) (Control)
Initial weight (g)	35.594 ± 0.006^a	$35.59^a \pm 0.004^a$	$35.596^a \pm 0.003^a$	$35.59^a \pm 0.003^a$
Final weight (g)	154.13 ± 0.03^b	154.81 ± 0.675^b	151.26 ± 0.294^a	151.17 ± 0.031^a
Weight gain (g)	118.53 ± 0.023^b	119.24 ± 0.674^b	115.67 ± 0.295^a	115.58 ± 0.033^a
Weight gain (%)	333.01 ± 0.006^b	334.99 ± 1.883^b	324.94 ± 0.843^a	324.76 ± 0.12^a
Weight gain (g day^{-1})	2.63 ± 0.001^b	2.65 ± 0.014^b	2.57 ± 0.006^a	2.57 ± 0.00^a
Initial biomass ($kg.m^{-3}$)	2.85 ± 0.0005^a	2.85 ± 0.0003^a	2.85 ± 0.0002^a	2.85 ± 0.0002^a
Final biomass ($kg.m^{-3}$)	12.33 ± 0.002^b	12.39 ± 0.054^b	12.1 ± 0.023^a	12.09 ± 0.002^a
Biomass gain ($kg.m^{-3}$)	9.48 ± 0.001^b	9.54 ± 0.053^b	9.25 ± 0.023^a	9.25 ± 0.002^a
Total feed fed (g)	128.14 ± 0.023^a	128.12 ± 0.014^a	128.15 ± 0.012^a	128.13 ± 0.011^a
Total protein fed (g)	58.78 ± 0.01^a	58.78 ± 0.006^a	58.79 ± 0.005^a	58.78 ± 0.005^a
Feed conversion ratio	1.08 ± 0.00^a	1.07 ± 0.006^a	1.1 ± 0.002^b	1.1 ± 0.00^b
Feed efficiency ratio	0.92 ± 0.00^b	0.93 ± 0.005^b	0.9 ± 0.002^a	0.9 ± 0.00^a
Protein efficiency ratio	2.02 ± 0.00^b	2.03 ± 0.011^b	1.97 ± 0.005^a	1.97 ± 0.00^a
Specific growth rate (% body weight.day^{-1})	3.26 ± 0.00^b	3.27 ± 0.009^b	3.21 ± 0.004^a	3.21 ± 0.00^a
Survival rate (%)	100^a	100^a	100^a	100^a

The reported values are presented as mean ± standard deviation. n = number of replicates. Mean values with different superscripts across the rows varied significantly ($P < 0.05$).

materials available in local areas may be more readily available and cheaper than imported materials (Neocleous and Polycarpou, 2010). In this study, the efficiency of various hydroponic systems was assessed. Water parameters and growth responses of both fish and plants were measured to determine the effectiveness of the hydroponic setups. Rainbow trout (*Oncorhynchus mykiss*) and lettuce (*Lactuca sativa*) were used as the test species, while river stone, crushed stone, and deep-water culture systems were employed as experimental units. Additionally, flow-through and soil bed units were included to compare

Table 6. Growth parameters of lettuce *Lactuca sativa* during the study period.

Parameters	Experimental units			
	T_1 (n = 3) (River stone)	T_2 (n = 3) (Crushed stone)	T_3 (n = 3) (Deep water culture/raft)	C (n = 3) (Control)
Initial leaves (No.)	1.87 ± 0.057^{a}	1.87 ± 0.152^{a}	1.87 ± 0.057^{a}	1.87 ± 0.208^{a}
Final leaves (No.)	14.53 ± 0.251^{c}	15.53 ± 0.305^{d}	13.43 ± 0.115^{b}	11.53 ± 0.251^{a}
Initial height (cm)	3.09 ± 0.02^{a}	3.09 ± 0.025^{a}	3.11 ± 0.015^{a}	3.11 ± 0.026^{a}
Final height (cm)	23.83 ± 0.02^{b}	24.44 ± 0.021^{c}	23.59 ± 0.02^{b}	20.64 ± 0.361^{a}
Initial weight (g)	0.23 ± 0.04^{a}	0.25 ± 0.01^{a}	0.26 ± 0.045^{a}	0.26 ± 0.03^{a}
Final weight (g)	103.02 ± 2.93^{b}	107.92 ± 2.164^{b}	102.46 ± 3.902^{b}	78.85 ± 4.095^{a}
Weight gain (%)	$45769.28 \pm 9339.224^{a}$	$43121.05 \pm 2174.433^{a}$	40207.5 ± 7682.84^{a}	$30052.31 \pm 2992.383^{a}$
Initial biomass (kg.m^{-2})	0.01 ± 0.001^{a}	0.01 ± 0.00^{a}	0.01 ± 0.002^{a}	0.01 ± 0.001^{a}
Final biomass (kg.m^{-2})	4.33 ± 0.123^{b}	4.53 ± 0.09^{b}	4.31 ± 0.163^{b}	3.31 ± 0.172^{a}
Biomass gain (kg.m^{-2})	4.32 ± 0.125^{b}	4.52 ± 0.091^{b}	4.29 ± 0.165^{b}	3.3 ± 0.171^{a}
SGR (% weight day^{-1})	13.59 ± 6.599^{b}	13.49 ± 4.818^{ab}	13.3 ± 8.742^{ab}	12.68 ± 9.058^{a}
Survival rate (%)	100^{a}	100^{a}	100^{a}	100^{a}

The reported values are presented as mean ± standard deviation. n = number of replicates. Mean values with different superscripts across the rows varied significantly ($P < 0.05$).

the growth and survival rates of both fish and plants. Locally sourced media bed substrates were used to reduce investment costs.

Water quality parameters are crucial indicators of the health of a fish farming system (Woynarovich et al., 2011). In this study, these parameters were well within the recommended range for the grow-out farming of rainbow trout. The control unit exhibited a significantly lower water temperature compared to all the treatment units. In the treatment units, water was recirculated throughout the 45-day experimental period, while the control unit utilised a flow-through system for regular water replenishment, which likely contributed to the observed decrease in water temperature in the control unit.

The experimental groups display a desirable range of pH during the study period. Extremely high or low pH are not conducive for the growth and survival of fish. In an aquaponic system, near to neutral pH facilitates better growth performance of both fish and plants and also boosts the rate of nitrification (Tyson et al., 2004). In the present study, the recorded pH values were near to neutral with only minor differences between the control and treatment groups. The lowering of pH in an aquaponics system is mainly because of nitrification as mild acids are produced during this process, which in turn utilises the alkalinity of water resulting in pH reduction (Timmons et al., 2018). In addition to this, several other factors like nitrification efficiency of hydroponic media, rate of water replacement, retention time of water and amount of fish feed supplied are also responsible for the alteration of alkalinity in aquaponic water (Loyless and Malone, 1997; Espinal and Matulic, 2019). In the conventional recirculatory aquaculture system, alkalinity is generally managed with the use of chemicals like $NaHCO_3$ and NaOH (Loyless and Malone, 1997; Timmons et al., 2018) but any kind of chemicals containing sodium should not be used in aquaponics as it may affect the water uptake rate of the plants (Timmons et al., 2018). The aquaponic water generally uphold the lowering of pH, one of the reasons could be the buffering effect of pH by the plants (Makhdom et al., 2017). Nitrates, the end product of aerobic nitrification, are being taken up as nutrients by the plants primarily for their growth. During this process, the plant roots intake and release cations and anions like H^+ and OH^- respectively, so that the grow-out media surrounded by the plant roots becomes alkaline (Touraine et al., 1988; Jackson et al., 1989). In addition to this, the alkalinity of the aquaponic water is also regained by the denitrification process, generally takes place at the anaerobic sites of the biofilter (Timmons et al., 2018).

The dissolved oxygen (DO) concentration should be in the optimum range for proper functioning of an aquaponics system. This study recorded 7 mg.L^{-1} DO in all treatment waters, which is well within the acceptable range for the growth for vegetables and fish, and for the wellbeing of microbial communities involved in nitrification. Slightly lower DO was recorded in the control unit than the treatments. As per reports, the fish and the microbes, involved in the production of nitrates from ammonia, perform at an optimum rate if DO content of water is >5 mg.L^{-1} and become literally non-functional when the DO is less than 2 mg.L^{-1} (Masser et al., 1999; Alleman and Preston, 2002). DO also play a vital role in plant performance. Lettuce needs more than 2.1 mg.L^{-1} and above 2.5 mg.L^{-1}, respectively to enhance its growth (Goto et al., 1996) and root respiration (Chun and Takakura, 1994). Hence, the DO level of aquaponic water should be kept at par with the magnitude required by the cultivable fish to perform better.

During the study, significant variations ($P < 0.05$) were observed in free carbon dioxide, total hardness, and total alkalinity among different experimental groups, although all values remained within desirable limits.

The water's conductivity was also within the acceptable range for fish culture and did not show significant differences among the experimental replicates. In a fish-only closed recirculating farming system without plants, conductivity tends to increase due to the accumulation of salts and nutrients, a phenomenon managed by water replacement (Rakocy and Hargreaves, 1993). However, in closed recirculating systems like aquaponics, plants actively absorb and utilise nutrients such as nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}), along with other ions and salts, maintaining the system balance.

Maintaining basic parameters of water at optimum condition for fish is most important for their growth and wellbeing (Yildiz et al., 2017). Buildup of ammonia and other effluents with depletion of DO are some of the major issues in closed recirculating fish culture systems (Rijn, 1995). These problems are counteracted earlier through the replacement of water (Hamlin, 2006) as the recommended level for ammonia is <1 $mg.L^{-1}$ (Nijhof and Bovendeur, 1995). Ammonia is excreted by the gills of fish as a result of breakdown of protein, which is again converted to nitrite and then nitrate. The final depends on the maturity and functionality of a biofilter (Timmons et al., 2018). In the control, the water was in flow-through condition which helps in maintaining these parameters within the desirable range. The aquaponic system configured for the present study was efficient enough in nutrient recycling and water quality improvement without any replacement of water (Rakocy et al., 2006; Makhdom et al., 2017). The accumulation of the nutrients helps the plants to utilise them for flourishing growth. Plants generally prefer nitrate than other form of nitrogen for their growth and nitrate is relatively safe for fish, even at higher concentrations (Rakocy et al., 2006). The level of ammonia, nitrite and nitrate were recorded as significantly higher in treatments than the control but were within the recommended levels for fish culture. The acceptable levels of these nitrogenous compounds in the fish-vegetable cultivated water unequivocally demonstrate that the aquaponics system functioned effectively (Buzby and Lin, 2014).

Total phosphate concentration did not vary significantly among the experimental (<2.6 $mg.L^{-1}$) and was less than the recommended limit (3 $mg.L^{-1}$) for salmonids (Davidson et al., 2009). This shows the potency of this indigenous low-tech system in maintaining the phosphate level of water within the acceptable range for fish culture. The phosphate content of aquaponic water merely comes from the phosphorus of fish feed (Davidson et al., 2009; BioMar, 2022) and was then subsequently taken up by the plants for their growth and welfare (Makhdom et al., 2017).

Unlike warm water aquaponics, very few fish species are candidates for cold water aquaponics. Rainbow trout is one among them, which was also taken as the experimental fish for this study. But as per reports, this fish is one of most notorious carnivorous species spread across the globe (Lowe et al., 2000), especially in some European provinces (Stankovi´c et al., 2015). However, the farming of rainbow trout in fish-only or fish-and-plant closed re-circulatory farming systems lowers the menace of the escapement of this fish compared to cage rearing trout in open water bodies. The aquaponics farming also has been referred to as one of the most suitable methods for best management practices and to safeguard the environment (Clay, 2008). Earlier studies claim the suitability of this species for cold water aquaponics in terms of growth and survival (Skar et al., 2015). During the present study, similar quantities of feed were fed to the fish in all experimental groups, but the river stone and crushed stone units had significantly lower FCR of near to one than the DWC and control systems (1.1, Table 5)(Pulkkinen et al., 2019; Salgado-Ismodes et al., 2020; Tunçelli and Pirhonen, 2021). Similarly, the final individual body weight, biomass gain, and specific growth rate of rainbow trout were significantly better in media bed treatments like river stone and crushed stone than DWC and control units. The media beds such as river stone and crushed stone units might facilitate better aeration with filtration efficiency than non-media bed systems hence, providing an environment for the fish to perform better.

The soil less systems bearing diverse groups of nutrients with variable quantity can support the better performance of both leafy as well as fruiting plants (Zaman et al., 2018). The present study recorded the availability of the nutrients like nitrite, nitrate and phosphate in the productive range, as needed for the growth of plants in an aquaponics system (Trejo-Téllez and Gómez-Merino, 2012; Maucieri et al., 2019; Van Rooyen and Nicol, 2022). The growth of lettuce in terms of final weight and final biomass were significantly higher in treatment units such as river stone, crushed stone and DWC compared to the soil bed, which served as control. The treatment units of the aquaponics system may serve as a nutrient pool for the transformation and bioavailability of the nutrients for the plants so that the cultivated vegetables perform optimally. As found in earlier studies, most of the leafy vegetables in an aquaponics system can grow substantially even at lower nutrient levels when compared with the readymade solutions as desirable for their nutritional requirements. However, some of the specific plants especially the higher ones and fruiting vegetables may be supplied with additional nutrients for their better performance (Bittsanszky et al., 2016) depending on the farming conditions, and stages of their development (Goddek et al., 2019). The vegetables and plants selected for an aquaponics system depends on consumer demand and their compatibility with the cultivated fish variety, including balancing the nutrient dynamics of the soilless system (Bosma et al., 2017). Hence, only selected plants such as lettuce, cucumbers, bell peppers, cabbage have been successfully grown in aquaponics systems (Kamal, 2006; Graber and Junge, 2009; Sajjadinia et al., 2010; Roosta, 2014).

Conclusion

In the present study, fish growth and plant growth including several parameters of water were considered as indicators for evaluating the competency of different low-cost, grow-out media in an indigenously developed novel aquaponics system. Rainbow trout and lettuce were taken as experimental species for conducting the study. The result of the trial indicates that the growth and biomass gain of lettuce were significantly better in all treatment groups compared to the control soil bed grow-out and the growth performance of rainbow trout was appreciably higher in media bed units i.e., river stone and crushed stone systems than deep water culture/raft systems and the control. Hence, the media bed systems, prepared with locally available low-cost materials like river stone and crushed stone, can offer better performance for aquaponics systems, without the need to install any additional biofilter.

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