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The effect of swimming activity and feed restriction of rainbow trout (*Oncorhynchus mykiss*) on water quality and fish-plant growth performance in aquaponics

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Abstract

In this study, we investigated the effects of swimming activity and feed restriction on juvenile rainbow trout (*Oncorhynchus mykiss*) in decoupled aquaponic systems. Our focus was on assessing their impact on water quality parameters within the aquaponic setup and evaluating the growth performance of the fish, including final weight (FW), condition factor (*K*), coefficient of variation (c.v.) in weight, specific growth rate (SGR), total feed intake (g/fish), feed conversion rate (FCR), hepatosomatic index (HSI), and viscerosomatic index (VSI), as well as the growth of lettuce (*Lactuca sativa* L. var. elmaria). The study involved 108 juvenile rainbow trout with an average initial weight of 26.54 ± 0.36 g and 60 ten-day-old lettuce seedlings, over a period of 42 days. We designed four treatment groups, each with three fish tanks: static ad libitum (SA), where fish were in static water conditions and fed to satiation; static restriction (SR), with fish in static water and a 25% feed restriction; current ad libitum (CA), where fish experienced forced swimming at 1 BL s^{-1}; and current restriction (CR), with swimming exercise at 1 BL s^{-1} and a 25% feed restriction. Using a flow rate of 1 BL s^{-1} in the tanks for rainbow trout yielded several benefits. Notably, the fish in the CA group exhibited increased feed intake (60 ± 1.78 g $fish^{-1}$) and enhanced fish growth with an FW of 91.72 ± 0.91 g, compared to the SA group (55.88 ± 0.88 g $fish^{-1}$ for feed intake and 89.26 ± 0.81 g for FW). In contrast, the CR group showed a reduced feed intake (39.02 ± 2.78 g $fish^{-1}$) and a lower FW (67.85 ± 1.49 g) compared to the CA group. In addition, the CA group demonstrated positive contributions to fish development with a reduced HSI (1.26 ± 0.02) in comparison to the SA group (1.56 ± 0.14). Inadequate nutrient provisioning in the SR and CR groups negatively impacted fish growth and system efficiency. Our findings suggest that optimizing water flow and feed benefits fish and plants and enhances system sustainability.

KEYWORDS

aquaponic system, feed restriction, lettuce, rainbow trout, swimming performance, water current

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1 | INTRODUCTION

The aquaculture sector has demonstrated remarkable growth over the past three decades, with an average annual expansion rate of 7%–10%, thereby establishing itself as the fastest-growing sector within global food production (FAO, 2018). This surge in aquaculture is primarily driven by escalating global food demands, a burgeoning world population, and an increased recognition of the importance of nutritious diets. However, this growth comes at a time when the depletion of water resources poses a significant global challenge, affecting natural reservoirs, economies, ecological balance, and society at large (Li et al., 2022). In contrast, agriculture, as the largest consumer of global fresh water, accounts for ~70%–80% of its total usage (Crovella et al., 2022). Yet, conventional agricultural practices, which are essential to meet dietary needs, often lead to a myriad of problems, including excessive water and fertilizer use, land degradation, and soil infertility (Goddek et al., 2015).

In this context, alternative cultivation methods, such as aquaponics, which integrates soilless growing techniques (hydroponics) with aquaculture, are gaining increasing importance (Somerville et al., 2014; Tůmová et al., 2020; Yavuzcan Yildiz et al., 2017). The aquaponic systems can be installed in all geographic regions, particularly in urban centers and locations close to markets, making them a feasible agricultural model. In this regard, aquaponic systems emerge as an ecological and economic farming model by reducing carbon and water footprints (Rakocy et al., 2004; Robaina et al., 2019). Another aspect of this study emphasizes the potential of aquaponic systems to enable increased production within the same unit area. By enhancing the flow in the fish tank to accelerate fish metabolism, aquaponic systems not only address the swimming needs of the fish but also facilitate a greater influx of nutrients into the water, thereby promoting a more efficient aquaponic system.

In aquaponic systems, where plants are typically the primary revenue source, fish often play a secondary role, primarily viewed as providers of nutrients for the plants. This perspective can lead to the neglect of fish welfare, especially for species like salmonids, which have specific swimming needs due to their migratory nature (Skov et al., 2015). Swimming is crucial for fish health, impacting their growth, survival, and reproduction (Palstra & Planas, 2011). Engaging in regular swimming exercise has been shown to improve meat quality, reduce stress and aggressive behavior, and enhance schooling dynamics (Brännäs, 2009; Palstra and Planas, 2013). Such activities also influence metabolic rates and can impact growth hormone levels, affecting protein synthesis (Davison, 1997; Deschamps et al., 2009; Skov et al., 2015). Although the efficiency of water usage in aquaponic systems has been studied (Hussain et al., 2014; Nuwansi et al., 2016), the interaction between the swimming needs of fish and the growth of plants in hydroponic systems remains underexplored.

In commercial aquaponic setups, fish may undergo feed restrictions to maintain a balance between the aquaculture and hydroponic components (Chu & Brown, 2022). These strategies, aimed at controlling growth, preventing disease, preserving water quality, and enhancing energy efficiency, can include periodic fasting (Robaina et al., 2019). Such fasting, often aligned with research sampling schedules, can lead to consistent conditions for evaluating animal health across different treatment groups (Tunçelli & Pirhonen, 2021). However, there is a lack of comprehensive research on the optimal feed levels for plant growth and their effects on fish metabolism, health, and welfare (Yavuzcan Yildiz et al., 2017).

This study investigates the effects of sustained swimming regimens and feed restriction on the water quality and growth performance of rainbow trout in an aquaponic system. It evaluates fish growth performance using metrics such as weight gain (WG), feed intake (FI), condition factor (*K*), specific growth rate (SGR), feed conversion ratio (FCR), coefficient of variation (c.v.) of weight, hepatosomatic index (HSI), and viscerosomatic index (VSI). In addition, this study examines the impact of swimming exercises and feed restrictions on the growth of lettuce plants (*Lactuca sativa*) in a decoupled aquaponic system.

2 | MATERIALS AND METHODS

2.1 | Experimental conditions of decoupled aquaponics

The care and use of experimental animals complied with the European Community Council Directive of 24 November 1986 regarding animal welfare laws, guidelines, and policies, as approved by the Istanbul University Ethics Committee (no. 2019/10, Istanbul, Turkey). The juvenile rainbow trout (*Oncorhynchus mykiss*) used in the experiment had an average total length of 13.41 ± 0.08 cm, a weight of 26.54 ± 0.36 g, and a condition factor of 1.10 ± 0.02. Fish obtained from the same broodstocks and kept under identical conditions showed no statistically significant differences between the groups at the beginning of the study ($p > 0.05$). The entire study lasted 10 weeks. The plants used in the study were 10-day-old Elmaria variety lettuce plants (*L. sativa*), with 60 seedlings in each system. The hydroponic subsystem was designed with four units, corresponding to each recirculating aquaculture system separately (Figure 1). The technique employed for hydroponic cultivation was deep water culture. The cultivation beds had dimensions of 220 cm in length, 50 cm in width, and 20 cm in depth. Within each study group, a pair of these plant beds was implemented. To facilitate optimal plant growth, each of these cultivation beds was equipped with five 200-watt LED lamps (SOL Led Plant Growing Lamps, Turkey). Each LED lamp consisted of 64 light-emitting diodes, rated at 3 watts each, collectively spanning a spectrum ranging from 380 to 780 nm, adeptly tailored to support plant growth requirements.

2.2 | Experimental groups of the aquaponic system

This research was conducted at the Aquatic Vertebrate Living Experiment Unit (İÜSUCAN), Faculty of Aquatic Sciences, Istanbul University, Turkey. The study examined the effects of both current presence and feed restriction. The study groups were designed as follows:

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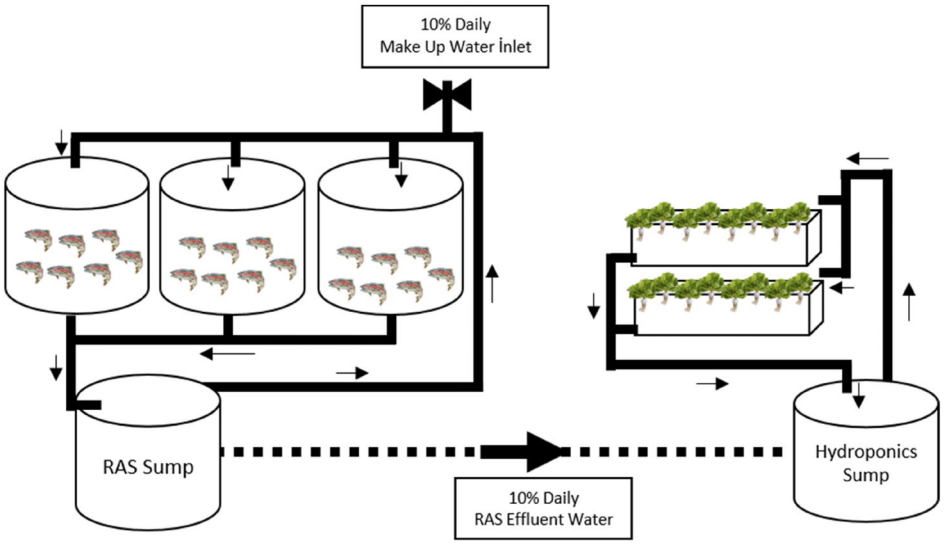


FIGURE 1 Schematic design of the decoupled aquaponics for four different experimental groups. RAS, recirculating aquaculture system.

SA group: The group was kept in static water (no current) (0 BL s^{-1}) and fed ad libitum.

SR group: The group was kept in static water (no current) (0 BL s^{-1}) and had a 25% feed restriction compared to the SA group.

CA group: The group was kept in the current at a rate of ~1 BL s^{-1} and fed ad libitum (until satiation).

CR group: The group was kept in the current at a rate of ~1 BL s^{-1} and had a 25% feed restriction compared to the CA group.

To provide current in water, the methods of McKenzie et al. (2012) and Skov et al. (2015) were used.

2.3 | Water quality parameters of the system

Water quality parameters such as temperature (°C), dissolved oxygen (mg L^{-1}), pH, and total dissolved solids (TDSs, mg L^{-1}) were measured daily. Measurements of phosphate (PO_4), total phosphorus, nitrite (NO_2), nitrate (NO_3), and iron (Fe) were monitored weekly. The assessment of water quality adhered to the methodologies outlined in APHA, AWWA, and WEF (1989) and was executed using a spectrophotometric apparatus.

2.4 | Growth performance of fish

The calculation of WG involved the formula FW IW, where FW represented the final weight of the fish (g) and IW denoted the initial weight of the fish (g). FI was computed using GF − CF, where GF was the amount of feed given (g) and CF signified the quantity of feed collected from the fish tank's outlet (g). K was determined as 100 ($W \times L^{-3}$), with W representing the fish's weight (g) and L indicating the total length of the fish (cm). The SGR (%) was ascertained through the formula: 100 (ln W_2 – ln W_1) × t^{-1}, with W_1 and W_2 designating the fish weights (g) at the commencement and conclusion of the experiment, respectively, and t denoting the study's duration in days. The computation of FCR involved feed intake (g) × biomass $gain^{-1}$. The C.V. of weight was determined for each fish tank by means of the expression: 100 (S.D. × W), where S.D. represented the standard deviation of fish weight within each fish tank and W stood for the mean weight of the fish (g). The HSI was calculated as 100 (LW × FW^{-1}), where LW indicated the liver weight of the fish (g) and FW denoted the fish's weight (g). Similarly, the VSI was computed as 100 (VW × FW^{-1}), with VW representing the visceral weight of the fish (g) and FW indicating the fish's weight (g).

2.5 | Growth parameters of plants

After the harvest and when the plants were planted in the system, the length of the shoot (cm), the length of the plant diameter (cm), the length of the root (cm), plant weight (g), plant root weight (g), and the number of leaves of the plants were determined. Plant diameter was measured by gauging the cross-sectional dimension from an overhead perspective. The determination of plant wet weight was executed by weighing the harvested plant on a digital balance (Radwag, Poland), with an accuracy of 0.01 g. Root length was measured in centimeters by detaching the roots from the hydrotons and measuring from the stem's base to the terminal root tip. The leaf count included only fully developed leaves, excluding pseudo-leaves. Notably, no nutrient solution was introduced to the hydroponic subsystem throughout the duration of the study.

2.6 | Statistical analysis

In this study, the calculation of mean ± S.E. values followed a specific procedure. Initially, two-way ANOVA was used to investigate the interactive effects of feed restriction and swimming exercise (fixed factors) on initial and final wet weight (WG), total length (K), C.V. of weight, SGR, FI, FCR, his, and VSI of juvenile rainbow trout. Prior to

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conducting ANOVA, two essential preliminary assessments were performed: Levene's test for equality of variance across groups and the Shapiro–Wilk test for normal distribution of the data. Each fish tank served as an individual observation unit, with each experimental group consisting of three such units (fish tanks).

For the assessment of plant growth parameters, such as shoot length, plant diameter length, root length, plant weight, plant root weight, and leaf number, each plant was considered as an individual observation unit. Each experimental group comprised 60 lettuce plants. To analyse the data on plant growth parameters, the Kruskal–Wallis test, a nonparametric method suitable for data with non-normally distributed characteristics, and Dunn's post hoc tests were employed.

Data analysis was performed using SPSS 29 for Windows, a software product from IBM SPSS Software, USA.

3 | RESULTS

3.1 | Water quality parameters

Throughout the study, the water temperature was maintained at a consistent level of 15.9 ± 0.03°C in the recirculating aquaculture subsystem where the fish were kept. However, in the hydroponics subsystem (HP) unit, the water temperature averaged 15.4°C, ranging from 15.3 to 15.6°C. The oxygen saturation level remained above 90% during the study, with dissolved oxygen levels ranging between 9.02 and 9.80 mg L^{-1}, pH levels averaging 8.3, ranging between 8.0 and 8.4, and TDS between 220.00 and 275.89 mg L^{-1} (Table 1). The desired optimal values in the system's water were maintained through water exchange, circulation, and aeration.

Regarding phosphate levels, the RAS subsystems contained values of 0.02–0.42 mg L^{-1}, whereas the HP unit had levels of 0.04–0.53 mg L^{-1}. Ammonia levels in the RAS ranged between 0.09 and 0.33 mg L^{-1} and between 0.06 and 0.35 mg L^{-1} in the HP unit. Nitrite values were 0.08–0.18 mg L^{-1} in the RAS and 0.01–0.48 mg L^{-1} in the HP unit. Nitrate values in the RAS ranged from 3.32 to 13.25 mg L^{-1}, whereas, in the HP unit, they ranged from 3.69 to 6.79 mg L^{-1}. Lastly, iron levels were determined to be 0.01–0.04 mg L^{-1} in the RAS and 0.01–0.03 mg L^{-1} in the HP unit (Table 2).

3.2 | Fish growth performance

To assess the growth performance of fish, samples were taken at the beginning and the end of the study. The analysis, presented in Table 3—the quantity of feeding impacts FW, WG, final length, *K*, c.v. of weight, SGR, FI, and HSI of juvenile rainbow trout—meanwhile revealed that swimming significantly influences *K*, c.v. of weight, FCR, and HSI. Upon examining the interaction between swimming and feeding restriction, it was observed that both factors collectively affect FW, WG, final length, SGR, FI, and FCR (Table 3). The initial

TABLE 1 Water temperature (°C), pH, dissolved oxygen (mg L^{-1}), oxygen saturation (%), and TDS comparison in different aquaponic treatment groups.

	RAS				HP				Two-way ANOVA (*p*-value)					
									RAS			HP		
Water quality parameters	SA	SR	CA	CR	SA	SR	CA	CR	1	2	3	1	2	3
Temperature (°C)	15.89 ± 0.22	15.91 ± 0.22	15.96 ± 0.25	15.90 ± 0.20	15.36 ± 0.25	15.33 ± 0.14	15.33 ± 0.15	15.37 ± 0.23	0.616	0.344	0.210	0.941	0.832	0.227
pH	8.11 ± 0.46	8.36 ± 0.31	8.19 ± 0.46	8.40 ± 0.31	8.07 ± 0.31	8.18 ± 0.04	8.00 ± 0.36	8.21 ± 0.09	<0.001*	0.346	0.787	<0.001*	0.694	0.193
Dissolved oxygen (mg L^{-1})	9.49 ± 0.45	9.56 ± 0.33	9.31 ± 0.34	9.6 ± 0.40	9.61 ± 0.14	9.67 ± 0.11	9.70 ± 0.25	9.68 ± 0.25	<0.001*	0.346	0.787	<0.001*	0.694	0.193
Oxygen saturation (%)	93.01 ± 3.08	93.24 ± 1.80	89.30 ± 2.24	93.82 ± 2.85	93.98 ± 2.10	93.37 ± 2.06	94.12 ± 3.13	94.16 ± 3.44	<0.001*	<0.001*	<0.001*	0.502	0.276	0.450
TDS	252.40 ± 34.03	229.10 ± 18.61	275.89 ± 21.33	227.09 ± 19.14	231.28 ± 11.13	222.91 ± 10.08	249.17 ± 13.80	220.00 ± 14.27	<0.001*	0.004*	<0.001*	<0.001*	<0.001*	<0.001*

Note: Data are presented as daily measurement's means (±S.E.; $n = 42$). SA group, the group kept in static water (no current) (0 BL s^{-1}) and fed ad libitum. SR group, the group kept in static water (no current) (0 BL s^{-1}) and 25% feed restriction compared to the SA group. CA group, the group that is kept in the current at a rate of ~1 BL s^{-1} and fed ad libitum (until satiation). CR group, the group that is kept in the stream at a fish total length rate of ~1 BL s^{-1} and 25% feed restriction compared to the CA group. 1, effect of the feeding system; 2, effect of the rate of water flow; 3, effect of the interaction.

Abbreviations: HP, hydroponics subsystems; RAS, recirculating aquaculture subsystems; TDS, total dissolved solids.

*Indicates statistical significance ($p < 0.05$, two-way ANOVA).

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TABLE 2 Comparative analysis of phosphate (A), ammonia (B), nitrite (C), nitrate (D), and iron (E) concentrations (mg L^{-1}) across various aquaponic treatment groups.

	RAS				HP			Two-way ANOVA (*p*-value)					
								RAS			HP		
Water quality parameters	**SA**	**SR**	**CA**	**CR**	**SA**	**SR**	**CA**	**CR**	**1**	**2**	**3**	**1**	**2**	**3**
Phosphate (mg L^{-1})	0.14 ± 0.04	0.10 ± 0.03	0.10 ± 0.03	0.13 ± 0.04	0.18 ± 0.05	0.18 ± 0.06	0.15 ± 0.04	0.20 ± 0.05	0.768	0.844	0.307	0.633	0.830	0.609
Ammonia (mg L^{-1})	0.16 ± 0.02	0.15 ± 0.02	0.17 ± 0.04	0.18 ± 0.04	0.21 ± 0.04	0.20 ± 0.02	0.20 ± 0.03	0.19 ± 0.02	0.935	0.607	0.684	0.671	0.716	0.903
Nitrite (mg L^{-1})	0.20 ± 0.10	0.10 ± 0.04	0.20 ± 0.12	0.13 ± 0.05	0.14 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	0.11 ± 0.01	0.318	0.892	0.876	0.104	0.779	1.000
Nitrate (mg L^{-1})	4.82 ± 0.63	4.79 ± 0.68	5.32 ± 0.74	4.61 ± 0.57	3.43 ± 1.40	3.01 ± 1.23	4.38 ± 1.79	3.37 ± 1.38	0.578	0.810	0.614	0.615	0.596	0.847
Iron (mg L^{-1})	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.01	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.01 ± 0.01	0.02 ± 0.00	0.846	0.846	0.591	0.223	0.223	1.000

Note: Data are presented as 6 weeks means (±S.E.; $n = 6$). SA group, the group kept in static water (no current) (0 BL s^{-1}) and fed ad libitum. SR group, the group kept in static water (no current) (0 BL s^{-1}) and 25% feed restriction compared to the SA group. CA group, the group that is kept in the current at a rate of approximately 1 BL s^{-1} and fed ad libitum (until satiation). CR group, the group that is kept in the stream at a fish total length rate of ~1 BL s^{-1} and 25% feed restriction compared to the CA group. 1, effect of the feeding system; 2, effect of the rate of water flow; 3, effect of the interaction.

Abbreviations: HP, hydroponics subsystems; RAS, recirculating aquaculture subsystems; TDS, total dissolved solids.

weights of the groups were determined at the beginning of the study, and there were no statistically significant differences between the groups for initial weights ($p > 0.05$).

3.3 | Plant growth performance

In assessing plant parameters, specifically plant root weight and leaf number, no significant differences were detected among the groups. The CA group displayed the highest shoot length, exhibiting a significant difference from the other groups, whereas the CR group showed lower values compared to the remaining groups ($p < 0.05$). The plant diameter also demonstrated the highest values within the CA group ($p < 0.05$). Notably, groups with ad libitum feeding consistently exhibited higher means than their counterparts subjected to restricted feeding until satiation. Analysing root length revealed that the SR group had statistically significantly higher values than the other three groups ($p < 0.05$). Regarding plant weight, the CA group demonstrated the highest mean, significantly surpassing both the SR and CR groups (Figure 2).

4 | DISCUSSION

In the present study, implementing a water flow rate of 1 BL s^{-1} in the rainbow trout tanks yielded several advantages, including heightened feed intake, improved fish growth, positive contributions to fish development, a reduced HSI, and improved plant yield when accompanied by an adequate feed supply. Insufficient nutrient provisioning, however, exerted detrimental effects on both fish growth and overall system efficiency. These findings underscore the importance of optimizing water flow and feed strategies, thereby conferring benefits to both aquatic organisms and overall system sustainability.

This study meticulously maintained water temperature at a constant 16.0 ± 1°C in the recirculating aquaculture subsystems, an optimal range for rainbow trout feed intake per Woynarovich et al. (2011). Throughout the experiment, no significant temperature differences were observed between the groups, either in the RAS subsystems or in the HP subsystems. The temperature conditions in this study, ranging from 15 to 22°C, are optimal for the productive growth of lettuce plants, as indicated by Somerville et al. (2014) and Atique et al. (2022).

The study also observed lower levels of dissolved oxygen (9.31 ± 0.34) in the group CA with a higher daily feed intake (60 ± 0.88) and a larger fish WG (65.08 ± 0.95). The consistently high oxygen saturation levels above 90% were pivotal for the welfare of rainbow trout, lettuce, and nutrient-transforming bacteria, ensuring a uniform experimental condition across the groups. The pH values also remained within the optimal range for these organisms, with no significant differences between groups, suggesting a well-balanced aquaponic environment. Similarly, the pH values fell within the appropriate pH range for rainbow trout (Bregnballe, 2015), bacteria (Goddek et al., 2015), and lettuce plants (Somerville et al., 2014), according to the literature

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TABLE 3 Initial and final wet gain (WG), total length (*K*), c.v. of weight, SGR, FI, FCR, HSI, and VSI of rainbow trout, *Oncorhynchus mykiss*, for each experimental group.

					Two-way ANOVA (*p*-value)		
Fish Growth Performance	**SA**	**SR**	**CA**	**CR**	**Feeding effect**	**Current effect**	**Feeding × current effect**
Initial weight (g)	26.51 ± 0.16	26.40 ± 0.38	26.64 ± 0.36	26.63 ± 0.60	0.804	0.463	0.825
Final weight (g)	89.26 ± 0.99	75.06 ± 3.14	91.72 ± 1.12	67.85 ± 1.83	<0.001*	0.069	0.003*
Weight gain (g)	62.75 ± 0.99	48.66 ± 2.85	65.08 ± 0.95	41.22 ± 2.23	<0.001*	0.051	0.002*
Final length (cm)	18.57 ± 0.13	18.21 ± 0.26	19.10 ± 0.10	18.07 ± 0.31	<0.001*	0.159	0.029*
K	1.38 ± 0.01	1.24 ± 0.08	1.32 ± 0.01	1.16 ± 0.05	<0.001*	0.030*	0.757
c.v. of weight	13.15 ± 0.77	18.99 ± 1.69	7.61 ± 0.56	11.34 ± 1.30	<0.001*	<0.001*	0.157
SGR	2.85 ± 0.03	2.45 ± 0.10	2.94 ± 0.03	2.21 ± 0.11	<0.001*	0.125	0.005*
Total FI (g/fish)	55.88 ± 1.35	41.13 ± 2.78	60 ± 0.88	39.02 ± 1.78	<0.001*	0.371	0.019*
FCR	0.89 ± 0.01	0.84 ± 0.01	0.92 ± 0.01	0.95 ± 0.01	0.108	<0.001*	<0.001*
HSI	1.56 ± 0.14	1.35 ± 0.13	1.26 ± 0.02	1.16 ± 0.03	0.028*	0.003*	0.408
VSI	8.48 ± 0.33	7.45 ± 0.39	6.95 ± 0.54	7.18 ± 0.30	0.353	0.054	0.153

Note: Data are presented as fish tank means (±S.E.; $n = 3$). SA group, the group kept in static water (no current) (0 BL s^{-1}) and fed ad libitum. SR group, the group kept in static water (no current) (0 BL s^{-1}) and 25% feed restriction compared to the SA group. CA group, the group that is kept in the current at a rate of ~1 BL s^{-1} and fed ad libitum (until satiation). CR group, the group that is kept in the stream at a fish total length rate of ~1 BL s^{-1} and 25% feed restriction compared to the CA group.

Abbreviations: FCR, feed conversion rate; FI, feed intake; HSI, hepatosomatic index; SGR, specific growth rate; VSI, viscerosomatic index.

*Indicates statistical significance ($p < 0.05$, two-way ANOVA).

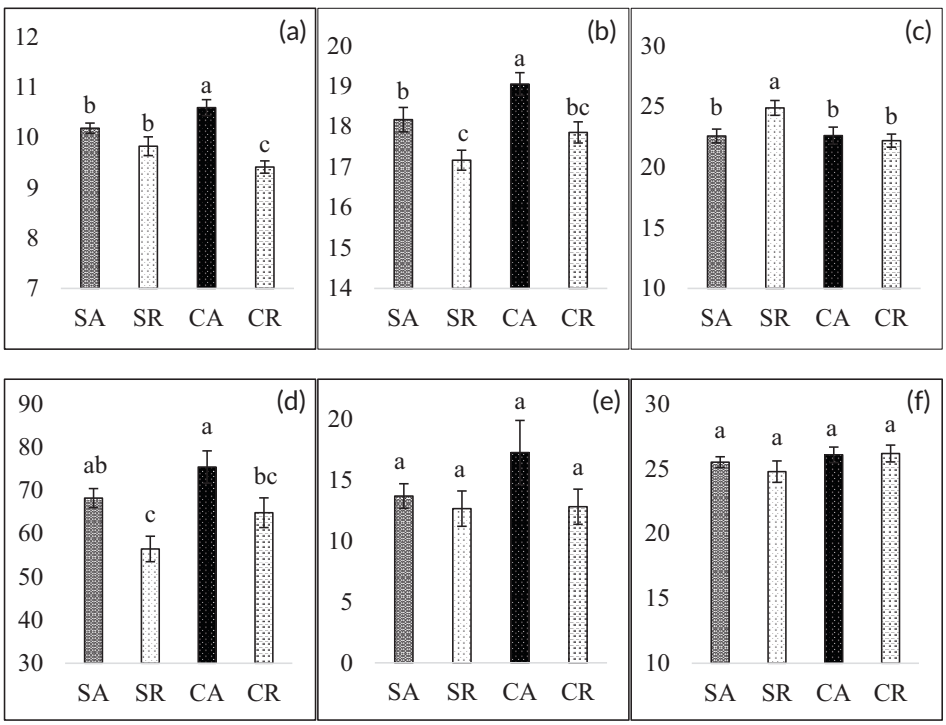


FIGURE 2 Plant growth performance across experimental groups. (a) Length of the shoot (cm). (b) Length of the plant diameter (cm). (c) Length of the root (cm). (d) Plant weight (g). (e) Plant root weight (g). (f) Leaf number. The bars and error bars represent mean ± S.E. Lowercase letters denote significant differences ($p < 0.05$) between experimental groups a Kruskal–Wallis followed by a Dunn's post hoc test ($n = 60$ plants). SA group, the group kept in static water (no current) (0 BL s^{-1}) and fed ad libitum. SR group, the group kept in static water (no current) (0 BL s^{-1}) and 25% feed restriction compared to the SA group. CA group, the group that is kept in the current at a rate of ~1 BL s^{-1} and fed ad libitum (until satiation). CR group, the group that is kept in the stream at a fish total length rate of ~1 BL s^{-1} and 25% feed restriction compared to the CA group.

(Birolo et al., 2020; Rakocy et al., 2004), and there were no intergroup differences. There was a pivotal link between feed management and water quality in aquaponic systems, evidenced by the observed variation in TDS levels. Higher feed intake resulted in an increase in TDS, attributed to the introduction of more soluble substances into the system. This relation is crucial as it underlines the dynamic interplay between feed input and nutrient balance, which significantly influences both fish and plant growth in aquaponics. These findings were particularly evident in the superior harvest outcomes of the CA group, underscoring the importance of strategic feed management in optimizing aquaponic production.

Further, the investigation into fish growth and performance revealed that water flow in tanks housing juvenile trout significantly boosts WG. This was particularly pronounced when trout were fed to

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satiety, highlighting the positive impact of swimming activity and tailored feeding strategies on the growth performance of rainbow trout. Specifically, in an aquaponic setting, implementing water flow in tanks with juvenile trout resulted in marked WGs (62.75 ± 0.99 g for SA; 65.08 ± 0.95 g for CA). In contrast, introducing a restricted feed regime, despite the presence of water flow, led to a notable decrease in live WG (41.22 ± 2.23 g for CR), a consequence of increased energy expenditure. However, the increase in length observed in the trout in the CA group is thought to be due to the elongation of their bodies (19.10 ± 0.10 cm) due to forced swimming caused by water flow. Yu et al. (2022) found that extended periods of induced swimming activity had no significant effect on the growth rate, feed efficiency, or morphological characteristics of muscle tissues in gilthead seabream. However, it did result in a significant alteration in their body shape.

The FCR values exhibited a lower trend among juvenile trout confined in static water conditions (0.89 ± 0.01 for SA; 0.92 ± 0.01 for CA). Interestingly, this outcome contrasts with prior research that suggests that swimming activities in water could lead to decreased FCR. For instance, Larsen et al. (2012) reported that rainbow trout maintained at reduced density and exposed to a current of 0.9 BL s^{-1} exhibited improved FCR values in comparison to fish kept in a constant current environment. Conversely, Birolo et al. (2000) documented an FCR of 1.58 in a study involving rainbow trout cultivated within an aquaponic system. Contrary to some previous studies (e.g., Birolo et al., 2000; Larsen et al., 2012), we found a lower FCR trend among fish in static water conditions. This divergence from prior research suggests that the impact of swimming activity on FCR may be more complex than previously understood, potentially influenced by additional factors such as feed regime and tank conditions.

In our study, the quantity of feeding significantly influenced the SGR values ($p < 0.001$), whereas the impact of the current was not statistically significant ($p = 0.125$). Larsen et al. (2012) further indicated that rainbow trout under low-density conditions and subjected to a current of 0.9 BL s^{-1} displayed enhanced SGR values relative to fish residing in an uninterrupted current. However, the findings from Skov et al. (2015) contradicted this, as they observed that engaging in exercise at a current of 1 BL s^{-1} exerted a significantly adverse influence on both SGR and FCR, potentially attributable to the application of a restricted feeding regimen. McKenzie et al. (2012) uncovered SGRs in trout ranging from 1.36 to 1.41 in static water and between 1.35 and 1.42 in flowing water. In their study, they noted that the current did not yield a positive impact on SGR. The existing body of research provides valuable insights into the influence of swimming activity and feeding regimes on the growth and physiological responses of various fish species. Houlihan and Laurent (1987) observed enhanced growth rates in trout reared at 12°C and swimming at a velocity of 1 BL s^{-1} when compared to non-swimming counterparts, although specific feed intake details were lacking. In contrast, McKenzie et al. (2012) reported no discernible improvements in growth or feed conversion when fish were subjected to a limited feeding regimen at 0.9 BL s^{-1} and 14°C. Skov et al. (2015) noted a noteworthy negative impact of exercise at a current of 1 BL s^{-1} on both specific SGR and FCR. This adverse effect on growth and feed efficiency could be attributed to the constrained feeding schedule, as also observed in the study by McKenzie et al. (2012).

When fish have unrestricted access to food, they may encounter an excess of energy, as highlighted by McKenzie et al. (2012). In such circumstances, the increased energy expenditure associated with swimming does not hinder their growth. Furthermore, the positive effects of water currents, such as the mitigation of aggressive behavior or erratic activity, could contribute significantly to noticeable growth.

Skov et al.'s (2015) findings suggest that rainbow trout compelled to swim at a rate of 1 BL s^{-1} experience an elevated demand for maintenance energy. To meet this demand, they must oxidize a significantly larger fraction of ingested energy, thereby sacrificing somatic growth. It is a well-recognized phenomenon that exercising salmonids, when provided with ample food, exhibit accelerated growth due to increased appetite. However, when food rations are limited, growth rates do not demonstrate similar enhancements (Davison, 1989).

In addition to increased feed intake, as observed by Skov et al. (2015), improved growth appears to be influenced by enhanced nutrient retention, as indicated by Grisdale-Helland et al. (2013). They noted higher maintenance energy requirements in Atlantic salmon swimming at speeds of 1.1 BL s^{-1} compared to 0.3 BL s^{-1}, although this difference did not translate into varied growth rates, despite both groups being maintained on rations of 0.9% body mass per day.

The variation in responses between fish subjected to forced swimming and those kept in stagnant water may be attributed to changes in plasma lactate levels. Largemouth bass forced to swim exhibited increased lactate in plasma, decreased phosphocreatine in white muscle, and increased cardiac output, which were not observed in fish reared in static water (Suski et al., 2007). However, some studies have found that induced swimming at sustainable speeds does not significantly affect plasma lactate levels, suggesting that sustained swimming could be supported primarily by aerobic metabolism, although the specific outcomes may depend on the species and the swimming conditions applied (He et al., 2013; Johnston & Moon, 1980; Palstra et al., 2020).

The *K* value of 1.32 ± 0.01 was determined due to the greater length displayed by fish within the exercise group under conditions of adequate nutrition, whereas a value of 1.38 ± 0.01 was noted for the group maintained in a static state without exercise. A parallel trend was observed within the groups subjected to dietary restriction. Among these cohorts, the *K* for the exercised group exhibited a lower value of 1.16 ± 0.04, in contrast to the value of 1.24 ± 0.06 observed for the group under constant aquatic conditions. The quantity of feeding ($p < 0.001$) significantly affected the *K* value, whereas the impact of the current ($p = 0.030$) also demonstrated a statistically significant effect on the *K* value. This variance is attributed to the water current's effect, which promotes fish elongation.

The C.V. of weight values demonstrated higher levels in the static water groups (13.15 ± 0.77 for SA; 18.99 ± 1.69 for SR), contrasting with reduced variation observed in groups exposed to water currents (7.61 ± 0.56 for CA; 11.34 ± 1.3 for CR). This aligns with established literature indicating that variation tends to increase in scenarios of

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inadequate feeding. An intriguing finding from this study is the decrease in variance under the influence of water currents, which can be attributed to fish swimming against the current to avoid aggressive interactions. Damsgård et al. (1997) noted that a reduction in nutrient provisions and/or water flow rate intensifies intraspecies hierarchy, leading to heightened interindividual variability in food intake and consequently elevating the c.v. of weight. Remarkably, subsequent normalization of flow and provision of adequate nutrition in this study resulted in a decrease in the c.v. of weight value, restoring it to its initial level. Considering that fish are collectively maintained within a tank, the imposition of feed limitations results in nonuniform growth, with increased feed scarcity intensifying competition and accentuating disparities in food consumption. In scenarios of restricted feeding, certain individuals may monopolize the available food supply, sustaining their growth, whereas others endure deprivation and weight loss due to limited access to sustenance, contributing to an upsurge in size variability over time (Grant, 1993; Jobling, 1995; McCarthy et al., 1992).

The HSI value was significantly influenced by the quantity of feeding ($p = 0.028$), and a statistically significant effect on the HSI value was also observed in relation to the current ($p = 0.003$). This investigation delved into the intricate interplay between feed restrictions and swimming activities, specifically scrutinizing their impact on various physiological and growth parameters. An insightful exploration of the HSI unveiled noteworthy dynamics. Initially, conjectures aligned with escalated energy demands linked to heightened piscine locomotion during swimming, postulating a resultant reduction in hepatic mass. This assumption was derived from the anticipation that robust exercise would induce a decline in glycogen reserves, potentially leading to diminished HSI values. However, empirical findings, while corroborating this supposition under ad libitum feeding conditions, revealed contrasting outcomes when the swimming regimen was introduced. Remarkably, these findings demonstrated elevated HSI values among cohorts engaged in current-assisted swimming, independent of the swimming effect, further modulated by the variations in fish lengths within the restricted feeding groups.

Furthermore, contrasting patterns emerged within the VSI data. The HSI value was not influenced by the quantity of feeding ($p = 0.353$), and no effect on the HSI value was also observed in relation to the current ($p = 0.054$). Specifically, the group subject to satiation-level feeding and swimming exhibited a diminished VSI (6.95 ± 0.93 for CA) in comparison to their static water counterparts (8.48 ± 0.57 for SA). This disparity may be attributed to the utilization of internal organ fat for energy during swimming activities. In contrast, the limited feeding groups showcased no significant VSI variations (7.45 ± 0.68 for SR; 7.18 ± 0.52 for CR), likely due to insufficient food consumption preventing fat accumulation in their internal organs. Notably, the impact of swimming exercises on VSI values in juvenile *Oncorhynchus tshawytscha*, as studied by Parker and Barnes (2014), yielded neither positive nor negative effects. Conversely, the study by Good et al. (2016) documented lower visceral weight in Atlantic salmon subjected to exercise, potentially attributed to reduced visceral fat reserves or heightened mobilization in response to sustained exercise. Simpkins et al. (2003) observed that inactive rainbow trout maintained relatively constant lipid levels, whereas active fish experienced a decline in lipid content. This can also affect the lipid reserves of the fish, potentially influencing various physiological aspects. In examining the implications of feed restriction and swimming activity on the physiological parameters of rainbow trout, the study unveiled complex interactions impacting the HSI and VSI. These findings contribute to a deeper understanding of how different aquaculture practices can affect the physiological state and health of fish.

An exploration of the repercussions of feed restrictions and swimming activities on lettuce plants within the hydroponic subsystem unveiled intriguing findings. Specifically, the group exposed to current-assisted swimming and fed until satiation exhibited significantly increased plant diameter and root length, with a marginal increment in plant weight. This divergence is likely attributed to variations in feed intake between groups, highlighting the distinct outcomes stemming from the implementation of current-assisted swimming. When the water flow in which trout reside is increased, there is a concurrent rise in total ammonia nitrogen excretion, coupled with a reduction in protein turnover (Skov et al., 2015). This phenomenon results in an increased availability of nutrients in the water, particularly enhancing plant growth by stimulating root development and overall plant expansion (Goss et al., 1993). Consequently, this leads to accelerated plant growth, fostering an environment where plants can assimilate more nutrients from the water.

Furthermore, the study underscored the paramount significance of accounting for swimming-induced effects when designing production systems. These effects can extend to tank morphology, impacting design considerations encompassing production cost, space utilization, water quality management, and fish husbandry. Empirical insights into tank designs tailored for intensive fish cultivation have been extensively documented in the literature (Timmons et al., 1998; Wheaton, 1977). The current trend toward large circular culture tanks in fish farming for human consumption aligns with the advantageous self-cleaning attribute of such tanks. However, maintaining this feature necessitates consistent water inflow and outflow, fostering uniform flow rates throughout the tank without impeding fish exercise. Although enhanced growth outcomes have been observed in relation to water flow rates, it is imperative to adhere to species-specific and growth stage–dependent speed thresholds to prevent overexertion.

Subsequent investigations have shed light on the implications of continuous swimming. Houlihan and Laurent (1987) observed an increase in protein accumulation in the gill and muscle tissues of fish engaged in 6 weeks of continuous swimming. According to Losordo and Westers (1994), water currents with a speed of 0.5–2.0 fish BL s^{-1} are optimal for fish health, muscle elasticity, and respiratory protection. This phenomenon is attributed to swimming's potential to promote protein synthesis while inhibiting muscle tissue degradation. However, the enhanced growth rate resulting from swimming is not solely due to increased synthesis retention efficiency; it also implies escalated feed intake to meet augmented energy and protein synthesis demands. Exercising trout, when fed to satiation, demonstrate accelerated growth due to amplified appetite; however, growth rates do not surge under diminished feed rations (Davison, 1989). In our study, this phenomenon is explained by the observation that

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swimming groups fed until satiation ingested more feed, resulting in enhanced growth compared to the static water group. The study also provided valuable insights into plant growth within the hydroponic subsystem, demonstrating the significant impact of fish activity and feeding regimes on plant growth parameters. This underscores the interconnected nature of aquaponic systems and emphasizes the importance of considering both components when optimizing these systems for production.

In conclusion, this study provides comprehensive insights into aquaponic systems involving rainbow trout and lettuce, emphasizing the critical roles of water flow and feeding strategies in optimizing overall productivity and sustainability. The intricate interplay between swimming activity, feeding regimes, and fish growth, influenced by factors such as food availability, underscores the need for further research to elucidate mechanisms and optimize fish management in diverse aquaculture conditions. The findings suggest that maintaining a current of 1 fish BL s^{-1} positively contributes to fish growth with adequate supplementary feeding, whereas static water conditions may compromise crucial functions. To enhance fish well-being and production efficiency, the study recommends a tailored approach, including a current flow rate at 1 BL s^{-1} and appropriate feeding practices. Encouraging outcomes in the growth of juvenile rainbow trout and lettuce plants highlight the importance of considering feeding dynamics and water flow parameters during the design and construction of aquaponic systems, with the integration of a flow rate equivalent to 1 BL s^{-1} emerging as a salient suggestion.

AUTHOR CONTRIBUTIONS

Gökhan Tunçelli: formal analysis, investigation, data curation, writing—original draft, and visualization. Devrim Memiş: conceptualization, methodology, validation, resources, writing—review and editing, supervision, and project administration.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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