The Effect of Light-Emitting Diodes (LEDs) on the Development of Duckweed (*Lemna minor*) in Co-Culture with Red Tilapia (*Oreochromis* spp.)

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ABSTRACT

The effects of artificial light source and photoperiod on duckweed (*Lemna minor*) growth and the impact of duckweed on red tilapia (*Oreochromis* spp.) growth in an aquaponic culture are not well understood. This study aimed to investigate: 1) effects of light source and photoperiod on growth of duckweed and water quality, and 2) the effects of feeding red tilapia with different ratios of duckweed: artificial feed. In Phase I, three different artificial light sources (LED white light, T5 fluorescent white light, and LED blue light) were used and then a consecutive experiment was conducted using LED white light with three different photoperiods: 24:0, 16:8, and 12:12 (light:dark). In Phase II, red tilapia were fed with three feeding regimes made up of different percentages (by weight) of duckweed (0%, 5%, and 10%) to artificial pellet feed. Overall, our results suggest that using LED white light with a photoperiod of 16:8 (light:dark) was effective for maximizing duckweed growth in aquaponic culture and consequently resulted in lowest total ammonia nitrogen (TAN) and NO_2^-, and that replacing pellet feed with duckweed at 5% or 10% can increase the growth rate of red tilapia.

Keywords: Aquaculture, Duckweed, *Lemna minor*, Nutrient, *Oreochromis* spp., Red tilapia

INTRODUCTION

Duckweed (*Lemna minor*) is a small floating plant that is often found in still or slow-moving bodies of water like ponds, lakes, and streams (Ozengin and Elmaci, 2007). It has a simple structure, consisting of a small circular leaf and a short root hanging from the leaf (Melaragno and Walsh, 1976). Duckweed is known for its ability to reproduce quickly, often resulting in large, dense mats on the water surface (Journey *et al*., 1991). The growth and development of duckweed is influenced by various environmental factors, including temperature, nutrients, and light (Coughlan *et al*., 2022). In particular, the type of light can significantly impact duckweed growth (Yin *et al*., 2015). The role of different light sources in aquaponics systems with koi carp is significant for the growth and development of plants such as lettuce, parsley, and cress (Memiş *et al*., 2023). Full-spectrum light, which consists of a range of wavelengths from ultraviolet to infrared, is known to be optimal for duckweed growth (Baek *et al*., 2021). However, there are diverse opinions regarding the effects of artificial light sources, such as fluorescent lamps or light-emitting diodes (LEDs), on duckweed growth (Engbers, 2006).

Photoperiod, or the length of time that an organism is exposed to light each day, can have a significant effect on the development of duckweed (Thomas and Vince-Prue, 1996). Research has

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shown that the photoperiod plays a key role in the development of duckweed, with longer periods of light exposure resulting in increased growth and reproduction (Clark, 2002). This is thought to be due to the fact that light is an important cue for the plant to initiate reproductive development (Fankhauser and Chory, 1997). Additionally, photoperiod can affect the distribution of duckweed across the water surface, as the plant is more likely to thrive in areas with longer periods of light exposure (Yin *et al*., 2015). Understanding the role of photoperiod in duckweed development is important for a variety of practical applications, including in an aquaponic culture (Baek *et al*., 2021).

Aquaponic culture is a sustainable and efficient method of food production that combines raising aquatic animals with cultivation of plants in a closed system (Tyson *et al*., 2011). This type of agriculture relies on the symbiotic relationship between the fish and plants, where the fish provide nutrients for the plants through their waste, and the plants, in turn, help to purify the water for the fish (Neori *et al*., 2004). One species of fish that is commonly used in aquaponic systems is the red tilapia (*Oreochromis* spp.), which is known for its hardiness and fast growth rate (Rakocy *et al*., 2003). Red tilapia is omnivorous, meaning they can be fed a diverse diet including both plant and animal-based sources of nutrition (Boonanuntanasarn *et al*., 2018). This versatility makes them well-suited for use in aquaponic systems that rely on nutrient cycling between the fish and plants (Tyson *et al*., 2011). In addition to their value as a food source for humans, red tilapia can also help to control algae and pests in the system, making them a valuable component of any aquaponic system (Rakocy, 2012).

The principle behind duckweed-based water treatment is rooted in its capacity to be utilized as a natural biofilter, whereby pollutants are effectively removed from contaminated water (Popa *et al*., 2017). This mechanism is primarily reliant on the plant's ability to absorb and accumulate various substances, including nutrients (e.g., nitrogen and phosphorus) (Liu *et al*., 2017), heavy metals, organic pollutants, and pharmaceutical residues (Ekperusi *et al*., 2019). The absorption process takes place through the root structures and fronds, which possess fine rootlets that allow for the absorption of dissolved nutrients and contaminants from the surrounding water.

Previous research has examined the impact of artificial light sources on the growth of duckweed. Notably, an experiment demonstrated that augmenting the light intensity from 50 to 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ resulted in a significant increase in the relative growth rate (RGR) for duckweed (Petersen *et al*., 2022). It has been reported that light source and photoperiod are important for weight increment of *Landoltia punctate*, one species of duckweed (Gallego *et al*., 2022). However, the impact of duckweed in an aquaponic culture with red tilapia is still unclear. Therefore, this study was designed in two phases with the following objectives: 1) Phase I, to determine the effect of LED white and LED blue light on duckweed growth compared to T5 fluorescent white light; and 2) Phase II, to investigate the effect of duckweed on red tilapia growth compared to commercial feed. Understanding the effect of these factors on the growth and development of aquatic organisms is important for optimizing and improving efficiency and profitability in aquaculture operations.

MATERIALS AND METHODS

Phase I

Procedure

The duckweed was collected in Yilan County, Taiwan, near a spring mouth, river, and canal. It was then cultivated in a 10-ton spherical tank containing commercial organic fertilizer (Taiwan Fertilizer Vitality Biotechnology Nutrition Formula 3). The compost included 0.5% nitrogen, 0.1% potassium oxide, 1% calcium oxide, 7.9% organic matter, and had a pH of 7.40 (Parkinson and Allen, 1975). An initial quantity of 1 g of duckweed was added to each plastic container.

During the 16-day trial, the temperature was kept between 28 and 29 °C. The experiment was set up by filling each black rectangular plastic container (15×10.5×7.5 cm) with diluted fertilizer solution, which had an initial nutrient concentration of 9.3 mg·L^{-1} TAN, 12.4 mg·L^{-1} NO_3^-, and 6 mg·L^{-1} PO_4^{3-} (Hasan and Rina, 2009).

Phase I was divided into two separate trials. In the first trial, three different light sources were used: LED white light, T5 fluorescent white light, and LED blue light. The photoperiod for this trial was set at 24:0 (light:dark). The light intensity of each treatment was controlled to 110 PPFD (mol·m^{-2}·s^{-1}) using a light meter (ISM-Lux, Taiwan) and IZUSU Optic Software v. 2.4.4.2 (Taiwan) (Yin *et al*., 2015). An initial duckweed quantity of 0.05 g (4-6 fronds) was added in each treatment. This resulted in a total of nine different treatments.

In the subsequent experiment, three photoperiods, 24:0, 16:8, and 12:12, were tested under the best light source identified in the previous experiment (LED white light). The experimental set up was similar to the first experiment, with three replicates.

Biomass of duckweed

Photographs of the duckweed were captured every four days, starting at 10:00 a.m., for 16 days. Water was carefully added to each container until it reached its initial level and then imaging equipment was set up, ensuring uniform resolution for the various regions of the duckweed fronds. To determine the biomass of the duckweed, a digital camera (EOS 500D, China) was employed. To capture image samples, a camera stand equipped with a camera holder and five white cover boards were used. The stand measured 10×10×18 inches and was used to provide a consistent spacing between each photographed sample, and also served as a light diffuser to create a more uniform lighting pattern. The camera was set with an aperture size of f2.2, a focal length of 29 mm, a sensor size of 1/3, and a pixel size of 1.22 m. After taking photographs, an image sample was individually evaluated for sample biomass by using Image J Fiji software (Figure 1). The calculation of frond area was well described in a previous study (Gallego *et al*., 2022).

Statistical analysis

Statistical Analysis Software (SAS) Studio Education (SAS Institute Inc., Cary, North Carolina) was used. To determine the optimal performance, we conducted individual analyses on three light sources and three photoperiods using one-way ANOVA. A post-hoc test, the Tukey procedure, was used to compare the differences between experimental groups at a significance level of 0.05.

Phase II

Procedure

Red tilapia weighing around 20–25 g were obtained from the Animal Research Centre at National Taiwan Ocean University. The tilapia were reared in a 220-L tank supplied with aeration and were fed with 30% protein commercial floating pelleted feed at 5% body weight twice a day. Any uneaten pellets were removed two hours after feeding, and 10% of the water was changed every day. The experiment was conducted in a co-culture system consisting of two connected plastic aquarium tanks, each 35×25 cm and 20 cm in height (with a water capacity of approximately 20 L and a water surface area of 500 cm^2). The tank system was aerated using an air stone and had a pipe to circulate water from the red tilapia tank to the duckweed tank. A schematic drawing is shown in Figure 2. In the 16-day trial, the tilapia were also arranged in a completely randomized design (CRD) with three replicates. The treatments consisted of three feeding regimes using different ratios of duckweed and pellets: 0% (0% duckweed, 100% pellets), 5% treatment (5% duckweed, 95% pellets), and 10% treatment (10% duckweed, 90% pellets) with a feeding rate of 5% body weight. During the experiment, water samples were taken once every four days at 10:00 in the morning over the entire 16-day trial for analysis of total ammonia nitrogen (TAN), NO_2^-, NO_3^-, and PO_4^{3-}. After sampling, tap water was added to the tanks to restore the water level. Measurements of the red tilapia were taken at the beginning of the experiment, and samples were collected on the final day (day 16) of the experiment.

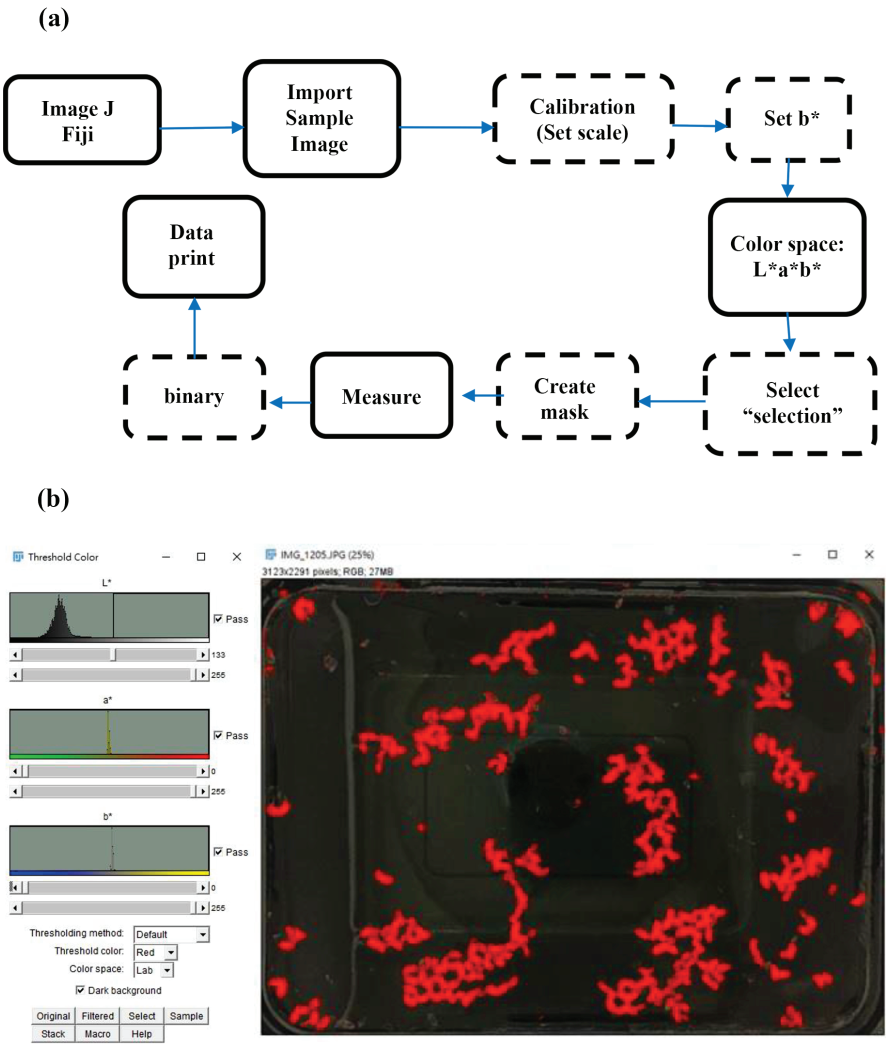


Figure 1. Schematic of the duckweed image analysis procedure, modified from Gallego *et al.* (2022). (a) Analysis of color grading selection method using CIE L*a*b*. (b) Frond regions are marked in red, and their corresponding histograms are presented in the 'Threshold Color' tab (left). L* = lightness, a* = green to red axis, and b* = blue to yellow axis.

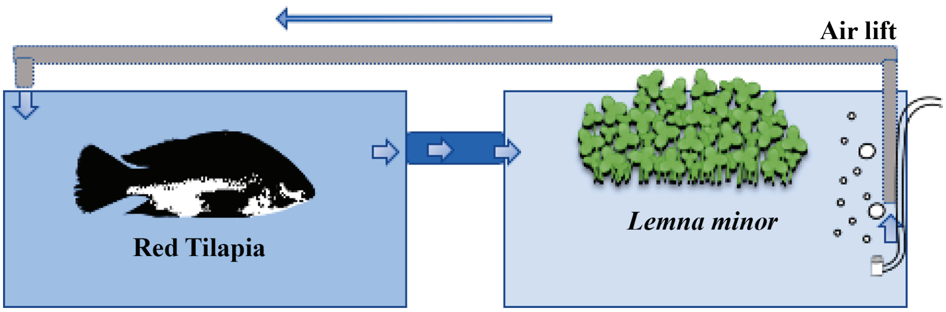


Figure 2. Schematic drawing of duckweed co-cultured with red tilapia.

Analysis of water quality

For the collection of water samples, we used 15-ml Labcon polypropylene centrifuge tubes. To measure dissolved oxygen (DO), water temperature, and pH, we used a Mettler-Toledo Lutron DO-5510 meter from Kutron Electronic Enterprise Co., Ltd. (Taipei, Taiwan) and an Easy pH meter from Mettler-Toledo International Inc. (Columbus, Ohio, USA). Water quality evaluations were conducted using the APHA (1998) standard methods for water and wastewater inspection; we analyzed TN, TAN, NO_2^-, NO_3^- and soluble PO_4^{3-} on a 96-well plate. ELISA was performed using a spectrophotometer (Hitachi High-Technologies Corporation of Tokyo, Japan) (APHA, 1998; Xu and Shen, 2011; Rice *et al*., 2012).

Sampling of red tilapia

The weight of each individual fish was determined using an electronic scale (TX2202L, Shimadzu Co., Tokyo, Japan). The growth performance of the experimental fish was assessed using the following parameters: % weight gain, specific growth rate (SGR), average weight increase (average WI), feed conversion ratio (FCR), and protein utilization efficiency ratio (PER) (Halver and Hardy, 2003).

Statistical analysis

Statistical Analysis Software (SAS) Studio Education (SAS Institute Inc., Cary, North Carolina) was used. One-way analysis of variance was conducted to test the effect of partial replacement of artificial feed with different percentages of duckweed. To compare the differences between groups at a significance level of 0.05, a post-hoc test, the Tukey procedure, was conducted.

RESULTS AND DISCUSSION

Phase I:

Effects of different light sources on growth of duckweed

The spectra of tested light sources are presented in Figure 3. LED blue light had a negative effect on weight gain and average weight increment of duckweed throughout the culture period (Figure 4a and 4c). In contrast, on day 4, the duckweed exhibited the highest growth rate under LED white light, followed by lower growth rates under fluorescent white T5 light and LED blue light ($p<0.05$) (Figure 4b). However, on day 8, the growth rate decreased under LED white light, while T5 light produced the highest growth rate and LED blue light showed the lowest. After eight days, the results indicated an increase in the growth rate of duckweed under LED blue light, whereby the duckweed in the containers of both fluorescent T5 and LED white light fully occupied the water surface. This indicated that different wavelengths of light have varying effects on duckweed growth.

There are conflicting results on the effects of blue light on duckweed growth, for example, a negative impact was reported by Islam *et al*. (2012) and Lee *et al*. (2023), while others demonstrated a positive effect (Muneer *et al*., 2014; Dănăilă-Guidea and Delian, 2020). This discrepancy could be attributed to various factors such as the intensity and duration of light exposure, the species of duckweed being examined, and the environmental conditions in which the plants were grown. In our study, the negative influence of LED blue light on duckweed growth might be because blue light had only one spectrum of photosynthetic photon flux density compared to other wavelengths (Figure 3), meaning that it was less effective at driving photosynthesis. The combination of these factors might contribute to the observed decrease in the growth rate of duckweed under LED blue lights after day 8 in our study.

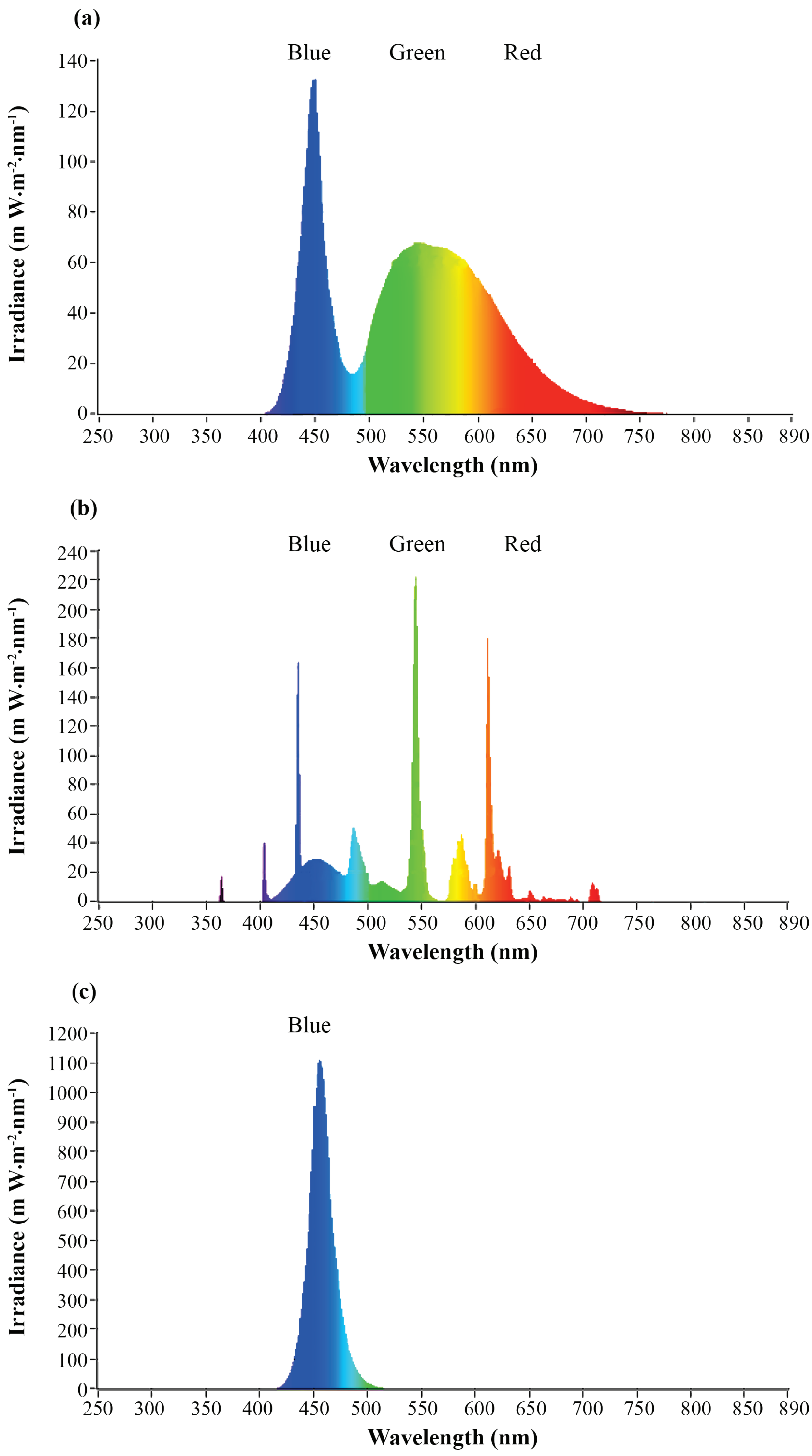


Figure 3. Irradiance value of wavelengths produced by three light sources: LED white light (a), fluorescent white T5 light (b) and LED blue light (c) measured by using SM-Lux and IZUSU Optic software v. 2.4.4.2, Taiwan.

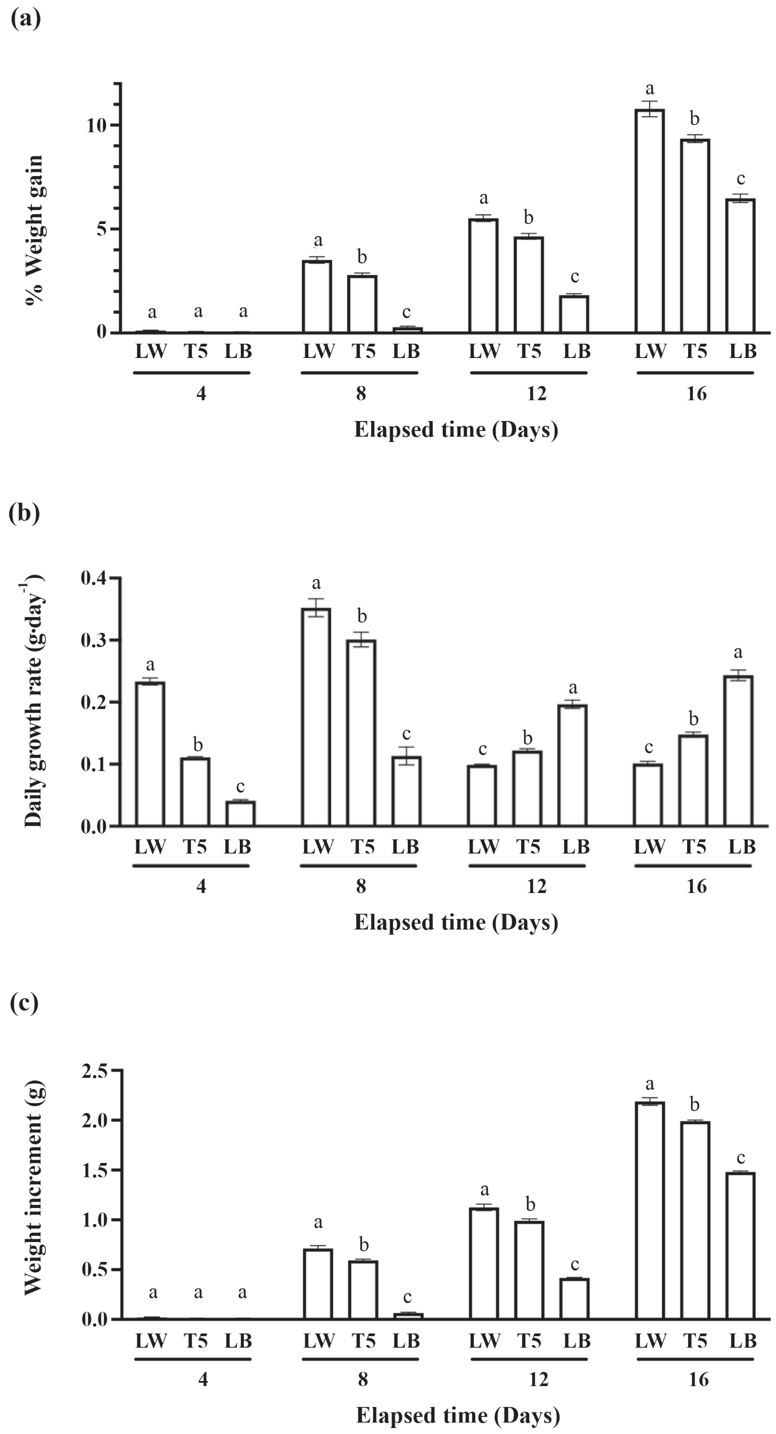


Figure 4. Effects of light source on growth rate of duckweed: (a) % weight gain; (b) daily growth rate (d^{-1}); (c) average weight increment (g). LW = LED white; T5 = fluorescent T5; LB = LED blue. Error bars indicate the SD; different lowercase letters above bars indicate significant ($p<0.05$) difference among means within each day.

Effects of different light sources on nitrogen species in water

In terms of water quality, TAN and NO_2^- significantly decreased under LED white light (Figure 5a and 5b). NO_2^- is produced by the breakdown of organic matter and is toxic to aquatic organisms at high concentrations (Lewis Jr and Morris, 1986). LED white light has been found to stimulate the growth of beneficial bacteria that can convert NO_2^- into less toxic forms, such as NO_3^-. Despite an expected increase, NO_3^- of the LED white light treatment was not different from other treatments at days 0, 4 and 16, and even was lower than fluorescent T5 and LED blue light at days 8 and 12. There is a possibility that under LED white light, nutrient uptake occurred, resulting in a decrease in NO_3^-levels on the 8th and 12th days (Figure 5c). This process, known as nitrification, can help to reduce NO_2^- and NO_3^- levels in aquatic systems (Gee *et al*., 1990). In addition, LED white light has also been shown to support the growth of nitrogen-fixing bacteria, which can convert atmospheric nitrogen into a form that can be used by plants (Matthijs *et al*., 1998). This process, known as nitrogen fixation, can also contribute to the decrease in NO_2^- and NO_3^- levels in aquatic systems under LED white light.

Effect of photoperiod on growth of duckweed

When the LED white light was used with different photoperiods, we found that the 16:8 (light:dark) photoperiod resulted in a significant increase in the weight gain, growth rate, and weight increment of duckweed on day 4 ($p<0.05$) (Figure 6a, 6b, and 6c). After day 8, the growth rates of duckweed exposed to each photoperiod varied, potentially due to the complete occupation of the container's surface by duckweed (Figure 6b). In general, longer photoperiods are associated with increased growth and productivity in aquatic plants because they allow for more time for photosynthesis to occur, which is the process by which plants convert light energy into chemical energy for growth and development. However, previous research has shown that a light-dark ratio of less than 0.3 (5.5:18.5) can inhibit the separation of budding leaflets and decrease the growth rate of duckweed (Lasfar *et al*., 2007). Furthermore, photoperiod did not have a significant effect on weight gain on the 16th day (Figure 6a). Therefore, it is important to note that the optimal photoperiod for duckweed may vary depending on the specific species and growth conditions.

Effects of different photoperiods on nitrogen species in water

Nitrogen species play a crucial role in the proliferation of duckweed, as emphasized by previous research (Lasfar *et al*., 2007). Among the nitrogen species investigated, Lemnaceae, a family of duckweeds, demonstrated a preference for ammonium as their primary nitrogen source, followed by nitrate (Cedergreen and Madsen, 2002). Moreover, the duration of exposure to light has been found to have a direct impact on the biomass of duckweed, as increased exposure enables the plants to absorb more light energy. This heightened light absorption enhances photosynthetic productivity, leading to improved plant growth (Yin *et al*., 2015). However, a specific photoperiod, namely a 24:0 cycle, did not exhibit the highest absorption of TAN and NO_3^-, as compared to the 16:8 photoperiod. Notably, in the 16:8 photoperiod treatment, on the 4th, 8th, and 12th days, the absorption of TAN, NO_2^-, and NO_3^- (Figure 7a, 7b, and 7c) surpassed that of other photoperiods, with statistical significance ($p<0.05$). These findings suggest that the 16:8 treatment is particularly suitable for promoting duckweed growth. This conclusion aligns with a previous study that observed inhibited growth rates for photoperiods shorter than 7 h (Lasfar *et al*., 2007).

Effects of photoperiod on phosphate in water

Additionally, it is important to note that duckweed exhibits rapid reproduction through gemmation and possesses the ability to uptake substantial quantities of nutrients, including nitrogen species and phosphorus, primarily in the form of phosphate when present in water. Phosphates play a vital role in the storage and transfer of energy during photosynthesis and respiration. They are indispensable for promoting regular growth, maturation, and the development of a healthy root system (Williamson *et al*., 2001; Ng and Chan, 2018).

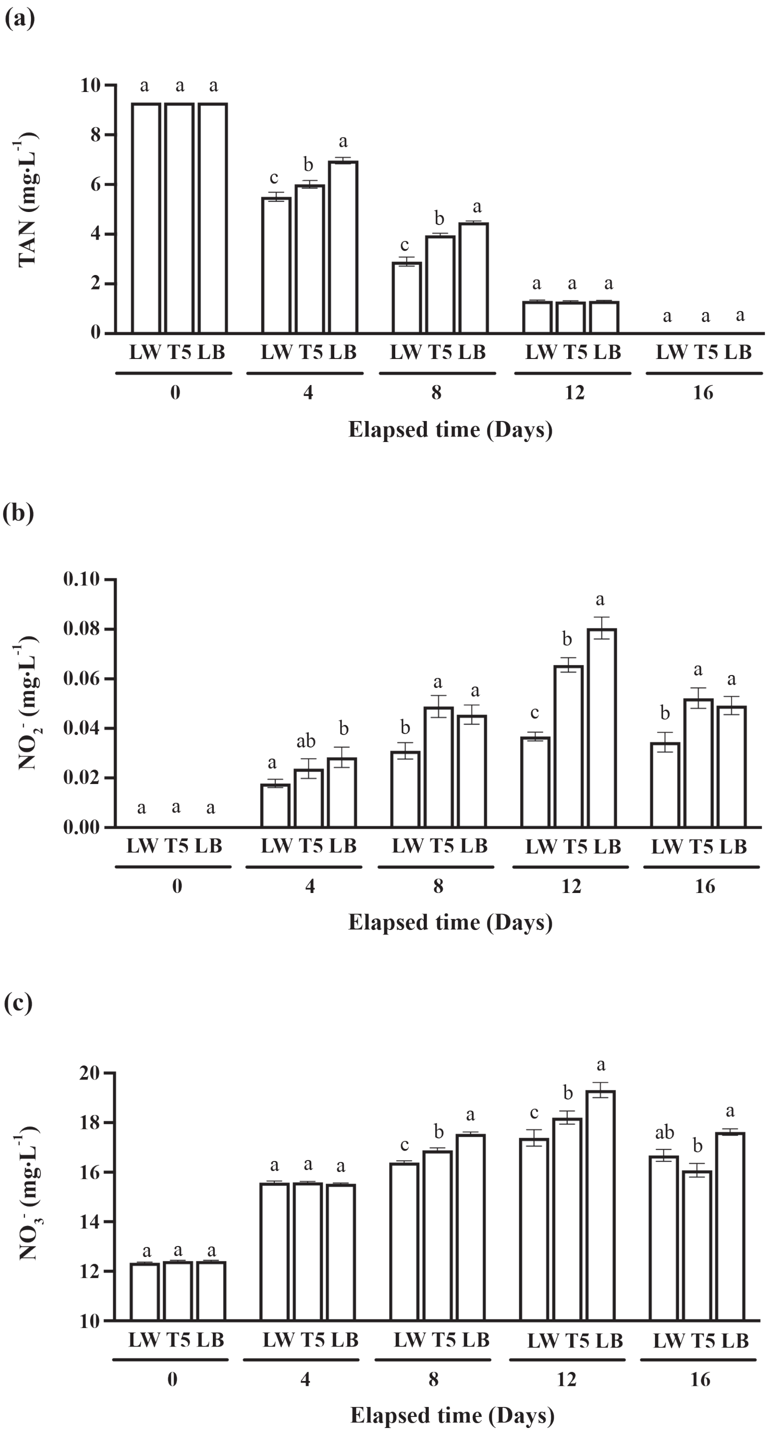


Figure 5. Light source effect on nitrogen species in water: (a) total ammonia nitrogen (TAN), (b) N-nitrite (NO_2^-), and (c) N-nitrate (NO_3^-). LW: LED white; T5: fluorescent T5; LED: LED blue. Error bars indicate the SD; different lowercase letters above bars indicate significant ($p<0.05$) difference among means within each day.

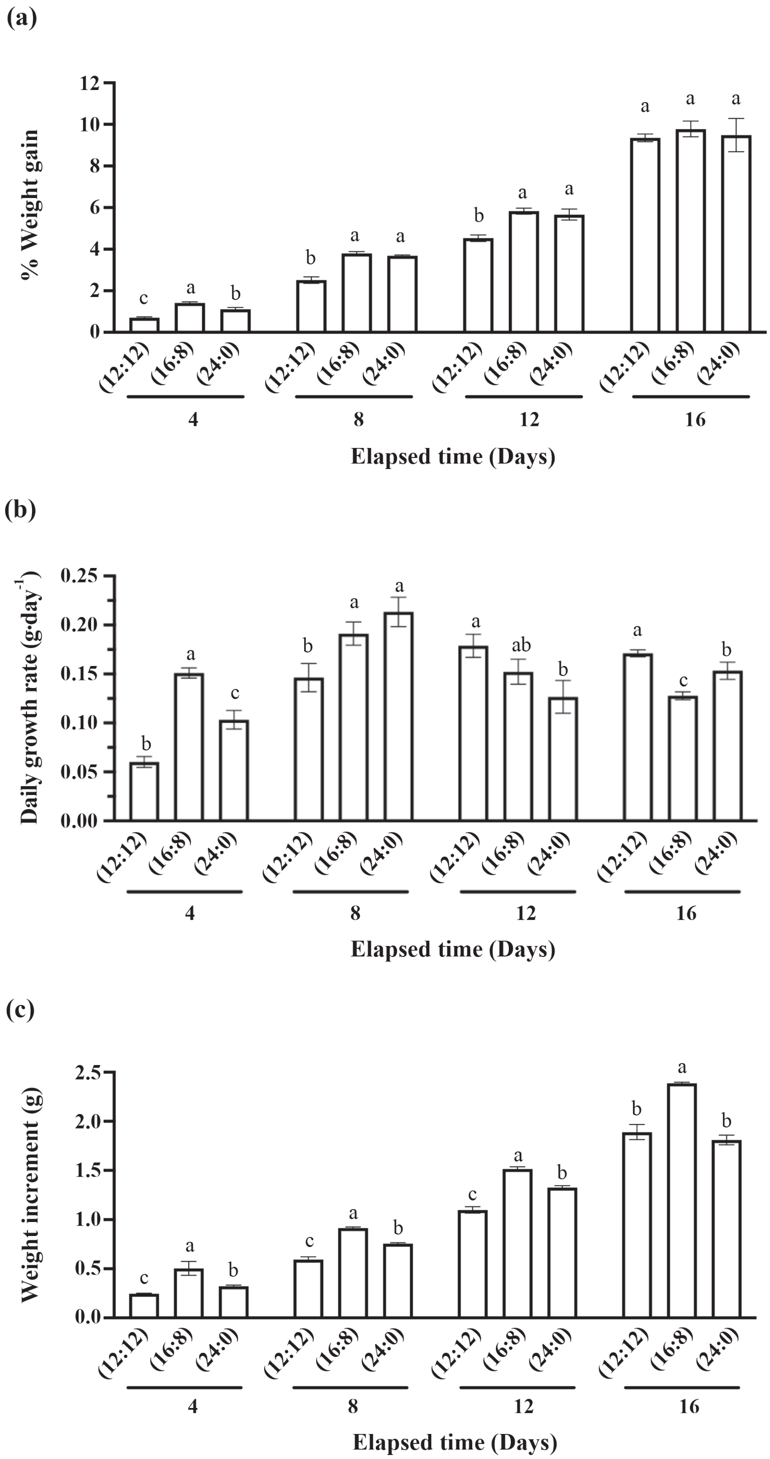


Figure 6. Effects of photoperiod (using LED white light as the light source) on growth performance of duckweed: (a) % weight gain; (b) daily growth rate (d^{-1}); (c) weight increment (in g). Photoperiod in hours (light:dark). Error bars indicate SD; different lowercase letters above bars indicate significant ($p<0.05$) differences within each day.

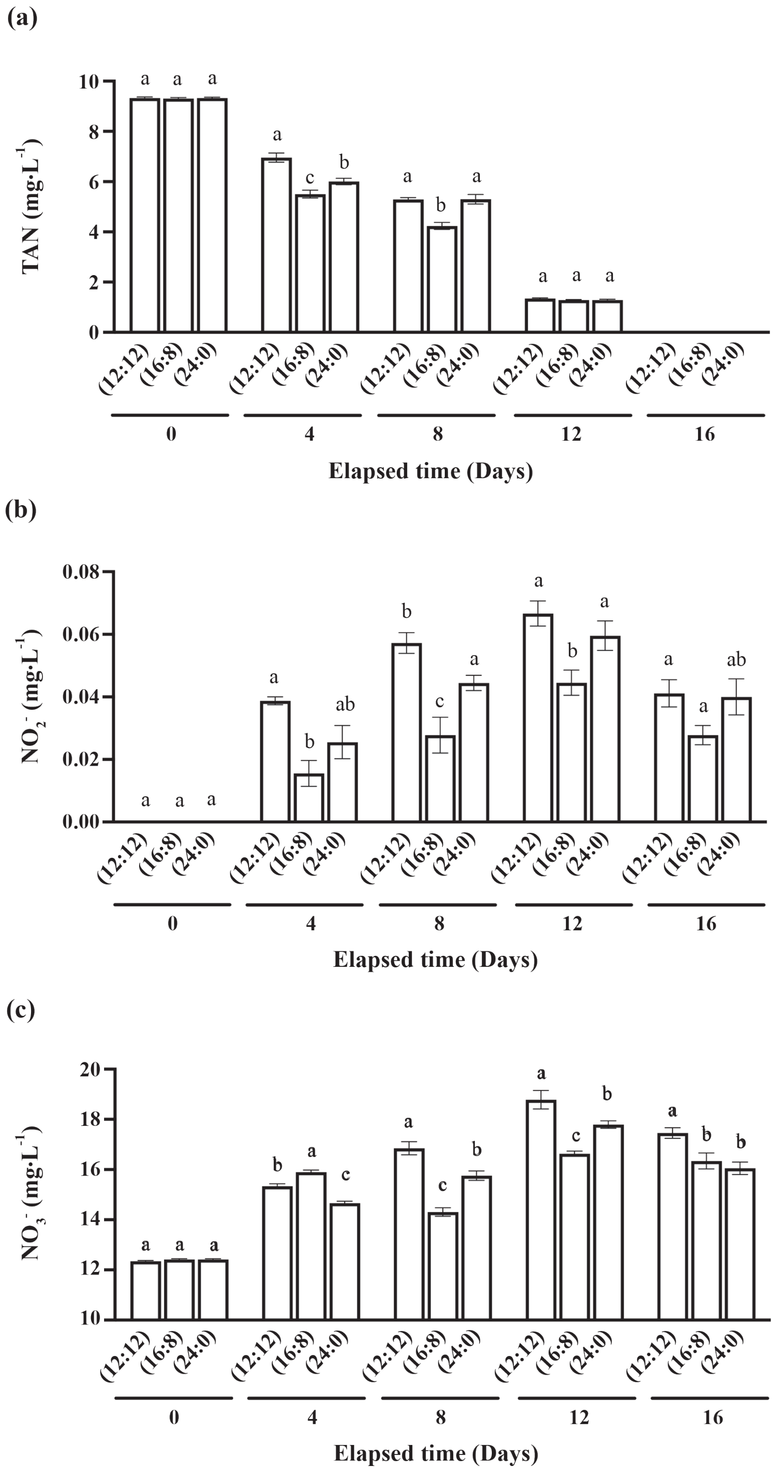
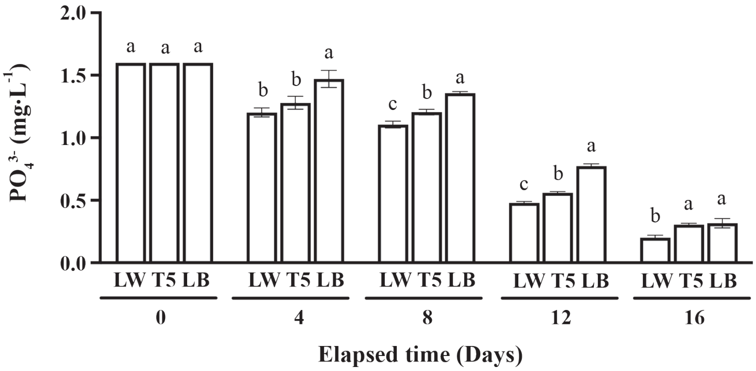


Figure 7. Photoperiod effect on nitrogen species in water: (a) total ammonia nitrogen (TAN); (b) N-nitrite (NO_2^-); (c) N-nitrate (NO_3^-). Photoperiods in hours (light:dark). Error bars indicate the SD; different lowercase letters above bars indicate significant ($p<0.05$) difference among means within each day.

Phosphate-accumulating organisms (PAOs) facilitate the regulation of PO_4^{3-} levels in aquatic systems through their proliferation (Li *et al*., 2020). PAOs are microorganisms that can absorb and store excess PO_4^{3-}, effectively removing it from the water (Saito *et al*., 2004). LED white light not only provides a better quality of spectrum than fluorescent lights for plant photosynthesis (Singh *et al*., 2018), it also accelerates the stimulation of enzyme production in microbes that break down organic matter. This consequently leads to the release of phosphate ions and other nutrients (Moran and Zepp, 1997). Furthermore, nitrogen compounds (TAN, NO_3^-) and PO_4^{3-} are essential for duckweed growth (Liu *et al*., 2017). The starvation of PO_4^{3-} resulted in a declined in the biomass yield of duckweed (Seiler *et al*., 2017). The study found that LED white light was the most effective light source (Figure 8a). Furthermore, the optimal photoperiod for duckweed's PO_4^{3-} uptake was observed after the 4th day with a photoperiod of 16:8 (Figure 8b). The utilization of PO_4^{3-} was consistent with the increase of duckweed biomass, as shown in Figure 6c.

(a)



(b)

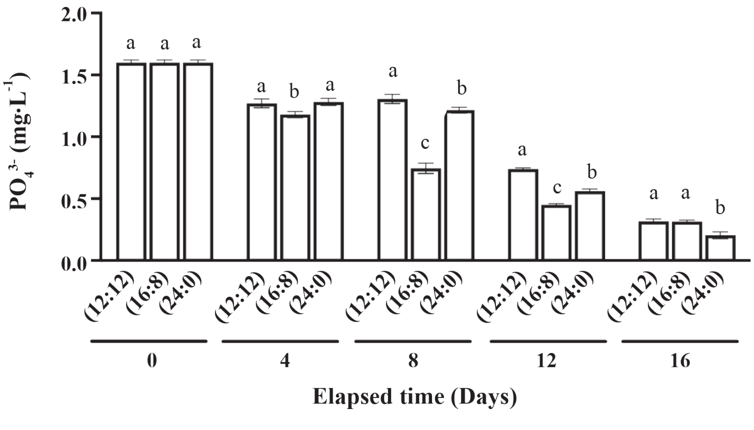


Figure 8. Effect of light source (using LED white light, LED blue light and fluorescent T5 light; panel a) on phosphate (PO_4^{3-}) concentrations for 16-day culture period. Effect of photoperiod (using LED white light as the light source; panel b) for 16-day culture period. Photoperiod in hours (light:dark). Error bars indicate the SD; different lowercase letters above bars indicate significant ($p<0.05$) differences within each day.

Phase II: Effects of partial supplement of artificial feed with duckweed on growth of red tilapia

The growth rate of red tilapia, including weight gain, SGR, average WI, and PER, improved significantly in the 5% and 10% duckweed feeding regimes compared to the control group with no duckweed. Additionally, the FCR significantly decreased in the 5% and 10% duckweed-supplemented groups (Table 1). It should be noted that in all treatment groups, there was no remaining feed. Duckweed is known for its high protein and other nutrients (Leng *et al*., 1995), making it a suitable supplement in the red tilapia diet. Adding duckweed to the diet of red tilapia can increase their growth rate due to increased nutrient availability. In addition, duckweed has a low FCR, meaning that the fish can efficiently utilize the nutrients in the duckweed for growth. The combination of these factors makes duckweed a useful tool for improving the growth rate of red tilapia in aquaponic culture.

Duckweed offers a compelling and eco-friendly substitute for conventional tilapia feed pellets, showing great promise in terms of sustainability (Uddin *et al*., 2007). With its exceptional nutritional composition, straightforward cultivation process, environmental advantages, and significant positive influence on tilapia growth and well-being, duckweed emerges as an appealing option for tilapia farmers (Tavares *et al*., 2010). With crude protein levels ranging from 25% to 45%, duckweed serves as a valuable and nutrient-rich feed for tilapia (Gupta and Prakash, 2013).

Our results showed that TAN and TN levels in the treatments with 5% and 10% duckweed feeding regimes were significantly lower than those in the control group with no duckweed (Table 2). The NO_2^- concentrations were low and similar in all treatments, ranging from 0.02 to 0.03 mg·L^{-1}. The NO_3^- concentrations were significantly lower in the treatments with 5% and 10% duckweed

Table 1. Effects of partial replacement of artificial pellet feed with duckweed (*Lemna minor*) on growth performance (% weight gain, specific growth rate [SGR], average weight increment, feed conversion ratio [FCR], and protein efficiency ratio [PER]) of red tilapia in a 16-day feeding trial (n = 12).

Parameters	%Weight gain	SGR (d^{-1})	Average weight increment (g)	FCR	PER
Fish fed with duckweed					
0%	0.15±0.02^{b}	0.84±0.09^{b}	3.50±0.33^{b}	5.53±0.46^{b}	0.66±0.06^{b}
5%	0.28±0.02^{a}	1.55±0.01^{a}	5.71±0.27^{a}	3.17±0.15^{a}	1.08±0.05^{a}
10%	0.22±0.01^{a}	1.23±0.04^{ab}	4.84±0.12^{ab}	3.67±0.10^{a}	0.92±0.02^{ab}

Note: Means±SD within each column superscripted with different lowercase letters are significantly ($p<0.05$) different.

Table 2. Effects of partial replacement of artificial pellet feed with duckweed (*Lemna minor*) on water quality (TAN, NO_2^-, NO_3^-, TN), phosphate (PO_4^{3-}) in a 16-day feeding trial of red tilapia (n = 12).

Parameters	TAN (mg L^{-1})	NO_2^- (mg L^{-1})	NO_3^- (mg L^{-1})	TN (mg L^{-1})	PO_4^{3-} (mg L^{-1})
Fish fed with duckweed					
0%	0.96±0.03^{a}	0.03±0.00^{a}	6.37±0.25^{a}	7.35±0.26^{a}	0.66±0.02^{a}
5%	0.46±0.03^{b}	0.03±0.00^{a}	1.77±0.08^{c}	2.25±0.09^{c}	0.53±0.02^{b}
10%	0.60±0.03^{b}	0.03±0.00^{a}	2.91±0.10^{b}	3.54±0.11^{b}	0.58±0.02^{b}

Note: Means±SD within each column superscripted with different lowercase letters are significantly ($p<0.05$) different.

compared to the control group with no duckweed. Additionally, the NO_3^- concentration in the 5% duckweed treatment was significantly higher than in the 10% duckweed treatment. High TAN and TN levels can be harmful to fish and other aquatic organisms in aquaponic systems (Randall and Wright, 1987), but duckweed can help to reduce TAN and TN levels and improve water quality by absorbing and converting ammonia into plant biomass and promoting the growth of beneficial bacteria that convert ammonia into less toxic forms (Lu *et al*., 2019). The use of duckweed as a natural filtration system can help to maintain optimal TAN and TN levels in aquaponic culture, improving the overall health and growth of the fish.

Our findings indicated that PO_4^{3-} levels were significantly higher in the control group with no duckweed compared to the treatments with 5% and 10% duckweed (Table 2). The PO_4^{3-} is an important nutrient that is required for the growth and development of aquatic plants and algae (Barko and Smart, 1983). However, excessive levels of PO_4^{3-} can lead to the overgrowth of algae, which can negatively impact water quality and harm aquatic life (Costa *et al*., 2020). Duckweed has been shown to be effective at reducing PO_4^{3-} levels in aquatic systems due to its ability to absorb and utilize PO_4^{3-} as a nutrient, leading to its removal from the water (Gupta and Prakash, 2013). Duckweed can also decrease PO_4^{3-} levels through its high uptake rate of this nutrient, rapid growth and ease of harvest, ability to create a balanced ecosystem, and promotion of beneficial bacteria that convert PO_4^{3-} into less bioavailable forms (Azeez and Sabbar, 2012). These factors all contribute to duckweed's effectiveness in reducing excess PO_4^{3-} and improving water quality in aquatic systems.

CONCLUSION

In this study, we aimed to understand the effects of different light sources and photoperiods on the growth of duckweed (*Lemna minor*) in a co-culture. Our results showed that LED white light was the most effective light source in promoting duckweed growth compared to fluorescent T5 and LED blue light. A photoperiod of 16:8 (light:dark) resulted in a significant increase in duckweed growth rate. To maximize duckweed productivity in aquaponic culture, we recommend using LED white light at a photoperiod of 16L:8D. In addition, our findings suggest that incorporating duckweed into the diet of red tilapia can increase their growth rate. We recommend including at least 5% duckweed in the diet of red tilapia to achieve this benefit.

ACKNOWLEDGEMENTS

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