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Investigation of Feeding Effects and Environmental Impact of Fish-Feed Quality: Evidence from Crucian Carp Feeding Experiments

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Abstract: The effects of three types of feed, purchased from online stores and having similar prices, on the growth performance and culture environment of crucian carp (*Carassius auratus*) were studied in this experiment, which aimed to provide a reference for the evaluation and selection of fish feed. The results showed that feeding different feeds had a significant effect on crucian carp, and that the growth-promoting effect of HD feed (feed produced by Haida Company Limited) was significantly better than that of the other two feeds. For example, the weight gain rate (*WGR*) of fish in the HD group was 47.1% higher than that in the LD group ($p < 0.05$), and the *WGR* of fish in the LD (feed produced by Lianda Company Limited) group was 81.4% higher than that in the TW (feed produced by Tongwei Company Limited) group ($p < 0.05$). Moreover, the activities of superoxide dismutase and catalase in fish in the HD group was significantly higher than that in the LD and TW groups. Furthermore, we found significant differences in the environmental effects of feeding different feeds. Compared to the LD and HD groups, the environmental impacts for the TW group were more pronounced. The body weight of crucian carp first increased and then stabilized with increasing total dissolved solids (*TDS*) values. Their quantitative relationship was established based on the von Bertalanffy and Logistic equations (R^2 = 0.942–0.995). The results above indicate that, due to differences in feed formulation and the quality of feed raw materials, different feeds have a significant impact on the growth performance and antioxidant indices of fish, as well as on the water environment. Therefore, selecting the appropriate feed is crucial for promoting high-quality development in the aquaculture industry.

Keywords: fish feeds; crucian carp; growth performance; environmental effects; antioxidant indices

Key Contribution: The biotoxicity and environmental effects of fish-feed quality were investigated simultaneously. We put forward the quantitative relationship between fish growth and water-total-dissolved solids.

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1. Introduction

Currently, there are widespread issues in aquaculture, such as blindly selecting feed, high feed conversion ratios, and significant impacts on water environments. These issues are not conducive to the sustainable development of the aquaculture industry. Additionally, due to the continuous rise in the prices of feed ingredients, the cost of aquaculture feed has risen by thousands of yuan per ton in recent years. Feed is the material foundation of aquaculture, and its quality has a profound impact on the benefits of aquaculture and the water environment. The production level of the fish-feed manufacturers greatly influences the quality of the feed [1], particularly its formulation and nutritional indicators [2]. With the rapid development of the aquaculture industry, the variety and production of aquaculture feed continue to increase [1]. Although most feeds meet production standards, the nutritional value and culturing effect of different feeds vary due to differences in formulas, ingredients, and processing techniques among various feed manufacturers. Therefore, it is particularly important to choose feed wisely.

Currently, scholars are conducting extensive research on the effects of different feeds on fish growth [3] or aquaculture environment [4], with particular emphasis on in-depth studies regarding the impact of specific nutrients in various feeds on fish growth [5]. However, there is a lack of research on the simultaneous effects of different feeds on aquaculture performance and environmental impacts. Zhou et al. [6] investigated the feeding effects of different feeds but did not study their environmental impact. Papatryphon et al. [4] examined the impact of fish feed on water quality but did not consider the effects of the feed on aquaculture performance. Kong et al. [1] found that fish feeds produced by different manufacturers have varying effects on the nutrient concentration in the water and also differ in their promotion of algae growth. Yang et al. [7] showed that feeding different feeds can have varying effects on fish growth, and that providing appropriate feed not only promotes the growth of fish but also reduces the impact of nutrient concentrations in the water. It can be inferred that by producing and using high-quality feed, it is possible to increase output while reducing the impact on water environments. The attention given to related issues is increasing day by day, and the field still requires more in-depth and extensive theoretical analysis and experimental research.

In addition, there has been extensive research on the effects of different nutrient levels or environmental factors on the antioxidant capacity of fish. Existing studies have confirmed that feed additives can influence the antioxidant capacity of fish [8]. Liu et al. [9] found that the addition of different levels of fat and lipase in feed can lead to changes in the antioxidant capacity of fish. Studies have shown that adverse environmental factors can impose stress on the healthy growth of fish, leading to changes in their antioxidant capacity [10]. The results of Qin et al. [11] indicated that environmental factors can affect the antioxidant capacity of fish. However, there is a lack of research on the impact of feeding different commercial feeds on the antioxidant capacity of fish.

Cyprinid fish account for the highest proportion of fish in China's aquaculture industry. Among them, the crucian carp is widely cultivated due to its tender flesh, rich flavor, and high nutritional value [12], making it an important species in freshwater aquaculture. The amino acid composition of crucian carp protein is similar to the human protein amino acid pattern, making it a high-quality, easily digestible protein. The aquaculture market prospects for crucian carp are very promising. Additionally, due to its moderate size, crucian carp is easy to cultivate in laboratory settings and has been widely used for experimental research [13].

Based on the above background, this study used crucian carp as the test organism to investigate the effects of commercially available feeds from different companies, which were similarly priced, on fish growth performance and the aquaculture water environment under laboratory conditions. The aim is to reveal the differences in aquaculture effects and environmental impacts of feeds of varying quality, and to further explore the quantitative relationships between fish growth and water quality indicators. This research can provide references for feed evaluation and selection in aquaculture activities, as well as offer valuable insights to enhance the overall benefits of aquaculture and promote high-quality development in the aquaculture industry.

2. Materials and Methods

2.1. Experimental Materials

The crucian carp used in this study were purchased from the farmers' markets surrounding Henan Agricultural University. Prior to the official start of the experiment, the crucian carp were acclimated under experimental conditions for two weeks in an aquarium with dimensions of 46.0 cm (length) × 38.5 cm (width) × 50.0 cm (height). Three types of commercially available crucian carp feeds, which are similarly priced and widely sold, were selected. The retail price of TW feed is CNY 7.5 per kilogram, LD feed is CNY 7.6 per kilogram, and HD feed is CNY 7.5 per kilogram. These prices were free of transportation. Their nutritional components are shown in Table 1.

Table 1. Nutritional indicators of fish feeds.

Fish Feed	Crude Protein (%)	Crude Fat≥ (%)	Crude Ash≤ (%)	Crude Fiber≤ (%)	TP (%)	Moisture≤ (%)	Lysine≥ (%)
TW	30.0	3.0	15.0	12.0	0.7	12.5	1.3
LD	35.1	3.5	13.0	13.5	0.7	10.0	1.4
HD	32.9	3.0	12.0	12.0	0.7	12.0	1.7

Note: TW, feed produced by Tongwei Company Limited; LD, feed produced by Lianda Feed Company Limited; HD, feed produced by Haida Feed Company Limited; and TP, total phosphorus in fish feed.

2.2. Experimental Methods

The purpose of this experiment was to investigate the aquaculture effects and environmental impacts of commercial feeds produced by 3 manufacturers, as well as to explore the quantitative relationships between fish growth indicators and water quality indicators. The experimental design was as follows: healthy crucian carp at 6 months of age (initial weight 18.6 ± 0.2 g and initial length 92.1 ± 0.1 mm) were randomly divided into three groups, which were fed TW, LD, and HD feeds, referred to as the TW group, LD group, and HD group, respectively. Additionally, a blank control group (CK) was set up with only water and no fish. Each group consisted of three replicates, with 3 crucian carp placed in each aquarium.

Except for the CK group, the experimental groups were fed daily at 9:00 a.m., with a feeding amount of 1.0% of the crucian carp's body weight [14]. It was observed that all the feed provided (0.56 g) was completely consumed by the fish. The experimental period lasted for 49 days, during which no water changes were made. Instead, water was added daily to compensate for evaporation losses in order to maintain a relatively constant water level. During the experiment, an electromagnetic air compressor was used to continuously supply oxygen, and dissolved oxygen level (6 mg L^{-1}) was maintained in aquariums. To ensure uniform lighting throughout the experiment, additional fluorescent tubes were installed. The light–dark ratio was set to 12 h:12 h, with corresponding light intensities of 3000 l× and 0 l×.

After the start of the experiment, the body weight and length of the crucian carp were measured every 7 days, and water quality indicators such as total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), total dissolved solids (*TDS*), and electrical conductivity (*EC*) were monitored every 4 days. At the end of the experiment, the activities of superoxide dismutase (SOD) and catalase (CAT), as well as the content of malondialdehyde (MDA), were measured in the fish. Additionally, the nitrogen and phosphorus contents in both the fish and the water sediments were determined.

2.3. Measurement of Monitoring Indicators

2.3.1. Measurement of Fish Growth Performance

The body weight of the crucian carp was measured using a precision electronic balance, and the body length was measured using a measuring ruler. First, a 500 mL beaker was taken, and approximately 100 mL of well-aerated tap water was added. The beaker was then placed on an electronic balance and tared. Then, a net was used to remove the crucian carp from the aquarium. After draining the excess water, the crucian carp were placed in the aforementioned beaker. Their body weight was then recorded before measuring their body length with a measuring ruler. The crucian carp were positioned on the ruler, and once they were still, their body length was quickly measured and recorded. Finally, the crucian carp were returned to the original aquarium.

2.3.2. Measurement of Water Quality Indicators

Water samples for monitoring TDN and TDP were filtered through a 0.45 μm microporous filter membrane. Prior to measurement, the water samples must undergo high-temperature and high-pressure digestion. The concentration of TDN was determined using the potassium persulfate oxidation method with ultraviolet spectrophotometry; the concentration of TDP was measured using the potassium persulfate digestion method [15]. *EC* and *TDS* were measured using a multifunctional water-quality-testing instrument [14].

At the end of the experiment, the aquaculture water was allowed to stand for 24 h. The upper layer of water was discarded, and the lower layer was centrifuged at 10,000 rpm for 15 min. After discarding the supernatant, the sediment was collected and mixed with the sediment from the aquarium. The mixture was then dried in an oven at 110 °C for 2 h to remove moisture. Took 0.5 g of the dried sediment, carbonized it on an electric stove, and then transferred it to a muffle furnace for incineration at 550 °C for 3 h. After cooling, we added 10 mL of (1 + 1) hydrochloric acid and 0.25 mL of nitric acid and boiled it for 10 min. After cooling, we transferred the solution to a 100 mL volumetric flask and diluted to volume. The method for determining total phosphorus in the digestion solution was the same as that used for TDP in water samples. The total nitrogen content in the water sediment was determined using the Kjeldahl method.

2.3.3. Detection of Biochemical Indicators in Fish

At the end of the experiment, the antioxidant indicators of crucian carp (SOD activity, CAT activity, and MDA content) were measured using a reagent kit from the Nanjing Jiancheng Bioengineering Institute. We mixed 100 mg of whole fish tissue with nine times its volume in physiological saline (0.86%) and ground it using a grinder (60 Hz, 4 °C) for 60 s. Then, we centrifuged at 4 °C and 8000 rpm for 10 min to obtain the supernatant for measuring the antioxidant indicators. All operations were performed according to the instructions provided with the reagent kit (Supplementary Materials).

After cleaning the fish and removing the scales, we wiped off any mucus and dried the fish flesh in an oven at 110 °C for 2 h to remove moisture. We took 0.5 g of the dried fish sample, charred it on an electric stove, and then transferred it to a muffle furnace for incineration at 550 °C for 2 h. After cooling, we used 1.25 mL of hydrochloric acid solution to transfer it into a 25 mL volumetric flask. Then, we took 2 mL of the sample solution and added it to a 25 mL colorimetric tube. We added 8 mL of the color reagent (a mixture of nitric acid (1 + 2), ammonium metavanadate, and ammonium molybdate in equal volumes). After allowing it to stand for 15 min, we measured the absorbance at 430 nm. The total nitrogen content in the fish body was determined using the Kjeldahl method.

2.4. Theoretical Basis

In this study, the growth performance of crucian carp was evaluated using the weight growth rate (*WGR*, %), specific growth rate (*SGR*, % d^{-1}), feed conversion ratio (*FCR*, −), and feed conversion efficiency (*FCE*, %) [16]. The calculation formulas are as follows:

$$WGR = \frac{W_t - W_0}{W_0} \times 100\% \quad (1)$$

$$SGR = \frac{\ln W_t - \ln W_0}{T} \times 100\% \quad (2)$$

$$FCR = \frac{F}{W_T - W_0} \quad (3)$$

$$FCE = \frac{W_T - W_0}{F} \times 100\% \quad (4)$$

in the formulas, W_0 (g) represents the initial body weight of the crucian carp; W_t (g) and W_T (g) represent the body weights of the crucian carp at time t (d) and time T (d), respectively; F (g) is the total amount of feed provided (the total amount of feed consumed by the crucian carp); and T (d) is the experimental duration (49 d).

The von Bertalanffy model is the most commonly used growth function in chondrichthyan age and growth studies. Based on the von Bertalanffy model [17], the growth of crucian carp can be described as follows:

$$W = W_{max}\left(1 - B_W e^{-K_w t}\right)^3 \quad (5)$$

$$L = L_{max}\left(1 - B_L L e^{-K_L t}\right) \quad (6)$$

where W (g) and L (mm) are the weight and length as a function of time (t), W_{max} (g) and L_{max} (mm) are the theoretical asymptotic weight and length of fish, K_W (−) and K_L (−) are rate constants; B_W (−) and B_L (−) are constants, and t (d) is time.

The Logistic equation can be used to describe the changes in nutrient concentration (C_F) in the water over time. The fitting equation is as follows:

$$C_F = \frac{C_{F-max}}{1 + e^{a_{C_F} - r_{C_F} t}} \quad (7)$$

in the equation, C_F (mg L^{-1}) represents the nutrient concentration at time t (d); $C_{F\text{-}max}$ (mg L^{-1}) is the maximum nutrient concentration; r_{C_F} (d^{-1}) is the rate constant; a_{C_F} (−) is a constant; and t (d) is the duration of feeding. $C_{F\text{-}max}$, a_{C_F}, and r_{C_F} can be obtained using Equation (7).

Similarly, the changes in water *EC* and *TDS* over time can be described by the following equations:

$$E = \frac{E_{max}}{1 + e^{a_E - r_E t}} \quad (8)$$

$$S = \frac{S_{max}}{1 + e^{a_S - r_S t}} \quad (9)$$

in the equations, E (μS cm^{-1}) and S (mg L^{-1}) represent the *EC* and *TDS* of the water at time t (d), respectively. E_{max} (μS cm^{-1}) and S_{max} (mg L^{-1}) are the maximum values of *EC* and *TDS*, respectively. r_E (d^{-1}) and r_S (d^{-1}) are the intrinsic growth rates, while a_E (−) and a_S (−) are constants, with t (d) representing time in days.

Based on Equations (5) and (9), the relationship between the weight growth process of crucian carp and water *TDS* can be described by the following equation

$$W = W_{max}\left(1 - B_W e^{-(K_w(a_S - ln(S_{max} - S) + ln\ S))/r_S}\right)^3 \quad (10)$$

the parameters in Equation (8) are the same as those in Equations (5) and (9).

2.5. Statistical Analysis

The experimental data were organized using Excel 2016, and graphs were created along with relevant model analysis using Origin 9.0. The statistical analysis is applied to identify the significant differences among groups with different fish feeds by a one-way ANOVA followed by the Duncan post hoc test (with SPSS 17.0). The measured data are presented as mean ± standard deviation, with a significance level of $p < 0.05$ for differences.

3. Results and Discussion

3.1. The Effects of Different Fish Feeds on Crucian Carp Growth

In recent years, the impact of different feeds on fish growth performance has garnered attention. Due to the variations in feed formulations and raw materials used, the content and quality of nutrients such as protein and fat differ significantly. For example, some commercial feeds may contain higher levels of plant-based proteins, while others might use animal-based proteins. These differences can greatly influence the growth rate, survival rate, and overall health of fish. The nutritional components of commercial feeds produced by different manufacturers vary, leading to notable differences in their aquaculture effects [18].

In this study, the changes in body length and weight of crucian carp in different feed groups exhibited a consistent trend. Specifically, there was a gradual increase during the first 30 days, followed by a tendency to plateau (Figure 1). Equations (5) and (6) can be used to describe the changes in body weight and length of crucian carp over time, respectively (R^2 = 0.942–0.995). Comparative analysis results indicated that although the prices of different feeds were similar and all met production standards, the aquaculture effects vary significantly due to differences in the quality of feeds produced by different manufacturers [1]. Compared to the LD group, the *WGR*, *SGR*, and *FCE* of crucian carp in the HD group were 47.1%, 46.2%, and 33.8% higher, respectively ($p < 0.05$). Additionally, the *WGR*, *SGR*, and *FCE* of crucian carp in the LD group were 81.4%, 85.7%, and 95.0% higher, respectively, than those in the TW group ($p < 0.05$) (Table 2). The corresponding ranking of *FCR* for crucian carp fed different feeds was HD < LD < TW ($p < 0.05$). It is worth noting that the feed conversion ratios in this study were relatively high, which was attributed to the fact that no water changes were made during the experimental period in order to study the environmental effects of feeding different feeds. The continuously increasing nutrient concentrations in the water had an adverse impact on the growth of crucian carp [7]. Additionally, the fitting results indicate that the maximum body weight of crucian carp in the HD and LD groups was similar and significantly higher than that of the fish in the TW group (Table 2). The final length growth rate of crucian carp in the LD group was similar to that of the TW group, but significantly lower than that of the HD group.

The above results indicate that there were significant differences in the aquaculture effects of different commercial feeds, even when their prices were similar. This is consistent with existing research findings [7], suggesting that there may be notable differences in the quality of feeds produced by different manufacturers, although their commercial value is similar, and they all meet production standards. A possible explanation in this study was that the quality of proteins in feed was different. Therefore, price should not be used as a direct criterion for assessing feed quality. Additionally, as the three types of feed selected in this study are all commercially available and theoretically meet production standards, the findings indirectly suggest that feed production standards need to be further refined.

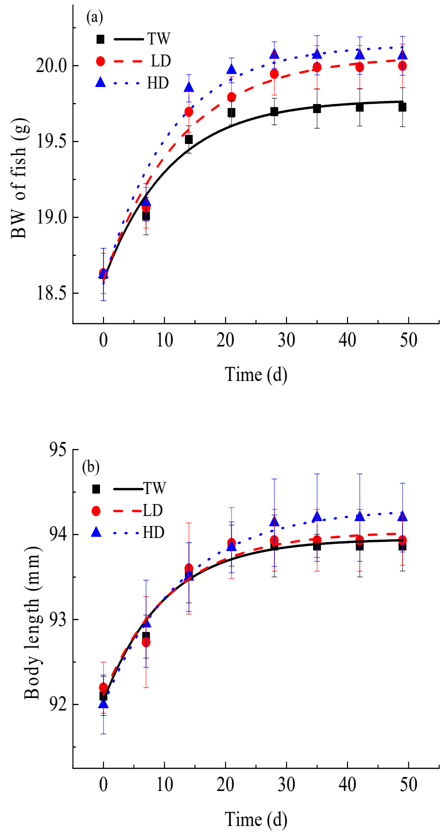

Figure 1. Variations in body weight (**a**) and body length (**b**) of crucian carp over time.

Table 2. Physiological and biochemical indices of fish in each group.

Parameters	TW	LD	HD
	Parameters that are related to the growth of crucian carp		
B_W	0.02	0.03	0.03
K_W	0.09	0.08	0.09
W_{max}	19.18	20.07	20.14
R^2	0.959	0.968	0.948
B_L	0.008	0.007	0.007
K_L	0.08	0.10	0.09
L_{max}	93.94	94.04	94.31
R^2	0.995	0.963	0.942
WGR (%)	3.65 ± 0.12^{c}	6.62 ± 0.13^{b}	9.74 ± 0.15^{a}
FCR	13.61 ± 0.39^{a}	6.98 ± 0.06^{b}	5.22 ± 0.07^{c}
SGR (%/d)	0.07 ± 0.01^{c}	0.13 ± 0.01^{b}	0.19 ± 0.01^{a}
FCE (%)	7.35 ± 0.21^{c}	14.33 ± 0.12^{b}	19.18 ± 0.26^{a}
	Body composition of fish in different groups		
TN (%)	10.89 ± 0.02^{b}	10.88 ± 0.11^{b}	11.68 ± 0.05^{a}
TP (%)	2.43 ± 0.00^{b}	3.04 ± 0.02^{a}	2.03 ± 0.08^{c}
	Antioxidant indexes of fish in different groups		
CAT (U/mg prot)	0.75 ± 0.35^{c}	1.65 ± 0.39^{b}	3.08 ± 0.73^{a}
SOD (U/mg prot)	0.93 ± 0.10^{b}	0.96 ± 0.01^{b}	1.56 ± 0.05^{a}
MDA (nmol/mg prot)	0.19 ± 0.01	0.17 ± 0.09	0.17 ± 0.03

Note: K_W (−) and K_L (−) are rate constants; B_W (−) and B_L (−) are constants; W_{max} is the maximum *BW* of fish; L_{max} is the maximum *BL* of fish; and R^2 is the correlation coefficient. Some of the data (*WGR*, *FCR*, *SGR*, *FCE*, TN, TP, CAT, SOD, and MDA) presented are the mean ± SD of three independent measurements. Values in the same column with different superscript letters are significantly different ($p < 0.05$), values followed by the same letter are not significantly different from one another ($p > 0.05$).

3.2. The Effects of Different Fish Feeds on Biochemical Indicators in Crucian Carp

Under normal physiological conditions, the production and clearance of free radicals in the body are maintained via a dynamic balance process, which helps sustain the normal functioning of life activities. When abnormalities occur, they can lead to the excessive accumulation of free radicals in cells and tissues, disrupting this balance and resulting in oxidative damage [19]. SOD can catalyze the conversion of superoxide anion radicals into hydrogen peroxide (H_2O_2). This hydrogen peroxide then reacts with CAT to produce water and oxygen, thereby terminating the free-radical chain reaction. Therefore, the activities of SOD and CAT are important indicators of the body's antioxidant capacity. MDA, as a significant end product of lipid peroxidation, reflects the intensity of lipid peroxidation reactions occurring in the body [20]. In this study, there were significant differences in the antioxidant indicators of crucian carp fed different feeds (Table 2). Specifically, the SOD activity in the crucian carp in the HD group was significantly higher than that in the LD and TW groups, while there was no significant difference in SOD activity between the LD and TW groups. The CAT activity in crucian carp from the HD group was significantly higher than that in the LD and TW groups ($p < 0.05$). Additionally, the CAT activity in crucian carp from the LD group was significantly higher than that in the TW group ($p < 0.05$). Furthermore, the MDA content in crucian carp from the TW group was higher than that in the HD and LD groups, but the differences among the groups were not statistically significant ($p > 0.05$). Based on these results, it can be inferred that HD feed is more beneficial for alleviating free-radical damage in crucian carp compared to TW feed and LD feed.

Lower activities of CAT and SOD may lead to increased levels of free radicals and other harmful substances in the fish, thereby inhibiting their growth. In this experiment, the activities of antioxidant enzymes in crucian carp fed different feeds were positively correlated with their growth performance, indicating that the impact of different commercial feeds on the antioxidant indicators of crucian carp was one of the reasons for the differences in their aquaculture effects. Additionally, antioxidant enzymes are the primary protective mechanisms against oxidative stress in fish tissues, and their activity is closely related to the immune function of the fish [21]. Therefore, feeding different commercial feeds may also affect the non-specific immunity of fish, this is an area that requires further research.

3.3. The Environmental Effects of Different Fish Feeds

Fish metabolic waste is a major substance affecting the quality of aquaculture water environments [22], with the nitrogen and phosphorus it releases having the greatest impact on the water environment [23]. During fish culture, their digestive activity and bioturbation can significantly influence nutrient concentrations in the water [6]. The results of this study indicate that the concentrations of TDP and TDN in the water of each experimental group continuously increased with the increase in total feed amount (Figure 2). The changes in nutrient concentrations over time can be well described by Equation (7) (R^2 = 0.972–0.995).

Differences in the quality of raw materials in different feeds lead to varying degrees of digestibility [24], which directly affects how much fish can digest the feed [25]. This, in turn, indirectly influences the nutrient concentrations in the water. During this experiment, the order of TDN concentrations in the water for different feed groups was TW > HD > LD, with average TDN concentrations of 12.98, 10.33, and 11.50 mg L^{-1} for the TW, LD, and HD groups, respectively. The differences among the groups were statistically significant ($p < 0.05$). This finding is inconsistent with the total nitrogen content of the three types of feeds. Yang et al. [7] observed a similar phenomenon, which may be attributed to varying degrees of digestion and utilization of different feeds by crucian carp. Additionally, the research results showed that the average TDP concentrations in the water for the LD and HD groups were similar ($p > 0.05$) and significantly lower than that of the TW group ($p < 0.05$). Given that most natural water bodies are rich in nitrogen salts but deficient in phosphorus salts, feeding with TW feed had the greatest impact on the eutrophication status of the water among the three types of feed tested in this study.

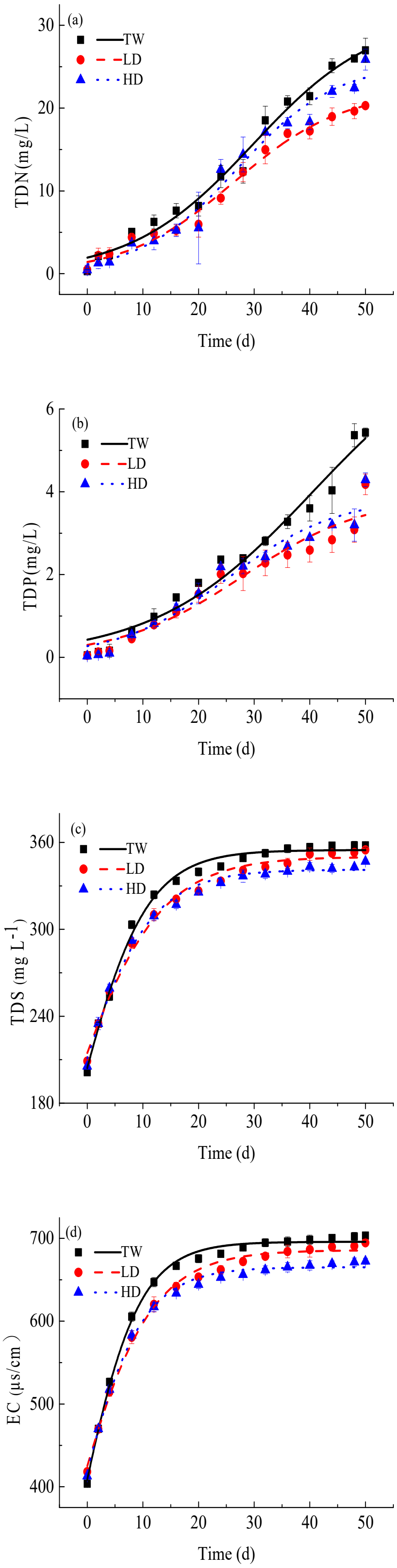

Figure 2. Variations in nutrient concentrations (**a**,**b**), TDS (**c**), and *EC* (**d**) with time.

TDS refers to dissolved salts, certain organic substances, and some insoluble filterable solids and microorganisms in the water, which can roughly reflect the content of dissolved or colloidal substances in the water [26]. *EC* represents the electrical conductivity of substances in the water, reflecting the types and quantities of various electrolytes or ions present in the aquaculture water, such as inorganic salt concentrations. It is an important indicator for evaluating aquaculture water quality [27]. In this experiment, both *TDS* and *EC* in the water exhibited a gradual increasing trend over time, and their changes can be described using Equations (8) and (9), which is consistent with existing research [14]. From Figure 2 and Table 3, it can be observed that the slope of the fitting curve for *TDS* and *EC* in the water is higher for the TW feed group than for the HD group, and the slope for the HD group is higher than that of the LD group. This indicates that the impact of feeding the three types of feed on water *TDS* and *EC* follows the order of TW > HD > LD. During the experiment, the average *TDS* and *EC* values in the water of the TW group were significantly higher than those of the HD and LD groups ($p < 0.05$), whereas there was no significant difference between the HD and LD groups ($p > 0.05$). The above results suggest that feeding with TW feed had a more significant impact on water *TDS* and *EC*, which may be related to the composition of the feed.

Table 3. Parameters related to the environmental impacts of different fish feeds.

Parameters	TW	LD	HD
	Parameters of TDN in water		
a_C	2.72	2.69	3.06
r_C	0.09	0.10	0.11
C_{max}	31.25	22.14	25.45
R^2	0.986	0.985	0.974
C_{ave}	12.98	10.33	11.50
	Parameters of TDP in water		
a_C	2.87	2.49	2.59
r_C	0.07	0.09	0.10
C_{max}	7.98	3.92	3.87
R^2	0.967	0.931	0.945
C_{ave}	2.30	1.71	1.83
	Parameters of *TDS* and *EC* in water		
a_S	−0.37	−0.53	−0.56
r_S/d^{-1}	0.22	0.18	0.21
S_{max}	340.81	332.12	323.30
S_{ave}	321.50	311.36	307.93
R^2	0.978	0.957	0.984
a_E	−0.37	−0.53	−0.56
r_E/d^{-1}	0.21	0.18	0.20
E_{max}	682.36	664.88	647.42
E_{ave}	642.21	622.07	614.79
R^2	0.978	0.954	0.986
	Parameters of aquatic sediment		
TN (%)	4.03 ± 0.02^{a}	3.57 ± 0.05^{b}	3.57 ± 0.07^{b}
TP (%)	2.72 ± 0.04^{a}	2.37 ± 0.06^{b}	2.29 ± 0.10^{b}

Note: a_C (−), constant; r (d^{-1}), rate constant; C_{max} (mg L^{-1}), the maximum concentration of nutrients; C_{ave} (mg L^{-1}), the average concentration of nutrients; R^2, correlation coefficient; a_S (a_E) (−), constant; r_S (r_E) (d^{-1}), rate constant; S_{max} (mg L^{-1}), maximum *TDS*; E_{max} (μs/cm), maximum *EC*; S_{ave} (mg L^{-1}), average *TDS*; and E_{ave} (μs/cm), average *EC*. Data were calculated according to the corresponding equations. Some of the data (TN, TP) shown are the mean ± SD of three independent measurements. Values in the same column with different superscript letters are significantly different ($p < 0.05$), while values followed by the same letter are not significantly different from one another ($p > 0.05$).

To further investigate the environmental impacts of using different feeds in fish farming, we measured the nitrogen and phosphorus content in the water sediments after the experiment. Results showed that the TN and TP contents in the sediments of the TW group were significantly higher than those in the LD and HD groups, with no significant difference between the LD and HD groups. This finding is inconsistent with the total nitrogen and total phosphorus content of the three types of feed, primarily due to the significant differences in the utilization rates of different feeds by crucian carp. In this experiment, the water sediments primarily consisted of crucian carp feces. The differences in formulations among various commercial feeds can affect the digestibility and utilization rates of the feed by the fish [28], leading to significant differences in the composition of their excreta. Since water sediments continuously release nutrients into the water [25], influencing the eutrophication status of the water and subsequently affecting fish growth, we believe that when selecting commercial feeds, consideration should be given to the composition of feces excreted by fish after feeding.

3.4. Correlations Between Fish Growth and the Physicochemical Parameters of Water

Mathematical models can be used to predict changes in biological and abiotic factors within aquaculture systems and reveal the quantitative relationships between different factors [29]. Our preliminary research has shown that the relationship between fish growth indicators and water nutrient concentrations can be derived from the Logistic equation [7]. Additionally, based on the Gompertz equation and the Logistic equation, relationships between fish growth indicators and water electrical conductivity can be established [14]. This demonstrates that mathematical models have significant application value when studying the interactions between biological and abiotic factors in aquaculture systems.

Fish growth is influenced by various environmental factors [30]. Previous studies have shown that high concentrations of salinity and alkalinity can lead to slower growth in fish [31]. *TDS*, as an important water quality indicator, is considered to affect the growth of aquatic organisms [32]. Based on the literature reports and our preliminary research findings, this study derived the relationship between the body weight of crucian carp and the *TDS* in the water, which is represented by Equation 10 (R^2 = 0.989–0.991). From Figure 3 and the calculation results, it can be seen that the weight growth of crucian carp fed with the three types of feed (TW, LD, and HD) tends to plateau when *TDS* concentrations exceed 353.94, 347.39, and 340.08 mg L^{-1}, respectively.

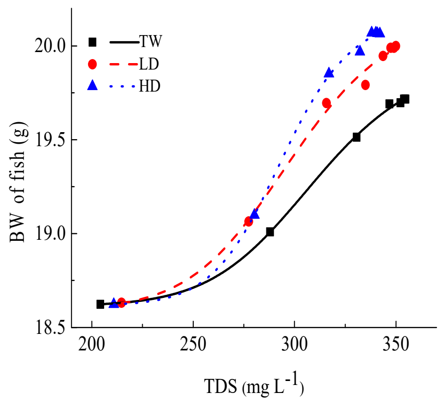

Figure 3. The relationship between fish growth and the *TDS* of water.

The above results indicate that there is a quantitative relationship between fish growth indicators and water quality indicators, which is consistent with our previous research conclusions. This finding contributes to a deeper understanding of the ecological processes in aquaculture systems, providing a theoretical basis for exploring strategies to maintain ecological balance in aquaculture waters.

4. Conclusions

This study evaluated the effects of three common commercial feeds on the physiological and biochemical indicators of crucian carp as well as on the aquaculture water environment. The experimental results indicate that feeding different feeds has varying impacts on the growth of crucian carp and the water environment, therefore, it can be concluded that fish-feed quality is a key factor in promoting the sustainable development of the aquaculture industry. We consider that high-quality feed can significantly stimulate fish growth and lessen its effects on the environment. Even when selecting commercially available feeds with similar prices, some feeds (such as the HD feed in this study) can significantly promote the growth of fish while having a minimal impact on the water environment. Furthermore, they help mitigate free-radical damage to crucian carp, thereby enhancing their non-specific immunity. It is evident that the quality of feeds on the market differs considerably. To promote the high-quality development of the aquaculture industry, relevant authorities should further refine the standards for the feed industry.

Research results indicate that when the *TDS* concentration in the water is low, an increase in its concentration has no significant effect on the growth of crucian carp. However, when the *TDS* concentration is high, the growth of crucian carp tends to plateau. The relationship between the weight growth of crucian carp and *TDS* in the water can be described using Equation (10) (R^2 = 0.989–0.991). This quantitative relationship lays the foundation for further research into the intrinsic mechanisms of aquaculture water ecosystem dynamics.

This experiment was conducted under indoor conditions. Considering the complexity of the evolution of aquaculture water ecosystems, future studies could be carried out in open aquaculture systems to investigate the effects of other factors (biological or abiotic) on the water environment and fish growth processes. Driven by the demand for high-quality development in the aquaculture industry, the research methods and results presented in this paper hold significant theoretical and practical values.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fishes10020050/s1, Method for determination of antioxidant index.

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