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RESEARCH

Modulation of toxic effects of ammonia on growth, pathology of liver and kidney tissues and relative expression of GH and IGF-1 Genes by CoQ_{10} Supplementation in *Oncorhynchus mykiss*

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Abstract Reducing the negative impact of environmental and stressful factors is a crucial step in achieving sustainable aquaculture. Therefore, a study was aimed at evaluating the impacts of Coenzyme Q_{10} (CoQ_{10}) supplementation on growth, relative gene expression of Growth Hormone (GH) and Insulin-like growth factor-1 (IGF-1), liver and kidney histopathology against stress induced by ammonia in Rainbow trout (*Oncorhynchus mykiss*). The fish were given feed containing different levels of CoQ_{10} for 8 weeks: Control – CoQ_{10} 0%, G1 – CoQ_{10} 0.1%, G2 – CoQ_{10} 0.5% and G3 – CoQ_{10} 1%. At the end of the experiment, fish were exposed to ammonia stress concentration at 0.6mg/L for 24 h to assess liver and kidney tissue damage. Results showed that there was a significant activity increase in GH and IGF-1 genes due to supplementation with CoQ_{10} alone ($p<0.05$). Gene expression for GH increased about two-fold whereas that for IGF-1 experienced a four-fold upregulation compared to controls ($p<0.05$). CoQ_{10}'s-related antioxidant effects probably minimized liver and kidney cellular injuries, as significant decreases were observed in ammonia-induced mortality ($p<0.05$). In summary, adding CoQ_{10} to the diet is a potential way to improve fish production through controlling the gene expression of GH and IGF-1, as well as making fish populations more resistant to possible future stress caused by ammonia in intensive or super-intensive aquaculture systems.

Keywords Aquaculture · Feed supplement · Blood indices · Growth · Pathology

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Introduction

The aquaculture industry has experienced significant growth over the past few decades and has become a crucial part of global food production (FAO 2020). Since 1970, it has grown consistently at an average rate of 9.8% per year (FAO 2020). As it's difficult to increase the supply of edible marine animals from natural sources, aquaculture is expected to be the primary method to meet the growing demand for seafood (Subasinghe et al. 2009; Hosseini Aghuzbeni et al. 2016). The aquaculture industry has shown remarkable resilience and expansion over the past 50 years, and it currently accounts for around half of all fish consumed by people. It's becoming increasingly evident that one of the significant future challenges will be to meet the nutritional needs of ever-growing societies (Neuhouser et al. 2023). Therefore, supporting infrastructures such as intensive and super-intensive

aquaculture can help cope with the rising demands for seafood. However, improper execution of aquaculture practices can cause stress among aquatic populations, resulting in reduced growth rates, disease proliferation and economic losses.

Fish farmers are inclining towards employing super-intensive culture systems. yet there are problems for creating these systems. Rearing of aquatic organisms in enclosed conditions that have high densities is stressful since their natural habitats had evolved through different time periods (Yu et al. 2023; Stoskopf 1993). By any means of modern aquaculture, the process of breeding aquatic species is intrinsically stressful. For reduction of stress levels, proper aquaculture management is critical (Stoskopf 1993). Thus, dietary supplements act as an important step here. Most oral supplements not only improve growth and enhance feed conversion efficiency but also can sustain the living organism's homeostasis system (Ringø et al. 2014; Hajirezaee et al. 2019a; Ciji and Akhtar 2021; Hajirezaee and Khanjani 2021; Vijayaram et al. 2023a).

As a result, such trait increases their tolerance to the rigorous environment of intensive cultural practices (Bortoletti et al. 2021). Hence, using such supplements constitutes a good and feasible practice to enhance fish propagation and survival in aquaculture.

Ammonia, a critical water quality parameter, greatly influences the homeostasis, food intake and growth efficiency of different aquatic species, especially fishes (Hajirezaee and Khanjani 2023; Zhang et al. 2023). It is one of the toxic compounds found in aquatic environments, occurring in two forms (Osman 2021; Hajirezaee et al. 2024a, 2024b), ionized ammonia (NH_4^+) and non-ionized ammonia (NH_3). For such aquaculture systems that imply conservative management, acute, lethal stress events are quite infrequent. Nevertheless, the stealthy peril of chronic stress continues and results in functional impairments such as increased energy consumption, reduced growth rates, damaged immune system and hindered development of gonads (Osman 2021). Mitigating stress in breeding systems greatly depends on the proper utilization of suitable management strategies involving water quality management, nutrition control and consistent observations of hygiene. (Zhang et al. 2023). An important feature of stress management at aquaculture is the utilization of food supplements with a broad spectrum of characteristics.

Coenzyme Q_{10} (CoQ_{10}), commonly known as an energy booster with antioxidant properties, has gained popularity for its capacity to strengthen immunity and facilitate growth (Jiménez-Jiménez et al. 2023; Huerta-Madroñal et al. 2023; Aramli et al. 2023). For growth stages, CoQ_{10} is a potential energy source; for pre-disease phases, it is a resistance enhancer; for post-treatment, it is a recovery accelerator. Its central role in adenosine triphosphate (ATP) synthesis, the main energy source for cellular activities, further highlights its significance. CoQ_{10} serves as a vital carrier in the electron transport chain within mitochondria helping in energy synthesis It also functions as a powerful antioxidant, offering cellular protection against the harmful effects of free radicals. Although CoQ_{10} is naturally low in various foods such as meat, liver, fish meat and grains (Aydoğan et al. 2023), reaching the optimal levels through dietary intake alone is difficult. Hence, CoQ_{10} oral supplementation becomes a viable option to attain the desired CoQ_{10} levels and exploit all the health benefits associated with this compound.

limited studies have been conducted about the exogenous application of CoQ_{10} supplementation in fish diets. In this regard, El Basuini et al. conducted studies in 2020 and 2021 focused on enriching animal feed with CoQ_{10} supplementation. Their findings revealed a range of positive outcomes, including increased growth, improved health status and the modulation of antioxidant defense mechanisms in *Oreochromis niloticus*. These effects were attributed to the antioxidant properties of CoQ_{10}, its pivotal role in the Krebs cycle, its ability to prevent cell membrane degradation and its synergistic interaction with vitamin E.

Also, more studies on dietary enrichment with CoQ_{10} in poultry yielded similar results. In 2007, Geng et al. observed a significant increase in final weight and improved feed efficiency when L-carnitine and CoQ_{10} were added to the diet of broiler chickens (Geng et al. 2007). Similarly, Huang et al. (2011) and Gopi et al. (2014) documented enhanced growth rates and better feed efficiency among broilers fed CoQ_{10}-supplemented diets.

Due to the lack of research on the effects of oral CoQ_{10} supplementation in aquatic animals, the present study was conducted with the primary aim of evaluating the impacts of CoQ_{10} utilization on growth performance, carcass composition and the enhancement of tolerance against ammonia-induced stress.

Materials and methods

Fish preparation and treatment

Rainbow trout fingerlings (*Oncorhynchus mykiss*) with an average weight of 5.5 ± 0.5g were purchased and subsequently acclimatized during a one-week adaptation period. The experimental groups were then randomly assigned to separate tanks. The study comprised four distinct nutritional groups (each has 3 replicates). CoQ_{10} was sourced from the commercial supplier Sigma-Aldrich (C9538 Sigma-Aldrich, USA). The basic commercial diet, as detailed in Table 1, was prepared by "Faradane Co. Iran". To establish the dietary treatments, CoQ_{10} was carefully prepared at various concentrations. Following the methodology outlined by Zargari et al. (2023), commercial diets were formulated to include the following configurations: a control group with 0% CoQ_{10} (Con.), a group featuring 0.1% CoQ_{10} (G1), a group with 0.5% CoQ_{10} (G2) and a group with 1% CoQ_{10} concentration (G3). Over 8 weeks, the fish were raised on these formulated diets, with feeding quantities adjusted 3 times a day in accordance with Table 2, provided by the manufacturer. During the 8 weeks, 50% of the water was changed daily. In addition, the aeration system and temperature control were constantly monitored.

Sampling

At the end of the experimental period, the fish were carefully caught then they were anesthetized using Eugenol solution in a concentration of 100 ppm (Zargari et al. 2018). Afterward, several assessments and samplings were carried out that encompassed the measurement of growth indices. Hematology tests were done and samples were taken to find the proportion of the carcass. Also, the relative expression of Growth Hormone (GH) and Insulin-like Growth Factor-1 (IGF-1) genes was determined. For histopathological studies, the liver and kidney tissue samples were collected to advance the investigations. This was done after inducing ammonia stress at a concentration of 0.6 mg/L for 24 h.

Table 2 Daily feed amount of Rainbow trout (*O. mykiss*) with commercial diet (Faradane Co., Iran)

Weight (g)	Temperature (°C)s				
	8–10	**10–12**	**12–14**	**14–16**	16–18
0.3–1	2.45	3.15	3.9	4.1	3.2
1–2	1.85	2.4	3	3.1	2.4
2–4	1.8	2.3	2.9	3.05	2.35
4–8	1.75	2.25	2.8	2.95	2.3
8–15	1.55	1.95	2.45	2.55	2
15–25	1.45	1.58	2.35	2.45	1.9

Growth indicators

To assess growth indicators at the end of the period, the weight and length of the fish in each group were measured using a digital scale (with an accuracy of 0.01g) and a ruler (with an accuracy of 1mm). Body weight increase (BWI), percentage of body weight increase (PBWI), specific growth rate (SGR), condition factor (CF) at the beginning and end of the period, feed conversion ratio (FCR) and survival rate (SR) were calculated utilizing standard equations as presented in Eq. 1 (El Basuini et al. 2020; Abidin et al. 2022).

$$\begin{aligned} \text{BWI (g)} &= \text{Final weight (g)} - \text{Initial weight (g)} \\ \text{PBWI (\%)} &= [\text{BWI (g)}/\ \text{Initial weight (g)}] \times 100 \\ \text{SGR (\%/day)} &= [[\text{Ln final weight} - \text{Ln initial weight}]/\ \text{Duration (day)}] \times 100 \\ \text{CF (g/cm}^3) &= [\text{Weight (g)}/[\text{Length (cm)}]^3] \times 100 \\ \text{FCR} &= \text{Feed intake (g)}/\ \text{BWI (g)} \\ \text{SR (\%)} &= [[\text{Initial fish count} - \text{Casualty count}]/\ \text{Initial fish count}] \times 100 \end{aligned} \quad (1)$$

Table 1 Proximate analysis of Rainbow trout (*O. mykiss*) commercial diet (Faradane Co., Iran)

Proximate analysis	Crude protein	Crude fat	Crude fiber	ash	Moisture	phosphorus
%	50–46	15–11	3–1.5	13–9	11–5	1.5–1

Hematological studies

Blood samples were collected aseptically in 2 ml sterile microtubes and the quantification of red blood cells (RBC) and white blood cells (WBC) was promptly conducted using Dice colored solution. To ensure accuracy, the number of cells counted in each replicate with differences less than 10% was documented and expressed as number/mm^3. For the differential count of WBCs, a cell spread was carefully prepared and the percentage of WBCs was determined. Hematocrit percentage (Hct) was determined using micro-hematocrit tubes, following the methodology outlined by Blaxhall (1972). Hemoglobin (Hb) levels were quantified using a commercial kit from "Ziest-Chem Diagnostics Co., Tehran, Iran," based on the cyanmethemoglobin method. Additionally, blood indices including mean corpuscular volume (MCV), mean corpuscular hemoglobin (MCH) and mean corpuscular hemoglobin concentration (MCHC) were calculated using established formulas as presented in Eq. 2 (Dacie and Lewis 2017).

$$\begin{aligned} \text{MCV (fL)} &= \text{Hct (\%)}/\ \text{RBC (106/mm3)} \\ \text{MCH (pg)} &= [\text{Hb (g/dL)} \times 10]/\ \text{RBC (106/mm3)} \\ \text{MCHC (g/dL)} &= [\text{Hb (g/dL)} \times 100]/\ \text{Hct (\%)} \end{aligned} \quad (2)$$

Relative carcass compositionAt the end of the period, following complete anesthesia and euthanasia of the fish, the relative composition of the carcass was examined. Initially, the dry body surface and muscle tissue samples were separated from the fish carcasses, yielding boneless fillets. Subsequently, the tissue samples were crushed and homogenized and utilized for further measurements. The proximate composition analysis of the fish carcass was conducted using standard methods (AOAC, 2005).

Relative gene expression

Following complete anesthesia of the fish using a 100 ppm Eugenol solution, samples of brain and liver tissues were collected to investigate the relative expression of the GH and IGF-1 genes, respectively, following the protocol outlined by Zargari et al. (2023). RNA extraction was initiated using a Wizol commercial kit. Subsequently, complementary DNA (cDNA) was synthesized using a Fermentase reverse transcriptase kit (France) following the manufacturer's instructions meticulously. The Real-Time PCR procedure was conducted after temperature adjustment, utilizing the Cyber Green Mastermix qPCR kit by AMPLIQON, Denmark. This procedure involved the use of specific primers for the GH and IGF-1 target genes, as well as a β-actin housekeeping gene primer (as detailed in Table 3). The reaction mixture comprised cDNA and DEPC water. Gene expression quantification was based on the values obtained through Real-Time PCR. These values were calculated using the CT difference calculation method, employing the formula $2^{-\Delta\Delta CT}$ for each respective gene, as outlined by Zargari et al. (2023).

Ammonia stress

To evaluate the effect of CoQ_{10} supplementation in the diet of Rainbow trout on their resistance to ammonia-induced stress, fish in each treatment group underwent a 24-h exposure to an ammonia stressor, administered at a concentration of 0.6 mg/L in the form of molecular ammonia (NH_4Cl). Ammonium chloride (NH_4Cl, Sigma-Aldrich, USA) was used to induce stressful conditions, following the methodology outlined by Zarantoniello et al. (2021). According to the water conditions of the reservoirs before the experiment, a pre-test was conducted to determine the LC_{50} value by examining the different concentrations of NH_4Cl (0.1, 0.3, 0.4, 0.5, 0.6, and 0.7 mg/L) in triplicate (Harsij

Table 3 Characteristics of the primers used in the study of relative gene expression in Rainbow trout (*O. mykiss*)

Primer sequence	Application	Accession number	gene
F: AATGGTCAGAAATGCCAACC R: AAGCAAGCCAACAACTCGTAG	Growth	NM_001124689.1	**GH**
F: ATGTGCTGTGTCTCCTGTACCC R: TAAAAGCCTCTCTCTCCACACA	Growth/Appetite	M95183.1	**IGF-1**
F: ATGGGCCAGAAAGACAGCTACGTG R: CTTCTCCATGTCGTCCCAGTTG	Housekeeping Gene	NM_001124235.1	**β-actin**

et al. 2020; Grobler et al., 2018; Wicks et al., 2002). Throughout the experiment, various water parameters were closely monitored. The average water temperature, dissolved oxygen levels, total hardness and pH were maintained at 14 ± 2°C, 5 ± 1 mg/L, 380 ± 55 mg/L and 7.6 ± 0.3, respectively. To regulate the levels of ionized ammonia and molecular ammonia in the water, measurements of water temperature and pH were conducted, utilizing the standard coefficients as presented in Table 4. Additionally, 1 normal potassium hydroxide (KOH) solution was employed to stabilize the water pH, following the protocol established by Zarantoniello et al. (2021).

The liver and kidney Histopathology

After the fish were completely anesthetized, liver and kidney tissue samples were collected. Subsequently, tissue section preparation and histopathological study were conducted following the method outlined by Zargari et al. (2023).

Statistical studies

In this study, treatments and sampling were conducted using a completely random design to obtain data. The Kolmogorov–Smirnov test was employed to confirm the normality of data distribution. The data were analyzed using IBM® SPSS version 22 statistical software with the one-way ANOVA test and Duncan's test was utilized to compare the means at the 95% confidence level. Relative gene expression studies were analyzed using the $2^{-\Delta\Delta CT}$ formula and the data were interpreted by comparing the expression level of each sample with the control group. All data were reported as mean ± standard deviation (SD).

Results

Growth indicators

Alterations in growth indices resulting from the inclusion of varying levels of CoQ_{10} in the diet of Rainbow trout fingerlings were computed according to the specifications presented in Table 5. Based on the data from this table, it was determined that the most substantial BWI compared to the Con. was evident in G3 ($P < 0.05$). Moreover, the highest statistically significant values for BWI, PBWI and SGR were observed in G2 and G3, as compared to the Con. ($P < 0.05$). Furthermore, it was observed that the FCR in G3 was significantly lower than the Con. ($P < 0.05$).

Hematological studies

The incorporation of CoQ_{10} into the diet of Rainbow trout fingerlings led to notable alterations in certain blood parameters. As indicated in Table 6, the count of RBCs exhibited the lowest values in G1 and the highest values in G2 ($P < 0.05$). Conversely, the count of WBCs showed an upward trend with increasing concentrations of CoQ_{10} in the diet. Consequently, the most significant increase was observed in G3, while the lowest count was recorded for the Con. ($P < 0.05$). However, other blood indices, Hct, Hb, MCV, MCH

Table 4 Coefficients involved in the amounts of reversible changes in the conversion of ammonia to ammonium according to water temperature and pH (Francis-Floyd et al. 2022)

pH	Temperature							
	6°C	8°C	10°C	12°C	14°C	16°C	18°C	20°C
7.0	0.0013	0.0016	0.0018	0.0022	0.0025	0.0029	0.0034	0.0039
7.2	0.0021	0.0025	0.0029	0.0034	0.0040	0.0046	0.0054	0.0062
7.4	0.0034	0.0040	0.0046	0.0054	0.0063	0.0073	0.0085	0.0098
7.6	0.0053	0.0063	0.0073	0.0086	0.0100	0.0116	0.0134	0.0155
7.8	0.0084	0.0099	0.0116	0.0135	0.0157	0.0182	0.0211	0.0244
8.0	0.0133	0.0156	0.0182	0.0212	0.0247	0.0286	0.0330	0.0381
8.2	0.0210	0.0245	0.0286	0.0332	0.0365	0.0445	0.0514	0.0590
8.4	0.0328	0.0383	0.0445	0.0517	0.0597	0.0688	0.0790	0.0904
8.6	0.0510	0.0593	0.0688	0.0795	0.0914	0.1048	0.1197	0.1361
8.8	0.0785	0.0909	0.1048	0.1204	0.1376	0.1566	0.1773	0.1998
9.0	0.1190	0.1368	0.1565	0.1782	0.2018	0.2273	0.2546	0.2836

Table 5 Length and weight changes at the beginning and end of the period along with BWI, PBWI, SGR, CF and FCR growth indices in Rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks. SR of Rainbow trout fingerlings calculated at the end of culture period, before inducing ammonia stress

	Con	G1	G2	G3
Initial Weight (gr)	5.56 ± 0.51^{a}	5.52 ± 0.51^{a}	5.44 ± 0.51^{a}	5.48 ± 0.51^{a}
Initial Length (cm)	6.72 ± 0.25^{a}	6.78 ± 0.25^{a}	6.68 ± 0.24^{a}	6.74 ± 0.25^{a}
Last Weight (gr)	20.68 ± 0.9^{c}	21.6 ± 1^{b}	22.16 ± 1.34^{b}	22.8 ± 0.96^{a}
Last Length (cm)	11.04 ± 0.5^{a}	10.86 ± 0.61^{a}	11.18 ± 0.66^{a}	10.84 ± 0.47^{a}
Initial CF (g/cm^3)	1.86 ± 0.34^{a}	1.79 ± 0.27^{a}	1.83 ± 0.21^{a}	1.80 ± 0.21^{a}
Last CF(g/cm^3)	1.56 ± 0.27^{b}	1.72 ± 0.3^{ab}	1.62 ± 0.3^{b}	1.81 ± 0.29^{a}
BWI (g)	15.12 ± 1.01^{c}	16.08 ± 1.32^{b}	16.72 ± 1.37^{ab}	17.32 ± 0.99^{a}
PBWI (%)	274.93 ± 37.5^{b}	295.33 ± 48.22^{ab}	310.4 ± 41.78^{a}	319.2 ± 39.34^{a}
SGR (%/day)	2.35 ± 0.18^{b}	2.44 ± 0.22^{ab}	2.51 ± 0.19^{a}	2.55 ± 0.17^{a}
FCR	1.02 ± 0.07^{a}	0.96 ± 0.08^{b}	0.93 ± 0.08^{bc}	0.89 ± 0.05^{c}
SR (before ammonia stress-%)	100^{a}	100^{a}	100^{a}	100^{a}

Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10}). Non-similar small English letters in each line indicate a significant difference at the 0.05 level. Data are mean ± SD

Table 6 Changes in RBC, WBC, Hct and Hb along with blood indices MCV, MCH, MCHC and percentage of Lymphocyte, Neutrophil and Monocyte in rainbow trout (*O. mykiss*) fingerlings fed different levels of CoQ_{10} at the end of the 8 weeks

	Con	G1	G2	G3
RBC ($\times 10^6$)	1.417 ± 0.012^{bc}	1.413 ± 0.012^{c}	1.443 ± 0.012^{a}	1.44 ± 0.017^{ab}
WBC ($\times 10^4$)	2.727 ± 0.042^{c}	3.447 ± 0.012^{b}	3.42 ± 0.035^{b}	3.507 ± 0.031^{a}
Hct (%)	37.5 ± 1^{a}	37.25 ± 0.661^{a}	37.5 ± 1^{a}	37.833 ± 0.764^{a}
Hb (g/dL)	5.827 ± 0.681^{a}	5.986 ± 1.037^{a}	5.802 ± 0.882^{a}	5.925 ± 0.127^{a}
MCV (fL)	264.718 ± 7.41^{a}	263.598 ± 6.838^{a}	259.794 ± 5.236^{a}	262.725 ± 3.597^{a}
MCH (pg)	41.157 ± 5.117^{a}	42.384 ± 7.581^{a}	40.218 ± 6.272^{a}	41.152 ± 1.21^{a}
MCHC (g/dL)	15.544 ± 1.851^{a}	16.056 ± 2.644^{a}	15.481 ± 2.411^{a}	15.669 ± 0.65^{a}
Lymphocyte (%)	87 ± 1^{a}	88 ± 1^{a}	87.33 ± 1.53^{a}	87.67 ± 1.15^{a}
Neutrophil (%)	7.33 ± 0.6^{a}	7.33 ± 0.6^{a}	8 ± 1^{a}	7 ± 1^{a}
Monocyte (%)	5.67 ± 0.61^{a}	4.67 ± 0.61^{a}	4.67 ± 2.52^{a}	5.33 ± 0.6^{a}

Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10}). Non-similar small English letters in each line indicate a significant difference at the 0.05 level. Data are mean ± SD

and MCHC, displayed no significant dependency on the presence of the CoQ_{10} supplement. No statistically significant differences were noted in the levels of these indices compared to the Con. ($P > 0.05$). Besides, differential counts of lymphocytes, neutrophils and monocytes did not exhibit any significant differences ($P > 0.05$) across the various treatment groups.

Relative carcass composition

Based on the findings presented in Table 7, the introduction of CoQ_{10} as an oral supplement into the diet of *O. mykiss* fingerlings did not result in any statistically significant differences in the levels of protein, moisture and ash content ($P > 0.05$). Essentially, the percentages of protein, moisture and ash in the experimental treatments did not show statistically significant disparities when compared to the Con. ($P > 0.05$). Nevertheless, it is noteworthy that the Con. displayed the highest fat content in muscle tissue, while the lowest fat content was observed in G3 ($p < 0.05$).

Table 7 Changes of carcass composition in different treatments in Rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks

	Con	G1	G2	G3
Fat (%)	1.51 ± 0.09^{a}	1.36 ± 0.05^{b}	1.29 ± 0.05^{bc}	1.22 ± 0.02^{c}
Protein (%)	18.30 ± 2.47^{a}	19.69 ± 1.74^{a}	20.07 ± 0.93^{a}	21.46 ± 2.09^{a}
Moisture (%)	77.21 ± 0.97^{a}	76.64 ± 1.57^{a}	76.52 ± 0.69^{a}	74.95 ± 1.84^{a}
Ash (%)	2.09 ± 0.15^{a}	2.17 ± 0.27^{a}	2.31 ± 0.47^{a}	1.98 ± 0.23^{a}

Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10}). Non-similar small English letters in each line indicate a significant difference at the 0.05 level. Data are mean ± SD

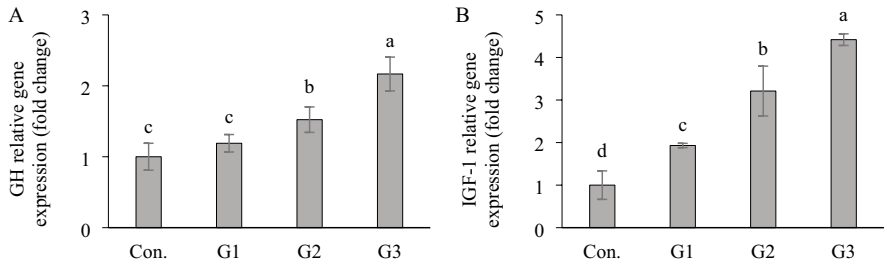


Fig. 1 Comparison of the relative gene expression levels in Rainbow trout (*O. mykiss*) fingerlings fish fed with different levels of CoQ_{10} at the end of the 8weeks. A: GH. B: IGF-1. Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10}). Non-similar small English letters at the top of each column indicate a significant difference at the 0.05 level. Data are mean ± SD

Relative gene expression

Figure 1-A reveals that the expression level of the GH gene was contingent on the concentration of the oral CoQ_{10} supplement. In G3, the relative expression of the GH gene was approximately two-fold in comparison to Con. ($P<0.05$). Conversely, no significant difference was observed between G1 and the Con. ($P>0.05$). As depicted in Figure 1-B, it can be inferred that the relative expression level of the IGF-1 gene exhibits a direct correlation with the concentration of oral CoQ_{10} supplements. G3 displayed a significant level approximately four-fold higher than Con. ($P<0.05$). Furthermore, a notable distinction was observed between G1 and G2 ($P<0.05$).

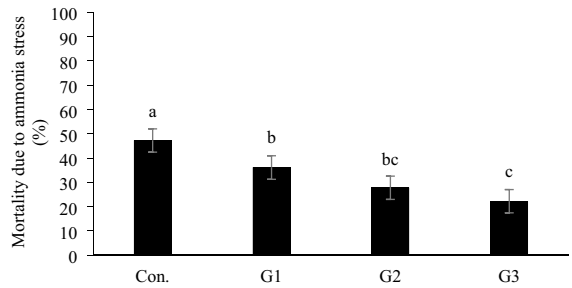
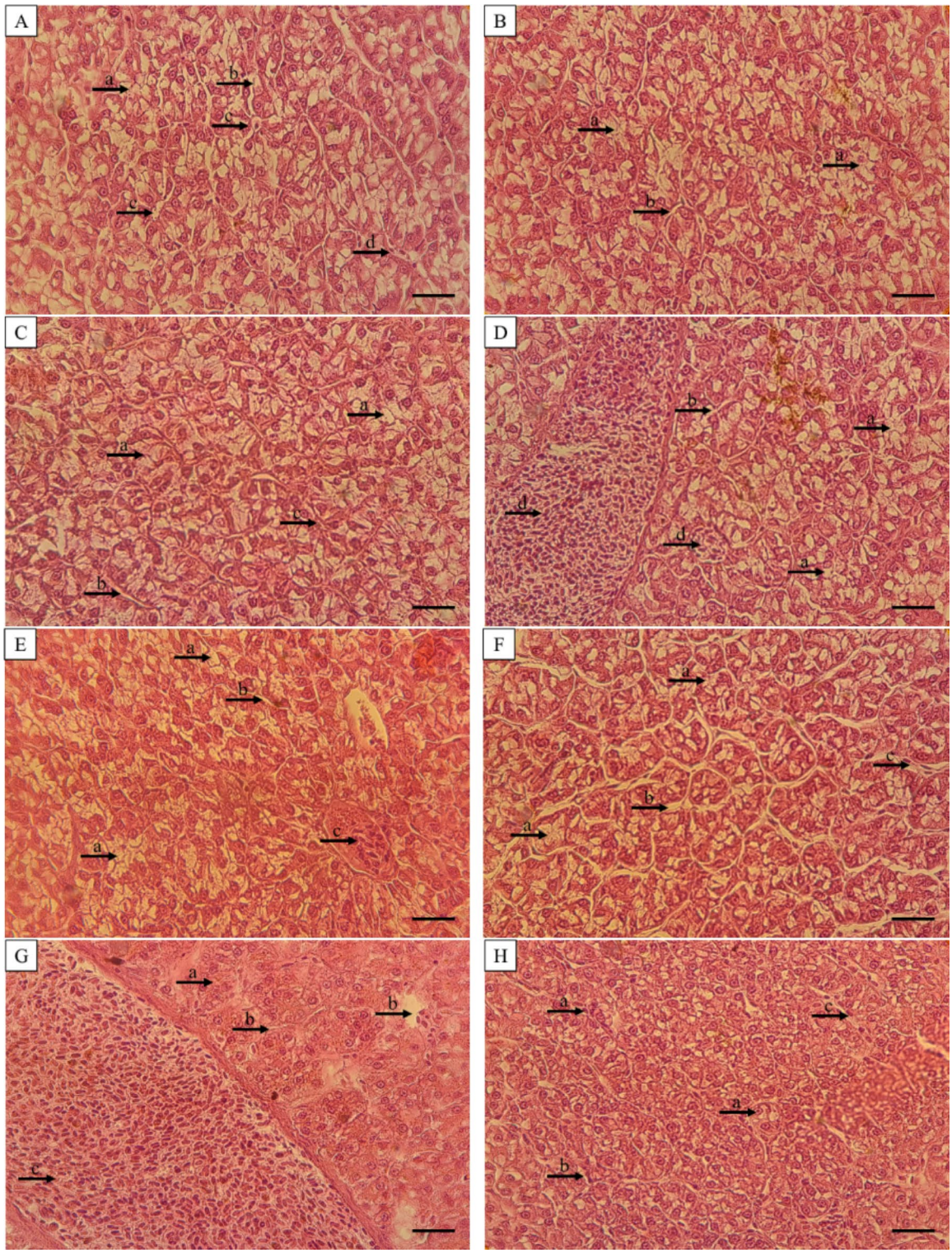


Fig. 2 Mortality rate in different treatments after induction of ammonia stress in Rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks. Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10}). Non-similar small English letters at the top of each column indicate a significant difference at the 0.05 level. Data are mean ± SD

Ammonia stress

Figure 2 shows the pattern of losses after ammonia stress in the Rainbow trout fingerlings across all groups. Remarkably, ammonia stress led to the highest degree of losses in the Con. group. However, as the concentration of oral CoQ_{10} increased, there was a significant reduction in losses. Consequently, with ammonia stress-induced, the mortality rate decreased from approximately 47% of the biomass in the Con. to roughly 22% of the biomass in G3 ($P<0.05$).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◂**Fig. 3** Liver tissue sections in Rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks (×100–400). Figures A and B: Liver tissue of the control group (Con.); Vacuolation of liver hepatocytes (**a**), Sinusoidal space (**b**), Bile duct (**c**), Blood cells (**d**). Figures C and D: Liver tissue of G1 (0.1% CoQ_{10}); Vacuolation of liver hepatocytes (**a**), Sinusoidal space (**b**), Bile duct (c), Blood cells in vein (**d**). Figures E and F: Liver tissue of G2 (0.5% CoQ_{10}); Vacuolation of liver hepatocytes (**a**), Sinusoidal space (**b**), Blood cells in vein (**c**). Figures G and H: Liver tissue of G3 (1% CoQ_{10}); Normal liver hepatocytes (**a**), Sinusoidal space (**b**), Blood cells in vein (**c**). The values of the scale bars are equal to 50 µm

The liver and kidney Histopathology

As presented in Fig. 3 A-H, comparative pathological investigations of liver tissue showed that the dietary CoQ_{10} supplementation of Rainbow trout would minimize the adverse effect of increased environmental ammonia levels on the liver tissues. This hepatoprotective characteristic matches directly with the CoQ_{10} content in the dietary plan. Importantly, the greatest hepatic tissue complications were noticed in the Con., while the damage was significantly alleviated in G3 Table 8 reflects the microscopic representation of the liver tissue pathology. In the Con., hepatocytes showed features like necrosis, marked vacuolation and an enlargement of the sinusoidal space. On the other hand, the complications to the liver tissue in G3 were markedly less as compared to the other groups.

Table 8 Determining of liver tissue complications in Rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks after the induction of ammonia stress

	Con	G1	G2	G3
Ballooning Degeneration	++++	+++	+	+
Necrosis	++++	+++	+	-
Destruction of Sinusoidal Space	+++	+	+	-
Hemosiderin Deposition	-	-	-	-
Cell Vacuolation	++++	+++	+	+
Bleeding	+	-	-	-
Enlargement of Cell Nucleus	++++	+++	+	+

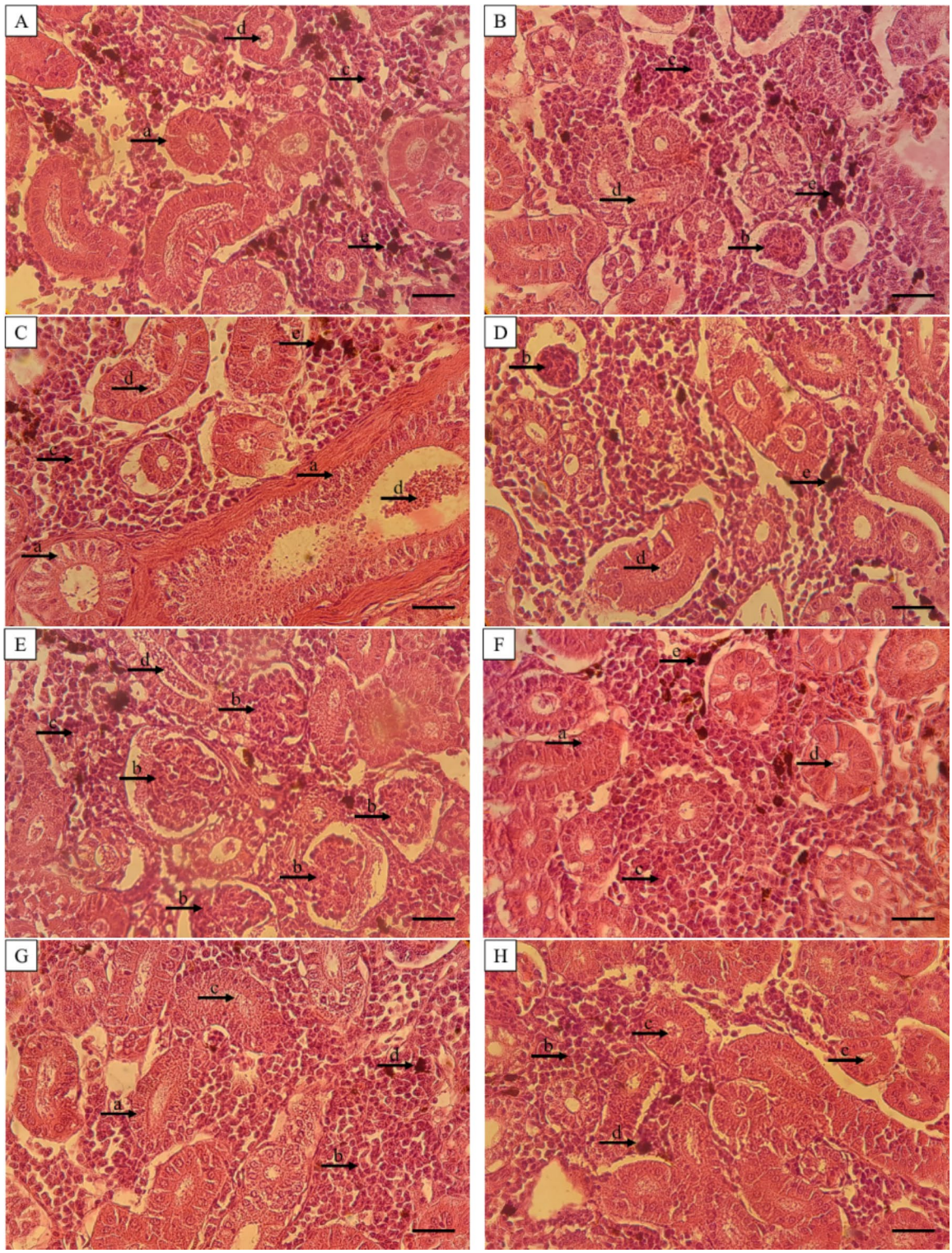
No complications observed (-), observed 1 to 3 complications (+), observed 3 to 5 complications (++), observed 5 to 7 complications (+++), observed more than 7 complications (++++). Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10})

According to Fig. 4 A-H, the evaluation of sections prepared for pathological examination of kidney tissue in fingerlings fed with different levels of CoQ_{10} indicates a significant reduction in kidney tissue complications in G3 compared to other groups. Table 9 provides a comprehensive overview of the diverse range of complications observed in the Con., including necrosis, interstitial cell destruction, expansion of melano-macrophage centers, augmentation of the space surrounding glomeruli and the accumulation of exudates within renal tubules. The addition of CoQ_{10} into the diet resulted in a decrease in the number of melano-macrophage centers within the interstitial cell space, a reduction in the incidence of necrosis and a decrease in the accumulation of exudates within the renal tubules.

Discussion

Growth

The growth rate of fish is influenced by several critical factors, including the size, environmental conditions and the quality of its diet (Jia et al. 2022). In the context of this study, the addition of 1% CoQ_{10} to the diet yielded enhancements in feed performance and growth parameters, including BWI, PBWI, SGR, CF, and FCR. For instance, in the Con., the average weight increased by 15 g, culminating in a final weight of 20.6 g. In G3, the average final weight reached 22.8 g, signifying a 2.3 g weight gain advantage over the control group within a 56-day duration. Furthermore, the FCR decreased by 0.13 units and reached from 1.02 in the Con. to 0.89 in G3. To corroborate the findings of this study, previous investigations on the effects of CoQ_{10} on growth in *O. niloticus* fish, African catfish (*Clarias gariepinus*), and European sea bass (*Dicentrarchus Labrax*) have reported similar outcomes (El-Houseiny et al. 2022; El Basuini et al. 2022, 2021). According to these reports, CoQ_{10} consumption tends to enhance metabolism, increase dietary energy utilization and bolster resistance to stressors, consequently promoting weight gain while consuming less feed (El-Houseiny et al. 2022; El Basuini et al. 2022). Due to its pivotal and well-established role in the mitochondrial bioenergetic process,


A
B
C
D
E
F
G
H

◂**Fig. 4** Sections of kidney tissue in Rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks (×100–400). Figures A and B: kidney tissue in control group (Con.); Degenerated renal tubules (**a**), Narrowing of renal glomerular space (**b**), Degeneration of interstitial cells (**c**), Accumulation of exudates (**d**), Expansion of melano-macrophage centers (**e**). Figures C and D: kidney tissue in G1 (0.1% CoQ_{10}); Degenerated renal tubules (**a**), Enlarged renal glomeruli with space (**b**), Degeneration of interstitial cells (**c**), Accumulation of exudates (**d**), Expansion of melano-macrophage centers (**e**). Figures E and F: kidney tissue in G2 (0.5% CoQ_{10}); Renal tubules (**a**), Renal glomeruli (**b**), Interstitial cells (**c**), Accumulation of exudates (**d**), Melano-macrophage centers (**e**). Figures G and H: kidney tissue in G3 (1% CoQ_{10}); Renal tubules (**a**), Interstitial cells (**b**), Accumulation of exudates in some tubules (**c**), Melano-macrophage centers (**d**). The values of the scale bars are equal to 50 µm

CoQ_{10} actively participates in the electron transfer chain through its quinone ring. This cascade action creates an electrochemical gradient across mitochondrial membranes, ultimately stimulating ATP synthesis. The increased ATP production enhances the energy available for metabolic processes and homeostasis within the organism (Hidalgo-Gutiérrez et al. 2021). Consequently, the surplus energy can meet the organism's requirements while reducing the need for excessive feed consumption, thereby contributing to a reduction in the FCR (Kondratiuk and Otchenashko 2021). A decrease in feed in fish farms produces many favorable effects. Secondly, it can reduce the amount of lost feed, hence limiting feed wastage. The reduction can also lead to a lesser quantity of excretion which gives rise to greater stability in environmental conditions and hence a decrease in pollution within the breeding farms. Hence, the organic load within the aquatic systems becomes lower and biological oxygen consumption is decreased. These factors cumulatively can reduce stress in aquatic animals and reduce the number of deaths. Moreover, the lower input of feed brings about a reduced quantity of manure and finally a lower quantity of pollutants discharged from farms into the natural environment. These benefits match the earlier studies and the research results (Bujas et al. 2022; Mousavi and Zorriehzahra 2021). Antioxidant activity in the mucous membrane of the digestive system performs a crucial function by facilitating the absorption of essential nutrient compounds and attenuating inflammatory responses. It has been reported that CoQ_{10} intake enhances the length of villi, microvilli and the depth of the Lieberkühn crypts within the intestinal mucosa (El Basuini et al. 2021, 2020). This anatomical modification may thus be able to promote food assimilation and decrease the feed conversion ratio (FCR). CoQ_{10} ingestion has the potential to impact the intestinal microflora through the promotion of the growth of beneficial gut bacteria. In addition, the pathogenic pathogens will be abated and it will add to the production of some vitamins and bioactive compounds which will eventually enhance the absorption of nutrients. The effects of CoQ_{10} on gut microbiota and digestive enzymes activity might be correlated with enhanced growth (El Bassuini et al., 2021; El Bassuini et al., 2020).

Table 9 Determination of kidney tissue complications in rainbow trout (*O. mykiss*) fingerlings fed with different levels of CoQ_{10} at the end of the 8 weeks

	Con	G1	G2	G3
Degeneration	++++	+++	+	+
Necrosis	++++	+++	+	-
Destruction of Interstitial Cells	+++	+	+	-
Accumulation of melano-macrophage centers	+++	+++	++	+
Bleeding	+	-	-	-
Accumulation of Exudate Fluids	+++	+++	++	+

No complications observed (-), observed 1 to 3 complications (+), observed 3 to 5 complications (++), observed 5 to 7 complications (+++), observed more than 7 complications (++++). Con. (group fed with basal diet), G1 (0.1% CoQ_{10}), G2 (0.5% CoQ_{10}), G3 (1% CoQ_{10})

Hematological studies

The hematopoietic system in animals is notably sensitive to the compounds they consume, and it responds with fluctuations in the levels of various hematological factors. Consequently, the hematopoietic system serves as a crucial indicator of both the physiological and pathological condition of these animals (Ahmed et al. 2022). Therefore, it can be affirmed that the analysis of blood parameters holds significant value in the evaluation of an organism's overall condition. The assessment of alterations in hematological indicators serves as an effective method for discerning the impact and properties of dietary compounds and supplements in the body.

Hematopoiesis and leukopoiesis are pivotal biological processes underlying the production of diverse blood cells including red blood cells, white blood cells and thrombocytes. In most vertebrates, these processes mainly occur in the bone marrow whereas in many fish species, they occur in the anterior part of the kidney. Regulation of these mechanisms comprises a complex network of signaling molecules, transcription factors and growth factors (Kondera 2019). Antioxidants play a crucially significant role in the regulation of hematopoiesis and leukopoiesis because they can scavenge ROS and mitigate oxidative stress (Kumar et al. 2022). Some research suggested that antioxidant supplements, such as vitamins C and E and β-carotene, might enhance hematopoiesis and leukopoiesis via their capacity to reduce oxidative stress and inflammation (El Basuini et al. 2021, 2020). For instance, vitamin C supplementation has been found to increase WBC count which in turn boosts immune system function (Khadim and Al-Fartusie 2021). The RBC count and their functionality are increased in sickle cell anemia patients treated with vitamin E. β-carotene stimulates the production of WBCs in healthy people. Nevertheless, one should be aware that a high intake of some antioxidants can be harmful to erythropoiesis and immunity (Khadim and Al-Fartusie 2021; Romiti et al. 2020). Elevated doses of vitamin E have been associated with disruptions in immune system function and an increased risk of bleeding in patients (Khadim and Al-Fartusie 2021; Romiti et al. 2020). According to the findings presented by El Basuini et al. (2020), which aimed to evaluate the effectiveness of CoQ_{10} dietary supplementation on hematology parameters, the administration of oral CoQ_{10} supplementation in tilapia did not lead to statistically significant alterations in Hematological factors. However, the inclusion of this compound in the diet of juvenile fish resulted in an observable increase in WBC counts. WBCs are a crucial component of the immune system, playing a pivotal role in the synthesis of antimicrobial compounds, enzymes, complement proteins and immunoglobulins (Kalafati et al. 2023; Uribe et al. 2011).

Relative carcass composition

Marine foods are highly acclaimed for their nutritional richness as reported by Yin and Shi (2023) and Badoni et al. (2021). Fish meat not only is a good source of high-quality protein but also contains more long-chain unsaturated fatty acids, these belong to the Omega-3 family (Badoni et al. 2021). These substances are very important especially because they are the only ones that can support the development of brains and neural tissues, a paramount aspect, particularly in children. On the other hand, they also participate in preserving the best visual function and act as a preventive factor for cardiovascular events (Wang et al. 2022). Nevertheless, fish carcasses are vulnerable to oxidative spoilage. This oxidation causes the development of undesirable taste and aroma, depletion of nutritionally essential unsaturated fatty acids, degradation of pigments, and loss of fat-soluble vitamins, which in turn reduces consumer acceptability (Aubourg 2023). Besides cold storage techniques, the utilization of antioxidant compounds, for instance, vitamin E and CoQ_{10} represents an effective approach to counter oxidative changes. These interventions, therefore, not only ensure the general quality of fish tissues is conserved during storage but also increase the shelf life thus making aquatic products sustainable and marketable (Aubourg 2023).

The composition of fish fillets is the proportion of different constituents in the edible part of the fish, that is fat, protein, moisture and ash. The constituents are critical in determining the nutritional value and inherent characteristics of fish meat. Fat, the main constituent of fish fillets, influences the flavor and texture to a great extent and its amount is species-dependent and influenced by the environmental conditions (Tarricone et al. 2022). In fish fillets, protein is a very important component; it is the source of essential amino acids required for muscle development and maintenance (Du et al. 2023). Fish protein content also differs depending on the particular species and other environmental factors (Jia et al. 2022). The content of moisture in fish fillets sways the tenderness and softness of the flesh and it depends on freshness and the conditions of the storage. Ash content is the mineral parts left after the complete incineration of organic material in tissue. These minerals among them Calcium, Phosphorus, Potassium, Magnesium and Sodium are vital in bone health and various other bodily functions (El Hosry et al. 2023). In the study of Harsij et al. (2020) that scrutinized the effects of nano-selenium, vitamin C, and vitamin E dietary supplementation on carcass composition of rainbow trout across different treatments no statistically significant changes in

crude body protein, crude lipid, crude fiber, dry matter, ash and carbohydrates were recorded from that of the Hoang (2021) study that looked into the impact of vitamin C when added to *Gnathanodon speciosus* diets reported similar results. Although protein content increased from 18% to 19.5%, the presence of vitamin C did not affect the protein content ($P > 0.05$). In the current study, the addition of CoQ_{10} to the diet of Rainbow trout did not result in a statistically significant alteration in the protein, ash and moisture content of the fish fillet. However, an increase in the concentration of CoQ_{10} in the dietary regimen led to a notable reduction in the adipose tissue content. Given the known properties of CoQ_{10} in enhancing energy production and metabolic processes within the organism, it can be inferred that the presence of this compound in the daily diet has prompted increased utilization of adipose tissue for energy generation over 8 weeks. Essentially, the inclusion of CoQ_{10} in the diet appears to facilitate the utilization of fat reserves for energy production (Hernández-Camacho et al. 2022).

Relative gene expression

Gene expression studies which are relative give us a picture of the molecular effects of CoQ_{10} supplementation. The GH and IGF-1 gene expression upregulation can be seen as a response to growth factors such as growth hormone and insulin (Martín et al. 2021). An increase in GH and IGF-1 gene expression plays a major role in growth induction. Nevertheless, it should be pointed out that the expression of these genes can also be regulated by many factors such as diet composition, physical activity and stress levels. For instance, diets rich in proteins and essential amino acids have been shown to increase IGF-1 gene expression, but energy restriction has the opposite effect leading to reduced expression (Caputo et al. 2021; Gulick et al. 2020). GH and IGF-1, being multifunctional hormones, perform multi-sided functions of sustaining life by stimulating growth, performing anabolic reactions, and improving overall body health. Under conditions of decreased energy resources within the body, wanting to preserve protein reserves and ensure survival, these hormones coordinate energy through carbohydrate oxidation and lipolysis via catabolic feedback mechanisms (Caputo et al. 2021). IGF-1/insulin signaling has been pinpointed as the main regulatory mechanism that is related to nutrient effects. Nutrients have an impact on the GH/IGF-1 axis, the hormones regulating nutrient intake at the cellular and tissue level. Thus, one can conclude that the administration of 1% CoQ_{10} in the diet considerably raises the expression of the GH and IGF-1 genes, because it affects energy levels, promotes appetite, increases food consumption, and as a result enhances growth. Moreover, IGF-1 synthesis can be induced by the presence of muscle activity, most notably within the skeletal muscle tissue (Li et al. 2021; Wibawa et al. 2021). Conversely, a reduction in gene expression may occur due to factors such as aging, disease, or environmental influences. Chronic inflammation, for instance, has the potential to diminish the expression of GH and IGF-1 genes, consequently impeding tissue repair and regeneration (Witkowska-Sędek and Pyrżak 2020). Diminished expression of these genes can give rise to a spectrum of disorders, including growth abnormalities and metabolic disturbances (Forbes et al. 2020). Some studies also reveal that various factors encompassing temperature, dietary constituents, and the utilization of specific supplements can exert an impact on the expression of GH and IGF-1 genes in fish (Perelló-Amorós et al. 2021; Geng et al. 2021).

Survival against *ammonia* stress

When a concentration gradient for ammonia exists outside a fish's body, it can release ammonia in the form of NH_3 through the lamellae on the gill filaments (Gilmour 2022). However, when environmental ammonia levels are elevated, this outward flow of ammonia diminishes, leading to a reverse gradient flow. In such circumstances, the concentration of ammonia in the fish's blood and tissues increases, consequently precipitating acute and chronic toxic reactions in the fish. Environmental ammonia gains entry into the fish's body via the lamellae, skin and intestinal mucosa, thereby raising the pH levels and diminishing the blood's oxygen-carrying capacity (Damsgaard et al. 2021). Prolonged exposure to ammonia can result in detrimental effects, including damage to gill tissues, hypertrophy and hyperplasia of lamellae, respiratory function inhibition, oxygen deficiency in fish, harm to liver and kidney tissues, and in severe cases even mortality (Al-Taee et al. 2021; Shokr 2019). Moreover, the deleterious effects of ammonia extend to its capacity to adversely impact the central nervous system of fish.

The investigation of ammonia production and excretion in fish holds substantial significance due to its physiological and ecological implications. This inquiry is particularly crucial for economically valuable species, including ornamental and cultivated aquatic varieties. In such contexts, ammonia toxicity emerges as a prominent threat during aquaculture, often resulting in mass mortality under unfavorable culture conditions (Yan et al. 2021). Hb, residing within RBCs, assumes a pivotal role in oxygen transportation to various body tissues. However, as ammonia levels rise in the bloodstream, the capacity of RBCs to carry oxygen effectively decreases. This phenomenon occurs due to the conversion of Hb into met-hemoglobin, disrupting the oxygenation mechanisms (Abdelrahman et al. 2023).

Based on the findings reported by Vasiljeva et al. (2022), Canals-Garzón et al. (2022), and Cunha et al. (2022) in treatments involving high levels of antioxidant supplements, there has been a notable reduction in the extent of damage observed in RBCs and hematopoietic tissue. A similar protective effect may be induced by CoQ_{10}, owing to its vigorous antioxidant properties (Jiménez-Jiménez et al. 2023; Huerta-Madroñal et al. 2023; Aramli et al. 2023). Adding CoQ_{10} to the diet can mitigate the harm caused by ammonia stress on hematopoietic tissue, promoting bodily homeostasis and modulation of tissue damage. Accordingly, in this study, the G3 group exhibited a mortality rate of 25% and SR of 78% compared to the Con. group.

Accumulation of ammonia in the circulatory system of fish can precipitate metabolic disturbances. Ammonia exerts its deleterious effects on the blood circulation system, thereby resulting in complications such as anemia (Guo et al. 2022; Mangang and Pandey 2021). Gao et al. (2021) observed a substantial decrease in Hb levels, Hct and RBC counts in *Takifugu rubripes* fish following exposure to elevated ammonia concentrations. Their findings proved that *T. rubripes* become severely anemic when exposed to ammonia. Das et al. (2006) documented alterations in RBC count and Hb levels in *Cirrhinus mrigala* following ammonia stress. This phenomenon is probably caused by tissue damage and hemodilution.

The liver and kidney Histopathology

Under normal conditions, the body synthesizes glutamine by converting glutamate and NH_4^+ as a means to eliminate ionized ammonia (Zimmermann et al., 2021; Sepehrinezhad et al. 2020). Consequently, an elevation in NH_4^+ concentration is frequently concomitant with an increase in glutamine levels. The excessive accumulation of glutamine within organs can trigger inflammation and ultimately, the death of the organism (Zimmermann et al., 2021; Sepehrinezhad et al. 2020). Furthermore, the escalation of NH_4^+ levels induces depolarization of the neuron surface. Subsequently, N-methyl-D-aspartate (NMDA) receptors located on neuron surfaces are activated. Excessive activation of these receptors results in an augmented production of nitric oxide (NO) and the activation of the sodium–potassium-ATPase pump. The activation of this pump not only leads to ATP depletion in the body but also fosters the accumulation of NO, culminating in oxidative stress and an increased generation of hydrogen peroxide (Huang et al. 2020). Fish exhibit diverse defense mechanisms against ammonia toxicity; however, stress responses can disrupt the body's adaptive regulation by giving rise to certain metabolites and instigating oxidative damage and widespread inflammation. These physiological perturbations can ultimately lead to the death of the organism (Xu et al. 2021). Hegazi et al. (2010) demonstrated that ammonia-induced stress instigates the generation of ROS, potentially intensifying the toxic properties of ammonia. Some studies conducted on aquatic animals suggest that ammonia toxicity correlates with an excessive inflammatory response within the body (Zou et al. 2023; Xu et al. 2021; Yan et al. 2021; Zhang et al. 2018).

Increased ammonia concentrations in the aquatic environment stimulate the production of ROS in the bodies of aquatic animals. Antioxidant enzyme activity is most often activated at low to moderate pollutant concentrations but is disturbed at higher concentrations (Maresca et al. 2022). Cellular oxidative stress happens when the physiological antioxidant system in the body cannot effectively handle the excess radicals generated. Such oxygen radicals readily bind with fatty acids and cholesterol, thereby, triggering lipid oxidation processes that may result in decreased membrane flexibility, increased permeability of the cell membranes, and disturbance in protein and electrolyte distribution on either side of the cell membrane (Nasri et al. 2022; Chai et al. 2022). These disorders can result in necrosis, extensive vacuolation, expansion of the sinusoidal space, interstitial cell destruction, expansion of melano-macrophage centers, augmentation of the space surrounding

glomeruli and the accumulation of exudates in the kidney and liver. Thus, the 1% CoQ_{10} supplementation into the daily diet can be hypothesized to cancel the free radicals produced due to the enhanced ammonia concentration. Thereby it significantly reduces the destruction of liver and kidney tissues. SOD level changes are highly correlated with ammonia tolerance in fish. Studies on several fish species including Rainbow trout (Harsij et al. 2020), *Seriola dumerili* (Zhou et al. 2023; He et al. 2022), *Takifugu obscurus* (Gao et al. 2021), and European seabass (Shahin et al. 2023), which were given Kim et al. (2020) also noted a substantial increase in SOD activity in the liver and gills of juvenile grouper under ammonia stress. The SOD enzyme activity is enhanced by elevated free radical levels. Nevertheless, the process continues as free radicals are produced in larger amounts. In such a context, the enzyme activity depreciates since the excessive ammonia produced tends to hinder its functioning. This intricate relationship was further elucidated by Sun et al. (2014), who reported that at elevated ammonia concentrations, SOD activity in *Hypophthalmichthys nobilis* larvae initially increased but subsequently decreased. Zhang et al. (2021) also reported a similar pattern of SOD and catalase (CAT) response in *Corbicula fluminea* under ammonia stress, where SOD and CAT first increased, then decreased steadily. This is the consequence of the inhibition of antioxidant enzymes which prevents the instant neutralization of ROS produced in tissues. The CAT activity also decreases with ammonia concentration increasing, indicating oxidative damage and stress. Based on these results it can be concluded that the CoQ_{10} in the present study, inhibits the formation of free radicals because of its antioxidant properties.

Conclusion

Although there is limited study on the effects of CoQ_{10} in aquaculture, it can be broadly asserted that adding CoQ_{10} into the diet of fish (particularly Rainbow trout in this study) has the potential to enhance growth by modulating the expression of GH and IGF-1 genes. Furthermore, CoQ_{10}, owing to its antioxidant properties, mitigates cell membrane lipid oxidation and complications in the kidney and liver such as necrosis, vacuolation, expansion of the sinusoidal space, interstitial cell destruction, expansion of melano-macrophage centers, augmentation of the space surrounding glomeruli and the accumulation of exudates. Therefore, the inclusion of CoQ_{10} in the daily diet at approximately 1% could lead to improved growth and increased resistance to ammonia stress in intensive and super-intensive aquaculture systems.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval All experimental procedures were approved by the Gorgan University of Agricultural Sciences and Natural Resources (GUASNR, Approval No. 9721304101, 2020) ethics committee. It confirmed that all experiments were performed in accordance with relevant guidelines and regulations as described by the ARRIVE guidelines (PLoS Bio 8(6), e1000412,2010). The study's compliance with these guidelines can be accessed through the provided link https://doi.org/10.1371/journal.pbio.1000412.

Competing interests The authors declare no competing interests.

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