

Effects of Cadmium Exposure on External Morphometric Traits of *Trichopodus pectoralis* (Snakeskin Gourami)

Wan Nuru Nazriah W. Abdullah, Mohd Sham Othman^{*}, Mohd Riduan Abdullah

Center for Toxicology & Health Risk Studies (CORE), Faculty of Health Sciences, Universiti Kebangsaan Malaysia, Kuala Lumpur, Malaysia

Email: *mso@ukm.edu.my

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Abstract

Heavy metal contamination, particularly cadmium, poses a critical threat to Malaysia's aquatic ecosystems due to its toxicity, persistence in the environment and bioaccumulative potential. Such contamination threatens biodiversity sustainability and public health, as consumption of contaminated fish can elevate human health risks through biomagnification. *Trichopodus pectoralis*, a sensitive biological indicator, was selected to assess cadmium's sublethal effects on external morphometric traits. Juvenile *Trichopodus pectoralis* were exposed to four cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L) over 16 weeks, with morphometric analyses performed at four-week intervals using descriptive statistics and the Kruskal-Wallis's test. The findings revealed that cadmium exposure significantly affected most external morphometric traits, including snout length, head length, postorbital length, pectoral fin length, body depth, caudal peduncle depth, standard length and total length ($p < 0.05$). Interestingly, traits such as postdorsal length increased at the highest concentration, suggesting compensatory responses. External morphometric traits of *T. pectoralis* serve as reliable indicators of cadmium toxicity. Notably, the current National Water Quality Standards threshold (0.010 mg/L) already impairs juvenile fish, highlighting the need for stricter monitoring and revision of safety margins to protect biodiversity and public health.

Keywords

Cadmium, *Trichopodus pectoralis*, External Morphometric Traits

1. Introduction

Freshwater pollution has become a pressing environmental issue in Malaysia, where rivers are critical for agriculture, aquaculture, domestic use, and drinking water [1]. Industrial effluents, intensive agriculture, ineffective waste management, and rapid urbanization have contributed to declining water quality. In 2023, 25 of 672 major rivers were classified as polluted, while 161 were moderately polluted, with Sungai Klang, Sungai Juru, and Sungai Segget identified as severely contaminated due to domestic and industrial discharges [1]. [2] reported significant increases in heavy metals such as lead, mercury, and cadmium in rivers near industrial zones.

Heavy metals are among the most concerning pollutants due to their persistence and toxicity. Cadmium does not naturally occur in organisms but can accumulate through ingestion, inhalation, or dermal contact. [3] linked cadmium contamination in aquatic ecosystems to anthropogenic sources such as industrial discharge, fertilizers, and domestic waste. [4] emphasized its long-term stability and potential for bioaccumulation and biomagnification in aquatic food chains. [5] further noted that freshwater fish play a key role in cadmium transfer within trophic levels, increasing risks for rural communities dependent on fish as a protein source. Chronic exposure has been associated with kidney damage, liver dysfunction, and carcinogenesis [6].

The economic and ecological consequences of freshwater pollution are significant. Declining water quality directly affects aquaculture productivity, reducing fish growth and survival rates, thereby threatening local economies [7]. Anthropogenic disturbances also favor invasive alien species, destabilizing native ecosystems [8]. In addition, cadmium contamination has been shown to impair fish physiology, growth, and reproduction [9] [10]. These findings highlight the interconnectedness of pollution, biodiversity loss, and economic sustainability.

Cadmium accumulates in fish tissues and enters the food chain, leading to biomagnification. [6] warned that chronic exposure can cause kidney damage, liver dysfunction, and cancer. [4] demonstrated cadmium's effects on fish embryos and survival rates, while [11] emphasized the importance of morphometric traits in assessing fish health under environmental stress. [12] highlighted diagnostic morphometric features such as body depth, head length, and fin dimensions for evaluating species differences and pollution impacts.

Fish are widely recognized as effective bioindicators due to their sensitivity to environmental changes, ability to accumulate pollutants, and ecological importance [13] [14]. *Trichopodus pectoralis* (snakeskin gourami) is a freshwater species native to Southeast Asia, found in Thailand, Vietnam, Cambodia, Laos, and Malaysia, and introduced to other countries including India, Bangladesh, and Indonesia [15]. [16] described *Trichopodus pectoralis* as an ideal model in toxicological studies due to its rapid reproduction, adaptability, and easily identifiable morphology. This study therefore aims to determine and compare the impacts of cadmium exposure at varying concentrations and durations on the external

morphometric traits of *Trichopodus pectoralis*, providing evidence for stricter monitoring and potential revision of the National Water Quality Standards (NWQS).

2. Materials and Methods

The study is experimental research at the Ecotoxicology Laboratory, Faculty of Health Sciences, Universiti Kebangsaan Malaysia, Kuala Lumpur. A total of 600 juvenile *Trichopodus pectoralis* measuring 2 - 3 inches were obtained from a local supplier in Krubong, Melaka. Fish were randomly assigned into four treatment groups exposed to different concentrations of cadmium (0.000 mg/L, 0.005 mg/L, 0.010 mg/L and 0.015 mg/L) for 16 weeks. Each treatment was maintained in three separate aquariums and sampling was performed at four-week intervals (weeks 0, 4, 8, 12, and 16). At each interval, 30 fish per group (10 individuals from each aquarium) were randomly selected for morphometric analysis. Fish density for each aquarium were adjusted and equalized after each sampling.

Aquarium (61.5 cm × 32.0 cm × 33.5 cm) were filled with 10 L of dechlorinated tap water. Cadmium exposure solutions were prepared by diluting a 1000 mg/L cadmium standard solution using the formula:

$$M_1 V_1 = M_2 V_2 \quad (1)$$

where M_1 : Concentration of the cadmium stock solution, V_1 : Volume of the cadmium stock solution, M_2 : Desired concentration of the cadmium solution and V_2 : Required volume of water, to achieve the desired concentrations (0.005, 0.010, and 0.015 mg/L). Control aquarium contained only dechlorinated tap water. Water was changed monthly to maintain quality, and fish were fed daily with commercial pellets at 1% - 8% of average body weight. The ad libitum feeding regime was used to avoid overfeeding [17].

Fish were acclimatized and maintained under controlled laboratory conditions. Each treatment group was housed in four aquaria to minimize density effects. Feeding was standardized across groups, and water quality was monitored regularly. At each sampling interval, 30 fish per group were euthanized using the ice-water method, following American Veterinary Medical Association (2020) guidelines [18]. Fish were dried with tissue paper to facilitate accurate measurements. External morphometric traits were measured using a digital vernier caliper. Traits included snout length, head length, postorbital length, pectoral fin length, body depth, caudal peduncle depth, standard length, total length [19]. Each measurement was taken three times, and the mean value was recorded.

All data were tabulated in Microsoft Excel and analyzed using SPSS version 29.0. Descriptive statistics were used to summarize morphometric parameters, and the Kruskal-Wallis's test was applied to determine significant differences among treatments and exposure durations. A significance level of $p < 0.05$ was adopted.

3. Results and Discussion

3.1. Craniofacial Morphometrics (Snout Length, Head Length, Postorbital Length)

Figure 1 shows a comparison of the mean snout length of *Trichopodus pectoralis* in four different treatment group which are 0.000 mg/L, 0.005 mg/L, 0.010 mg/L and 0.015 mg/L. Based on **Figure 1**, the highest mean snout length of *Trichopodus pectoralis* was recorded at the concentration of 0.005 mg/L, measuring 5.78 ± 0.72 mm, whereas the lowest mean snout length was observed at the concentration of 0.015 mg/L, measuring 4.35 ± 0.40 mm. The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean snout length of the fish was found to be non-normal ($p < 0.05$) based on the normality test. According to the results of the Kruskal-Wallis's test, there were significant differences ($p < 0.001$, $p < 0.05$) in the mean snout length of *Trichopodus pectoralis* across different cadmium concentrations.

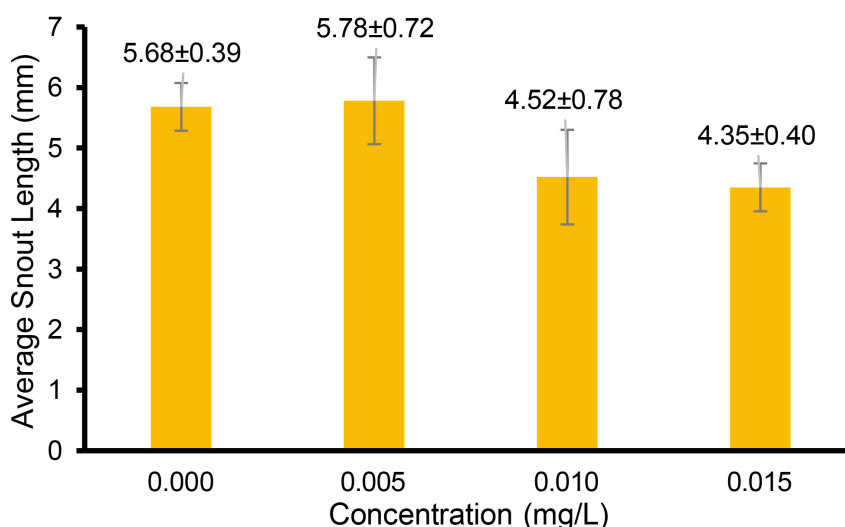


Figure 1. The average snout length in different treatment group.

Figure 2 shows a comparison of the average snout length of *Trichopodus pectoralis* according to different time exposure in four different concentrations of cadmium. Based on the figure, Overall, the mean snout length of *Trichopodus pectoralis* exhibited gradual changes across different exposure periods, with an initial mean of 4.95 mm at week 0 for all cadmium concentrations.

At 0.000 mg/L, the lowest mean was observed at week 4 (3.74 mm), followed by increases at weeks 8 (5.06 mm) and 12 (5.92 mm), before declining at week 16 (5.68 mm). At 0.005 mg/L, the lowest mean occurred at week 12 (4.28 mm), while the highest was recorded at week 16 (5.78 mm), with intermediate values at week 4 (4.93 mm) and week 8 (5.06 mm). At 0.010 mg/L, the lowest mean was noted at week 4 (4.36 mm), with progressive increases at week 8 (4.38 mm), week 12 (4.77 mm), and week 16 (4.52 mm). At 0.015 mg/L, the lowest mean was observed at

week 4 (4.01 mm), followed by increases at week 8 (4.09 mm) and week 12 (4.86 mm), before declining again at week 16 (4.35 mm).

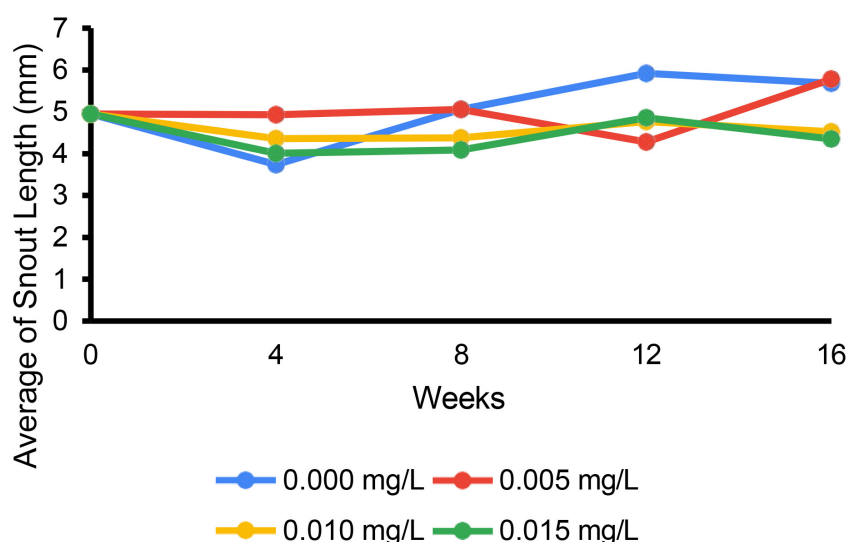


Figure 2. The comparison of average snout length of each treatment group with time exposure.

The Kruskal-Wallis statistical test was performed after the distribution of the overall mean snout length of the fish was found to be non-normal ($p < 0.05$) based on the normality test. According to the Kruskal-Wallis results, there were significant differences ($p < 0.001$, $p < 0.05$) in the mean snout length of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

The reduction in mean snout length at 0.015 mg/L cadmium concentration indicates the impact of cadmium on calcium homeostasis. Cadmium possesses a high affinity for substituting calcium ions within bone structures, thereby disrupting the process of bone ossification. According to [20], reduced opercular bone growth was observed within six days post-fertilization (dpf) in larvae exposed to cadmium, and an increased incidence of skeletal deformities was documented within 20 days post-larvae. Consequently, when this process is impaired, the snout—one of the earliest developing structures in fish—undergoes stunted growth. [21] further reported that certain metals such as cadmium, copper, and zinc exhibit strong affinities for specific organs and are capable of accumulating at high concentrations within these tissues.

Figure 3 shows the mean head length of *Trichopodus pectoralis* across four cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L). The highest mean head length was recorded at 0.005 mg/L (18.41 ± 1.36 mm), while the lowest value was observed at 0.015 mg/L (14.41 ± 1.32 mm). The overall trend indicates a fluctuating pattern, with mean head length decreasing progressively from 0.000 mg/L to 0.015 mg/L. Based on the results of the Kruskal-Wallis's test, there were significant differences ($p < 0.001$, $p < 0.05$) in the mean head length

of *Trichopodus pectoralis* across different cadmium concentrations.

Figure 4 shows comparison of the average head length of *Trichopodus pectoralis* according to different time exposure in four different concentrations of cadmium. Overall, the mean head length exhibited a gradual trend of change across different exposure periods. At week 0, the mean snout length for all cadmium concentrations was 16.94 mm.

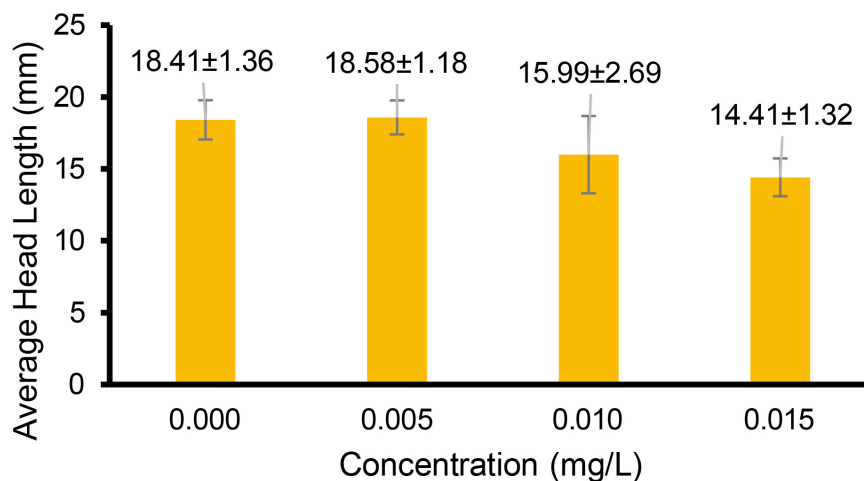


Figure 3. The average head length in different treatment group.

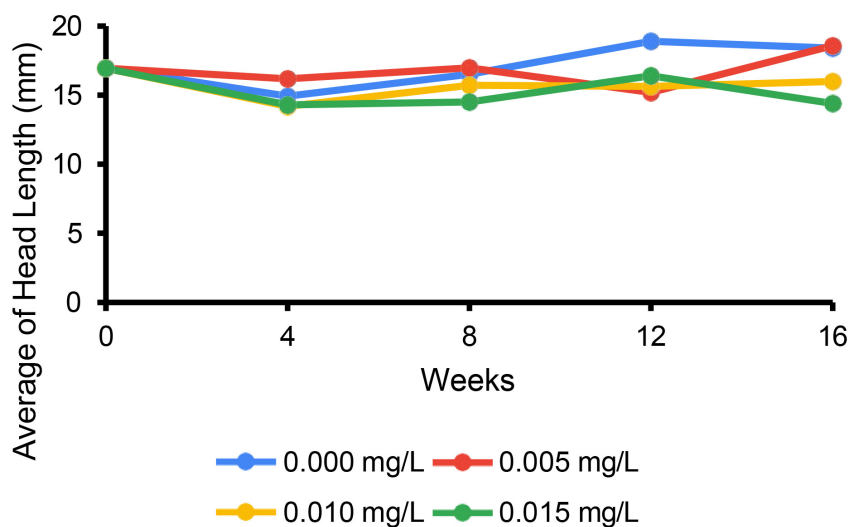


Figure 4. The comparison of average head length of each treatment group with time exposure.

At 0.000 mg/L cadmium, the mean head length decreased at week 4 (14.93 mm), increased at weeks 8 (16.52 mm) and 12 (18.90 mm), before declining slightly at week 16 (18.41 mm). At 0.005 mg/L, the lowest mean was observed at week 12 (15.20 mm), while the highest was recorded at week 16 (18.58 mm), with intermediate values at week 4 (16.17 mm) and week 8 (16.99 mm). At 0.010 mg/L, the

lowest mean occurred at week 4 (14.19 mm), followed by increases at week 8 (15.72 mm), week 12 (15.63 mm), and week 16 (15.99 mm). At 0.015 mg/L, the lowest mean was noted at week 4 (14.30 mm), with increases at week 8 (14.50 mm) and week 12 (16.39 mm), before declining again at week 16 (14.41 mm). Overall, the results indicate fluctuating trends in head length across exposure durations, with higher cadmium concentrations (0.010 - 0.015 mg/L) generally associated with reduced values compared to lower concentrations (0.000 - 0.005 mg/L).

The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean body width of the fish was found to be non-normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean head length of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

In addition, the process of bone formation or osteogenesis in cranial bones also responds to the presence of cadmium ions, due to cadmium's tendency to compete with and replace calcium within the bone matrix. This statement is supported by [22], who reported that cadmium disrupts the metabolism of calcium, magnesium, iron, zinc, and copper in cells, leading to demineralization, osteomalacia, osteoporosis, and disturbances in regulatory functions involving these ions. Consequently, a reduction in head elongation was observed when fish were exposed to higher cadmium concentrations, specifically at 0.010 mg/L and 0.015 mg/L.

Figure 5 shows the mean postorbital length of *Trichopodus pectoralis* across four cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L). Based on **Figure 5**, the highest mean postorbital length was recorded at 0.000 mg/L (8.78 ± 0.75 mm) while the lowest mean was observed at 0.015 mg/L (6.95 ± 0.96 mm). The overall trend indicates a progressive decline in mean postorbital length with increasing cadmium concentration. Based on the results of the Kruskal-Wallis test, significant differences ($p < 0.001$, $p < 0.05$) were observed in the mean postorbital length of *Trichopodus pectoralis* across different cadmium concentrations.

Figure 6 shows comparison of the average postorbital length of *Trichopodus pectoralis* according to different time exposure in four different concentrations of cadmium. The mean postorbital length across all cadmium concentrations was 8.12 mm at week 0. At 0.000 mg/L cadmium, the mean postorbital length decreased at week 4 (6.95 mm), increased at weeks 8 (7.63 mm) and 12 (8.85 mm), before declining slightly at week 16 (8.78 mm). At 0.005 mg/L, the lowest mean was observed at week 4 (7.47 mm), while the highest was recorded at week 16 (8.50 mm), with intermediate values at week 8 (8.12 mm) and week 12 (8.42 mm). At 0.010 mg/L, the lowest mean occurred at week 4 (6.31 mm), followed by increases at week 8 (7.14 mm), week 12 (7.19 mm), and week 16 (7.70 mm). At 0.015 mg/L, the lowest mean was noted at week 4 (6.35 mm), with increases at week 8 (6.68 mm) and week 12 (8.56 mm), before declining again at week 16 (6.95 mm).

Overall, the results demonstrate fluctuating trends in postorbital length across exposure durations, with higher cadmium concentrations (0.010 - 0.015 mg/L)

generally associated with reduced values compared to lower concentrations (0.000 - 0.005 mg/L). Based on the results of the Kruskal-Wallis's test, significant differences ($p < 0.001$, $p < 0.05$) were observed in the mean postorbital length of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

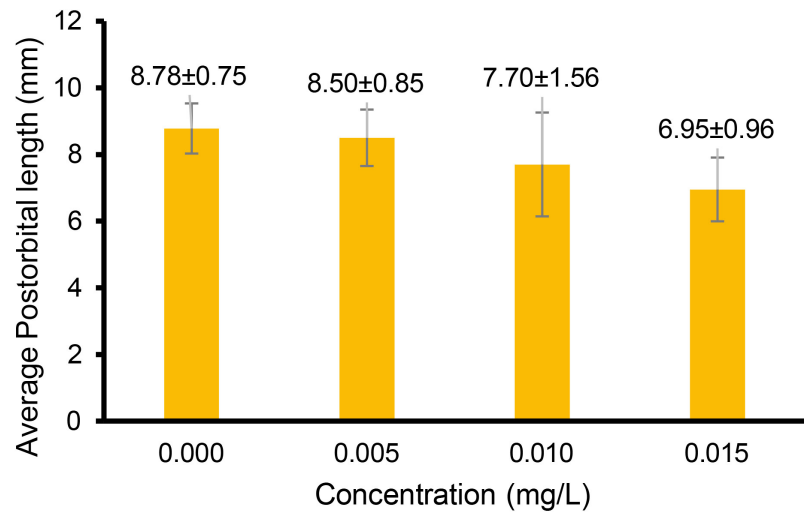


Figure 5. The average postorbital length in different treatment group.

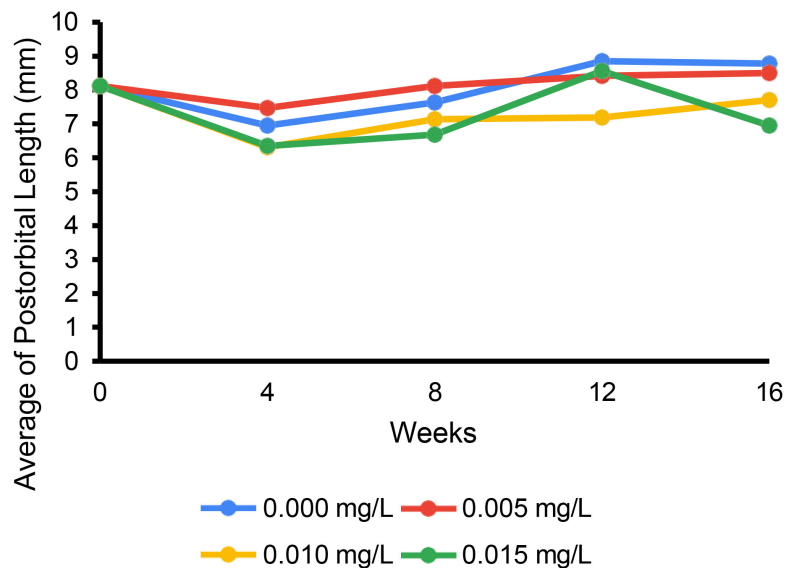


Figure 6. The comparison of average postorbital length of each treatment group with time exposure.

The linear decreasing trend indicates that cadmium concentration influences postorbital length, with higher concentrations resulting in shorter postorbital dimensions. In addition, the fluctuating pattern of mean interorbital length suggests that increasing cadmium concentrations also affect interorbital growth. As cranial

development is stunted, postorbital length is reduced in larvae exposed to cadmium [23]. Cadmium exposure disrupts growth-related hormones such as thyroid and steroid hormones, which regulate craniofacial tissue development. Disturbances in steroid hormone levels can lead to abnormal growth, reproductive dysfunction, and other adverse effects [5]. Therefore, hormonal alterations may impair osteogenesis, subsequently influencing both postorbital and interorbital lengths.

3.2. Body Depth and Size Morphometrics (Body Depth, Caudal Peduncle Depth, Standard Length and Total Length)

Figure 7 shows comparison of the mean body depth for *Trichopodus pectoralis* in four different treatment groups which are 0.000 mg/L, 0.005 mg/L, 0.010 mg/L and 0.015 mg/L. Based on **Figure 7**, the highest mean body depth was recorded at 0.005 mg/L cadmium concentration (21.14 ± 2.73 mm), followed by 0.000 mg/L (20.86 ± 2.31 mm), 0.010 mg/L (16.93 ± 4.08 mm), and the lowest at 0.015 mg/L (15.94 ± 1.95 mm). The overall trend indicates an increase in mean body depth from 0.000 mg/L to 0.005 mg/L, followed by a decline from 0.010 mg/L to 0.015 mg/L. From Kruskal-Wallis's test, there is a significant difference ($p < 0.001$, $p < 0.05$) were observed in the mean body depth of *Trichopodus pectoralis* across different cadmium concentrations.

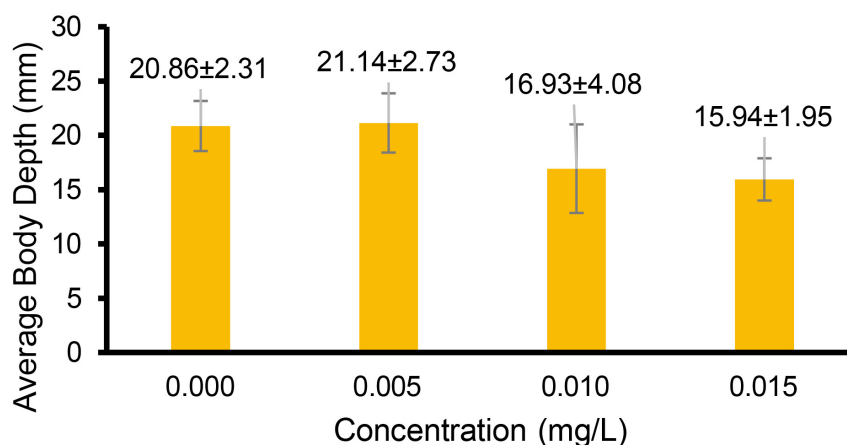


Figure 7. The average body depth in different treatment group.

Figure 8 presents the mean body depth of *Trichopodus pectoralis* at different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L) across varying exposure periods (weeks 0, 4, 8, 12, and 16). Overall, the mean body depth exhibited a gradual trend of change with increasing exposure duration. At week 0, the mean body depth across all cadmium concentrations was 17.99 mm.

At 0.000 mg/L, the mean body depth decreased at week 4 (15.95 mm), increased at weeks 8 (16.98 mm) and 12 (20.90 mm), before declining slightly at week 16 (20.86 mm). At 0.005 mg/L, the lowest mean was observed at week 12 (14.47 mm), while the highest was recorded at week 16 (21.14 mm), with intermediate values

at week 4 (16.62 mm) and week 8 (18.26 mm). At 0.010 mg/L, the lowest mean occurred at week 4 (15.20 mm), followed by increases at week 8 (15.53 mm), week 12 (16.11 mm), and week 16 (16.93 mm). At 0.015 mg/L, the lowest mean was noted at week 8 (14.87 mm), with values at week 4 (15.45 mm), week 12 (19.43 mm), and week 16 (15.94 mm). Taken together, these results indicate fluctuating trends in body depth across exposure durations, with higher cadmium concentrations (0.010 - 0.015 mg/L) generally associated with reduced values compared to lower concentrations (0.000 - 0.005 mg/L).

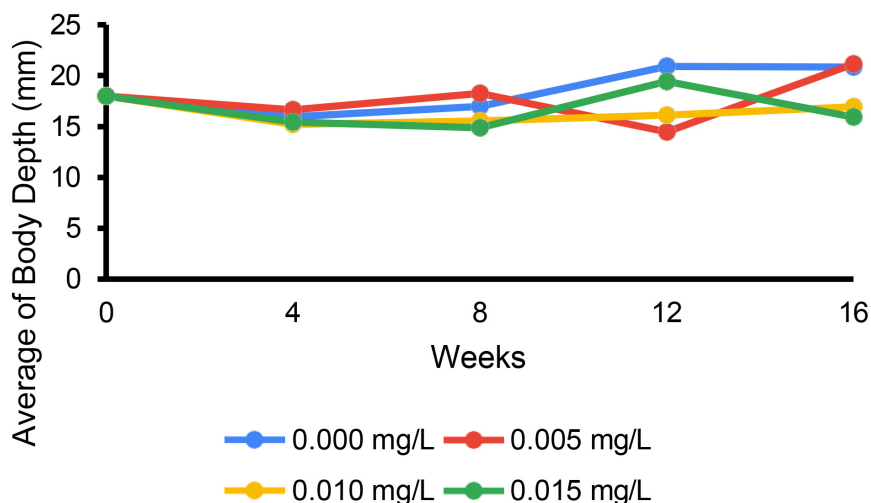


Figure 8. The comparison of average body depth of each treatment group with time exposure.

The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean body depth was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean body depth of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

Figure 9 illustrate the mean caudal peduncle depth of *Trichopodus pectoralis* at four different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L). The highest mean caudal depth was recorded at 0.005 mg/L (8.56 ± 2.25 mm) while the lowest at 0.015 mg/L (6.91 ± 1.32 mm). Based on the results of the Kruskal-Wallis's test, significant differences ($p < 0.001$, $p < 0.05$) were observed in the mean caudal depth of *Trichopodus pectoralis* across different cadmium concentrations.

Figure 10 present the comparison mean caudal peduncle depth of *Trichopodus pectoralis* at different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L) across varying exposure periods (weeks 0, 4, 8, 12, and 16). Overall, the mean caudal depth exhibited a gradual trend of change with increasing exposure duration. At week 0, the mean caudal peduncle depth across all cadmium concentrations was 7.92 mm.

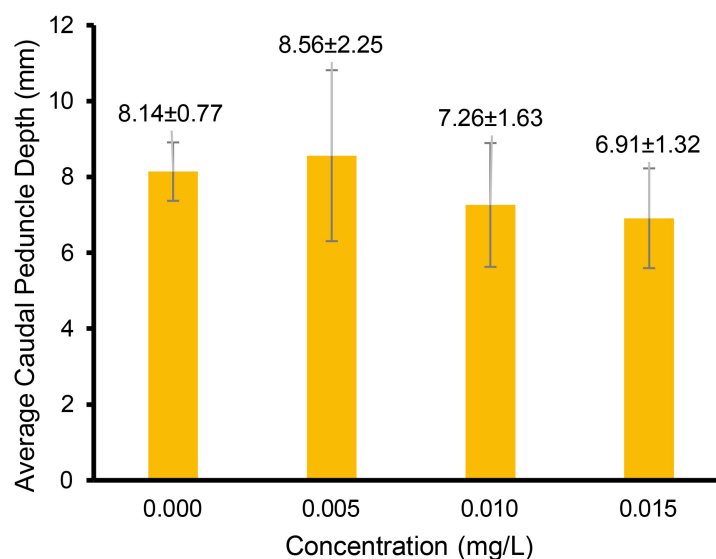


Figure 9. The average caudal peduncle depth in different treatment group.

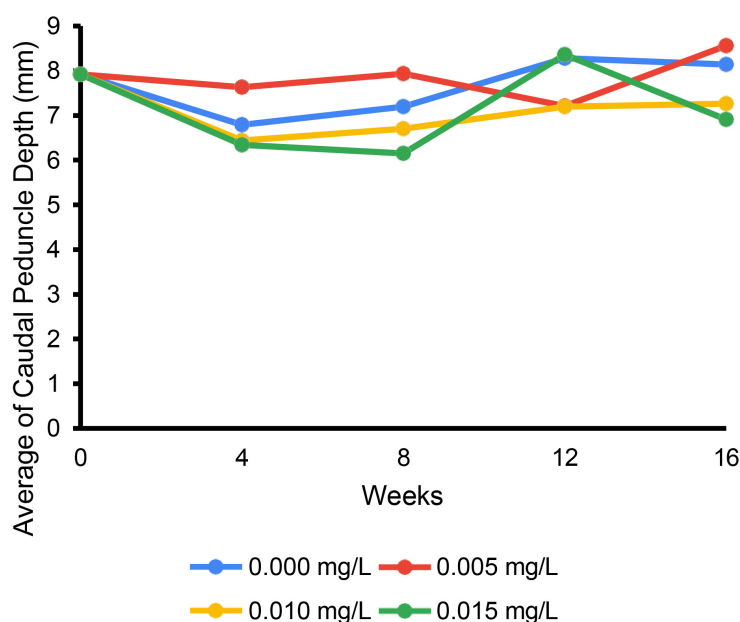


Figure 10. The comparison of caudal peduncle depth of each treatment group with time exposure.

At 0.000 mg/L cadmium, the mean caudal peduncle depth decreased at week 4 (6.79 mm), increased at weeks 8 (7.20 mm) and 12 (8.28 mm), before declining slightly at week 16 (8.14 mm). At 0.005 mg/L, the lowest mean was observed at week 12 (7.21 mm), while the highest was recorded at week 16 (8.56 mm), with intermediate values at week 4 (7.63 mm) and week 8 (7.93 mm). At 0.010 mg/L, the lowest mean occurred at week 4 (6.44 mm), followed by increases at week 8 (6.70 mm), week 12 (7.20 mm), and week 16 (7.26 mm). At 0.015 mg/L, the lowest mean was noted at week 8 (6.15 mm), with values at week 4 (6.34 mm), week 12

(8.36 mm), and week 16 (6.91 mm).

The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean caudal peduncle depth was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean caudal peduncle depth of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

Body depth and caudal peduncle depth provide a general indication of fish physiology, as reductions in these parameters demonstrate exposure to heavy metal pollution. Exposure to cadmium concentrations can influence energy allocation within the fish body as well as muscle and lipid formation. This is supported by [24], who reported that cadmium stress significantly decreases crude protein and crude lipid content. Therefore, cadmium stress has the potential to alter muscle composition, subsequently reducing body and caudal peduncle depth when fish are exposed to higher cadmium concentrations, specifically 0.010 mg/L and 0.015 mg/L.

Figure 11 shows the mean standard length of *Trichopodus pectoralis* at four different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L). Based on **Figure 11**, the highest mean standard length was recorded at 0.005 mg/L (62.87 ± 5.71 mm) while the lowest at 0.015 mg/L (46.48 ± 7.26 mm). The overall trend indicates a fluctuating pattern, with an increase from 0.000 mg/L to 0.005 mg/L, followed by a decline from 0.010 mg/L to 0.015 mg/L. The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean standard length was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean standard length of *Trichopodus pectoralis* across different cadmium concentrations.

Figure 12 presents the comparison mean standard length of *Trichopodus pectoralis* at different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L) across varying exposure periods (weeks 0, 4, 8, 12, and 16). Overall, the mean standard length exhibited a gradual trend of change with increasing exposure duration. At week 0, the mean standard length across all cadmium concentrations was 55.85 mm.

At 0.000 mg/L, the mean standard length decreased at week 4 (45.65 mm), increased at weeks 8 (52.90 mm) and 12 (63.03 mm), before declining at week 16 (55.14 mm). At 0.005 mg/L, the lowest mean was observed at week 12 (49.14 mm), while the highest was recorded at week 16 (62.87 mm), with intermediate values at week 4 (51.98 mm) and week 8 (56.24 mm). At 0.010 mg/L, the lowest mean occurred at week 4 (47.06 mm), followed by increases at week 8 (51.18 mm) and week 12 (51.55 mm), before declining at week 16 (50.15 mm). At 0.015 mg/L, the lowest mean was noted at week 4 (42.03 mm), with values at week 8 (43.89 mm), week 12 (51.39 mm), and week 16 (46.48 mm). Taken together, these results indicate fluctuating trends in standard length across exposure durations, with higher cadmium concentrations (0.010 - 0.015 mg/L) generally associated with reduced

values compared to lower concentrations (0.000 - 0.005 mg/L).

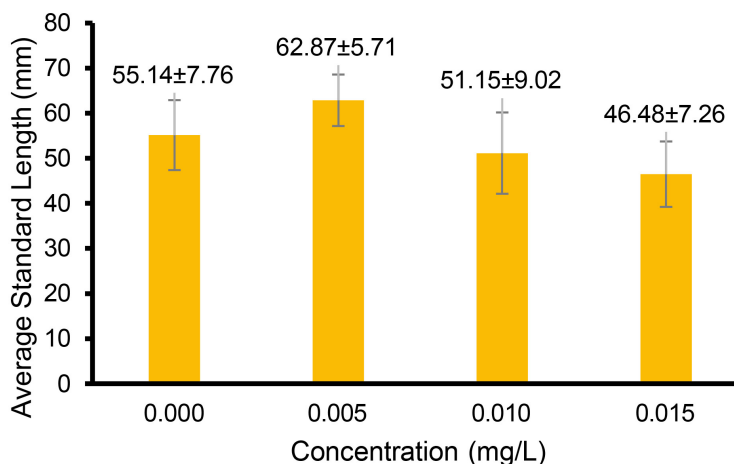


Figure 11. The average standard length in different treatment group.

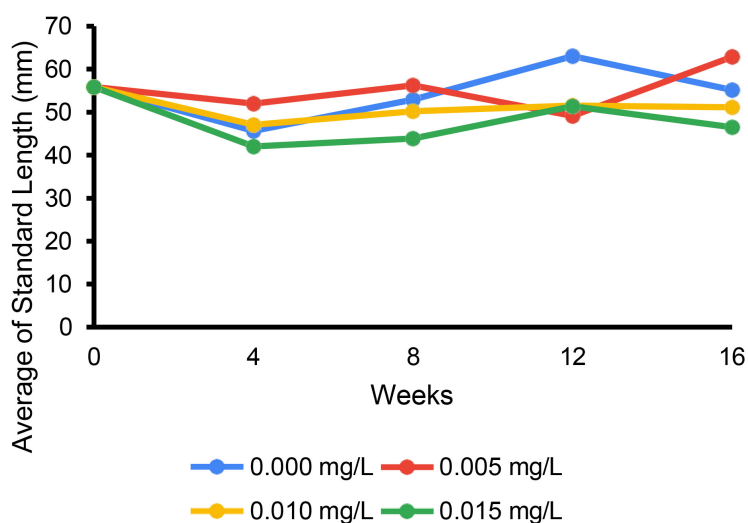


Figure 12. The comparison of standard length of each treatment group with time exposure.

The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean standard length was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean standard length of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

Figure 13 illustrates the mean total length of *Trichopodus pectoralis* at four different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L). Total length was measured from the tip of the snout to the end of the caudal fin. Based on **Figure 13**, the highest mean total length was recorded at 0.000 mg/L (77.95 ± 5.38 mm) and the lowest at 0.015 mg/L (62.88 ± 7.76 mm). The overall trend indicates a gradual decline in mean total length from 0.000 mg/L to

0.015 mg/L cadmium concentration. The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean total length was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean total length of *Trichopodus pectoralis* across different cadmium concentrations.

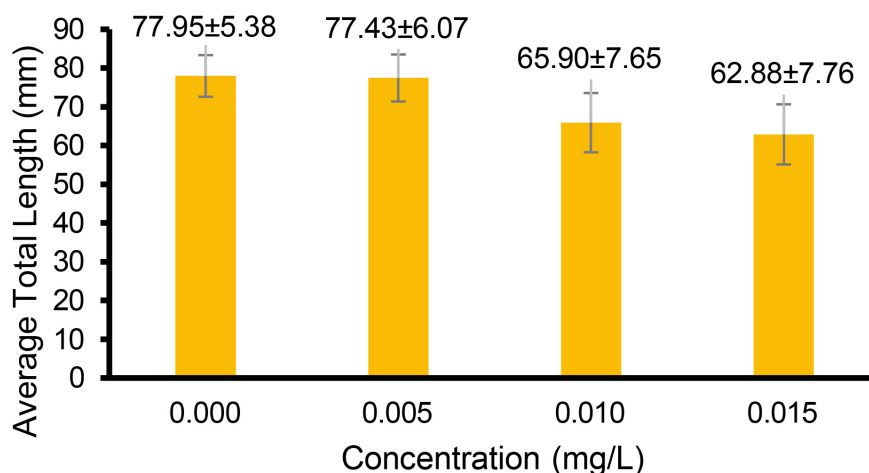


Figure 13. The average total length in different treatment group.

Figure 14 presents the mean total length of *Trichopodus pectoralis* at different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L) across varying exposure periods (weeks 0, 4, 8, 12, and 16). Overall, the mean total length exhibited a gradual trend of change with increasing exposure duration. At week 0, the mean total length across all cadmium concentrations was 71.29 mm.

At 0.000 mg/L, the mean total length decreased at week 4 (60.96 mm), increased at weeks 8 (67.23 mm) and 12 (77.99 mm), before declining slightly at week 16 (77.95 mm). At 0.005 mg/L, the lowest mean was observed at week 4 (65.97 mm), while the highest was recorded at week 16 (77.43 mm), with intermediate values at week 8 (70.71 mm) and week 12 (66.35 mm). At 0.010 mg/L, the lowest mean occurred at week 4 (57.59 mm), followed by increases at week 8 (64.28 mm) and week 12 (64.76 mm), before declining at week 16 (65.90 mm). At 0.015 mg/L, the lowest mean was noted at week 4 (53.76 mm), with values at week 8 (61.13 mm), week 12 (73.11 mm), and week 16 (62.88 mm). Taken together, these results indicate fluctuating trends in total length across exposure durations, with higher cadmium concentrations (0.010 - 0.015 mg/L) generally associated with reduced values compared to lower concentrations (0.000 - 0.005 mg/L).

The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean total length was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean total length of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

Based on [25], the maximum total length of *Trichopodus pectoralis* is 250 mm.

The reduction in standard length and total length of *Trichopodus pectoralis* at higher cadmium concentrations (0.010 mg/L and 0.015 mg/L) is attributed to changes in feeding behavior and dietary patterns. Similarly, [24] found that the final weight and survival rate (SR) of juvenile genetically improved farmed tilapia (GIFT) decreased significantly ($p < 0.05$) in groups exposed to 0.6 mg/L Cd^{2+} compared to the control group (0 mg/L Cd^{2+}). This indicates a reduction in appetite and feed intake at higher cadmium concentrations. Furthermore, cadmium exposure increases basal energy expenditure, as fish require additional energy for heavy metal detoxification, leaving insufficient energy for somatic growth. Consequently, the mean standard length and total length of *T. pectoralis* decreased under higher cadmium concentrations.

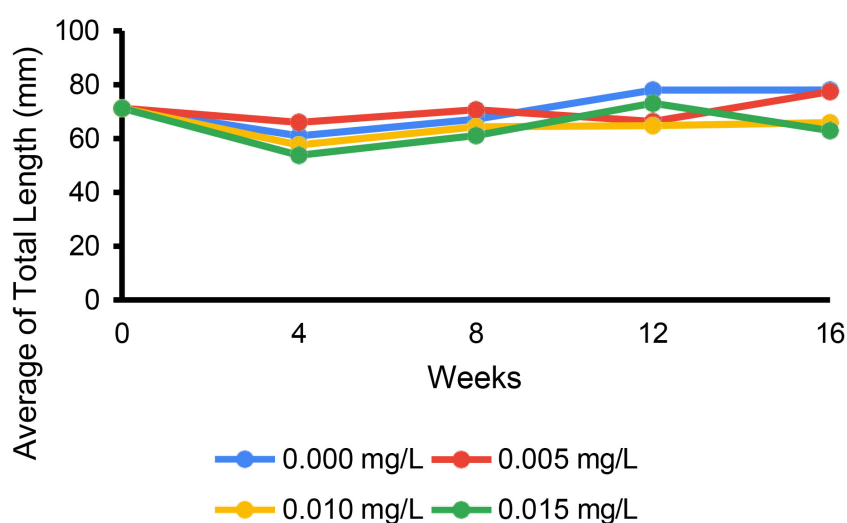


Figure 14. The comparison of total length of each treatment group with time exposure.

3.3. Fins Morphometrics (Pectoral Fin Length)

Figure 15 shows a comparison of the mean pectoral fin length of *Trichopodus pectoralis* at four different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L). Based on **Figure 15**, the highest mean pectoral fin length was recorded at 0.005 mg/L (17.54 ± 1.70 mm) while the lowest at 0.015 mg/L (14.39 ± 1.74 mm). The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean pectoral fin length was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean pectoral fin length of *Trichopodus pectoralis* across different cadmium concentrations.

Figure 16 presents the mean pectoral fin length of *Trichopodus pectoralis* at different cadmium concentrations (0.000 mg/L, 0.005 mg/L, 0.010 mg/L, and 0.015 mg/L) across varying exposure periods (weeks 0, 4, 8, 12, and 16). Overall, the mean pectoral fin length exhibited a gradual trend of change with increasing exposure duration. At week 0, the mean pectoral fin length across all cadmium concentrations was 15.95 mm.

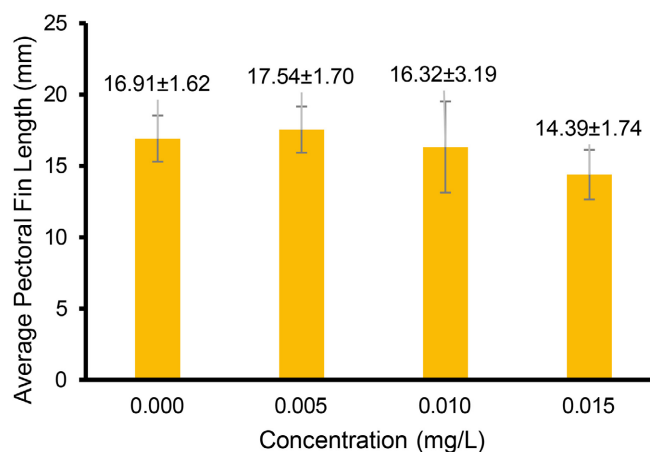


Figure 15. The average pectoral fin length in different treatment group.

At 0.000 mg/L, the mean pectoral fin length decreased at week 4 (13.39 mm), increased at weeks 8 (15.29 mm) and 12 (17.73 mm), before declining at week 16 (16.91 mm). At 0.005 mg/L, the lowest mean was observed at week 12 (15.58 mm), while the highest was recorded at week 16 (17.54 mm), with intermediate values at week 4 (15.93 mm) and week 8 (16.45 mm). At 0.010 mg/L, the lowest mean occurred at week 4 (13.38 mm), followed by increases at week 8 (15.09 mm), week 12 (15.48 mm), and week 16 (16.32 mm). At 0.015 mg/L, the lowest mean was noted at week 4 (11.70 mm), with values at week 8 (13.48 mm), week 12 (16.55 mm), and week 16 (14.39 mm).

The Kruskal-Wallis statistical test was conducted after the distribution of the overall mean pectoral fin length was found to be not normal ($p < 0.05$) based on the normality test. The results of the Kruskal-Wallis's test revealed significant differences ($p < 0.001$, $p < 0.05$) in the mean pectoral fin length of *Trichopodus pectoralis* across all treatment groups under different exposure durations.

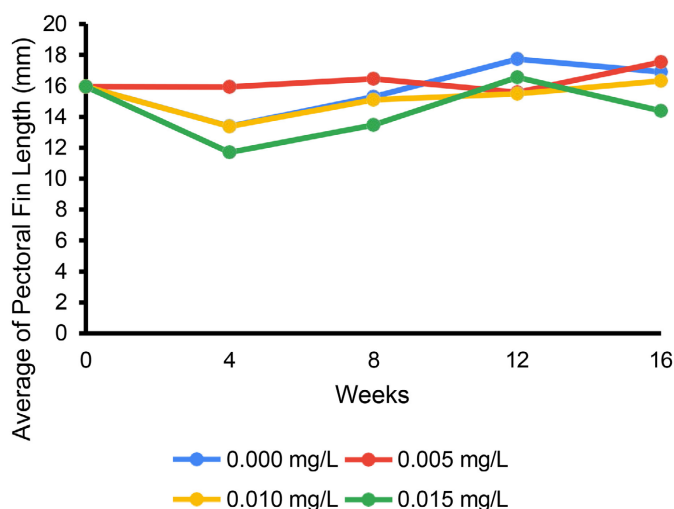


Figure 16. The comparison of pectoral fin length of each treatment group with time exposure.

Moreover, prolonged exposure to cadmium stress resulted in a marked increase in the production of reactive oxygen species (ROS), exceeding the capacity of the endogenous antioxidant defense system. Consequently, excessive physiological stress led to irreversible tissue damage, while cellular necrosis simultaneously inhibited the expression of antioxidant genes [26] [27]. Therefore, exposure to lower cadmium concentrations was associated with higher mean pectoral fin length compared to exposure at higher cadmium concentrations.

4. Conclusions

This study demonstrated that *in-situ* cadmium exposure significantly the external morphometric traits of *Trichopodus pectoralis* over a 16-week period. Out of the 23 parameters measured, 22 showed statistically significant differences across concentrations and exposure durations, with body depth, standard length, and head length being the most sensitive indicators. These reductions highlight cadmium's cumulative and disruptive effects on somatic growth, craniofacial development, and fin structures. Overall, the findings confirm that cadmium contamination compromises multiple aspects of fish morphology, reflecting impaired growth regulation, skeletal development, and condition factor.

The consistency of these morphometric changes across concentrations and time underscores the suitability of *T. pectoralis* as a bioindicator species for aquatic pollution. The results align with previous studies that identified morphometric traits as reliable endpoints for assessing toxic stress, reinforcing the ecological and aquacultural importance of monitoring heavy metal contamination. By integrating morphometric analysis with statistical validation, this research provides evidence for stricter regulation of cadmium levels in freshwater ecosystems. Protecting fish health is not only crucial for biodiversity conservation but also for sustaining aquaculture productivity and safeguarding food security in regions where *T. pectoralis* is a key resource.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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