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Seasonal Variations in the Protein Content in Different Body Parts of *Lamellidens marginalis* due to Exposure of Heavy Metal

R.D. Sonwane*, G.D. Suryavanshi and S.G. Kamble
Department of Zoology, Yogeshwari Mahavidyalaya, Ambajogai, Beed (Maharashtra), India.

(Corresponding author: R.D. Sonwane)*
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ABSTRACT: This study examines how cadmium chloride exposure impacts protein content in *Lamellidens marginalis* across different seasons. Acute toxicity tests (96 h) in monsoon, winter, and summer revealed LC50 values of 8.07, 11.39, and 3.54 mg/L, respectively, with protein levels analyzed in various body parts. Results revealed significant reductions in protein content across all tissues, with the extent of depletion varying by season and duration of exposure. During the monsoon, the protein content showed a non-significant decrease after 24 hours, but this reduction became significant over extended exposure periods, especially in the foot and mantle. In winter, the control group exhibited higher protein levels than in the monsoon, but exposure led to a marked decline, particularly in the gill and hepatopancreas. Summer showed the most significant decreases in protein content, with the gonad and gill being most affected. This study highlights the seasonal variability in cadmium toxicity, emphasizing the importance of considering environmental factors in ecotoxicological assessments.

Keywords: Cadmium chloride, Pollution, Acute Toxicity, Environment, Bivalve, Freshwater.

INTRODUCTION

Heavy metal pollution has become a significant environmental issue, particularly in aquatic ecosystems where contaminants like cadmium can accumulate and cause detrimental effects on aquatic organisms. Cadmium, a non-essential and highly toxic metal, is frequently introduced into water bodies through industrial discharges (Synthetic rubber, paints, pigments, electroplated parts, batteries, plastics, photographic and engraving process, photoconductors, and photovoltaic cells), mining activities, and agricultural runoff (Kaware and Manzoor 2022; Pan and Wang 2012). Once released into the environment, cadmium can be absorbed by aquatic organisms, including bivalves, which are often used as bioindicators due to their sensitivity to environmental changes and ability to accumulate contaminants in their tissues (Rainbow, 2002).

Among aquatic species, *Lamellidens marginalis*, a freshwater bivalve, has gained prominence in toxicity research as it serves as an effective biofilter and bioaccumulator of heavy metals like cadmium (Jana and Das 1997; Suryawanshi 2017). The species exposure to cadmium results in bioaccumulation, leading to disruptions in biochemical pathways, including protein metabolism. The adverse effects of cadmium exposure on various organisms, particularly bivalves, are not only limited to direct toxicity but also to secondary responses such as oxidative stress, depletion of antioxidants, and altered expression of stress-responsive genes. Studies have demonstrated that cadmium primarily accumulates in specific tissues such as gills, hepatopancreas, and gonads, impairing the overall functioning of these organs (Lysenko *et al.,* 2014). *Lamellidens marginalis,* like many other bivalves, utilizes various biological mechanisms to mitigate cadmium toxicity, such as metallothionein induction, antioxidant enzyme activity, and detoxification pathways (Ivanina *et al.,* 2008; Sarkar *et al.,* 2008). These mechanisms often involve the synthesis of specific proteins, which either serve a direct role in detoxifying heavy metals or provide protection against cadmium-induced oxidative stress. This leads to a significant reallocation of metabolic resources towards protein synthesis, stress-response proteins, and enzymes associated with cellular repair and detoxification processes (Marie *et al.,* 2006).

Biochemical changes in animals exposed to various metals are often early indicators of excess accumulation and stress which are useful for understanding the mechanisms of toxicity. Protein levels are crucial indicators of the organism's metabolic status and can reflect the activation of stress-response mechanisms. Cadmium exposure triggers protein degradation pathways, such as the ubiquitin-proteasome system, and disrupts cellular protein homeostasis, resulting in a decline in total protein content (Ibrahim *et al.,* 2021). Furthermore, proteins associated with metal detoxification, such as metallothioneins, undergo increased synthesis during metal exposure, while proteins related to other metabolic processes may decrease due to energy reallocation (Waisberg *et al.,* 2003). The role of these proteins in maintaining cellular homeostasis and mitigating oxidative stress is critical in determining the organism's survival and adaptation to cadmium pollution (Amiard *et al.,* 2006).

Despite the existing knowledge of cadmium toxicity in aquatic organisms, there is a need to further investigate tissue-specific protein changes in relation to Cd exposure in *L. marginalis,* especially across different seasons. Environmental factors such as temperature, food availability, water quality or internal factors such as metabolic and reproductive activities may influence the biochemical composition of bivalve (Shafakatullah *et al.,* 2013). The seasonal variations observed in the control groups of this study suggest that the metabolic activities of bivalves fluctuate with environmental changes, affecting their baseline protein content. By comparing these seasonal variations with the cadmium-exposed groups, we aim to further elucidate the tissue-specific responses and tolerance mechanisms in *L. marginalis.*

This study aims to provide a detailed understanding of the protein alterations in *L. marginalis* upon exposure to cadmium across different seasons, offering insights into the physiological and biochemical defence mechanisms employed by the species. By analyzing the protein content in various tissues (mantle, foot, gill, gonad, hepatopancreas, and adductor muscle) the results of this study can serve as a basis for environmental monitoring and conservation efforts in aquatic ecosystems contaminated by heavy metals like cadmium.

By characterizing the changes in protein content in response to cadmium exposure, this research will also shed light on molecular mechanisms of metal toxicity, with a focus on oxidative stress, detoxification, and cellular repair systems, all of which play a pivotal role in the organism's survival under adverse environmental conditions (Panda *et al.,* 2022).

MATERIALS AND METHODS

Study area and collection of species: Freshwater bivalves *Lamellidens marginalis* were collected from the Manjara Dam, located in Dhanegaon, District Dharashiv, Maharashtra, India (geographical coordinates: 18.9869° N, 76.9378° E). The site was selected due to its relatively low pollution levels, ensuring that the bivalves collected were in a natural state, with minimal pre-existing contamination from heavy metals or other pollutants. Sampling was conducted during three distinct seasons: summer (April), monsoon (July), and winter (December) of 2018, in order to assess seasonal variations in protein content under cadmium exposure. On each sampling date, bivalves were randomly collected using a handpicking method. Care was taken to ensure that the specimens chosen were of uniform size, ranging from 90-100 mm in shell length, to standardize physiological parameters across samples. The collected bivalves were immediately placed in aerated containers filled with water from the collection site, minimizing transport stress. The water conditions, including temperature, pH, and dissolved oxygen levels, was continuously monitored during transport to replicate the natural habitat. The specimens were transferred to the laboratory within 2 to 4 hours of collection.

Upon arrival at the laboratory, the bivalves were acclimatized for 48 hrs under controlled conditions that simulated their natural habitat. During this acclimatization period, they were maintained in large glass aquaria (50L capacity) filled with filtered water from the collection site and the water was replaced every 12 h to ensure adequate dissolved oxygen levels and prevent accumulation of waste. The parameters were used constant during acclimatization and throughout the experiment like Water temperature (25 ± 2°C), pH (7.5 and 8.0), Dissolved oxygen: (Above 5 mg/L), Photoperiod (A 12-hour light and 12-hour dark cycle) was maintained. Water quality free from any visible pollutants or contaminants checked regularly using a multi-parameter water quality meter (APHA, 2017). The bivalves were not fed during the acclimatization period to avoid interference from metabolic by products during the acute toxicity testing.

Acute toxicity tests (96-hours) were performed in triplicates to determine the lethal concentration (LC) values of cadmium chloride ($CdCl_2$) for *L. marginalis.* The toxicity tests were conducted seasonally (summer, monsoon, and winter), and for each season, the bivalves were exposed to a specific range of cadmium concentrations. The use of different cadmium concentration ranges across seasons was based on previous studies indicating that factors like temperature, dissolved oxygen, and bioavailability of cadmium vary with seasons, influencing the sensitivity and response of aquatic organisms to metal exposure (Chandrudu *et al.,* 2008; Shaikh *et al.,* 2012). These studies highlight that higher cadmium concentrations may be needed to achieve lethal effects in summer, when elevated temperatures can increase metabolic activity and detoxification capacity, whereas lower concentrations may be effective in winter when metabolism slows down.

Toxicity tests were conducted by using plastic troughs containing 5 L of water. Bivalves were exposed to ten cadmium chloride concentrations (mg/L) across different seasons: summer (1.5 to 6 mg/L), winter (7 to16 (mg/L), and monsoon (4 to13 mg/L). Ten bivalves per concentration were tested, with a control group of ten bivalves exposed to water without cadmium. Mortality was recorded at 24, 48, 72, and 96 h, with dead specimens promptly removed. The LC50 values for cadmium chloride were determined using probit analysis, following the standard protocols established by the Organisation for Economic Co-operation and Development (OECD, 1992). The cadmium chloride solutions were prepared using distilled water, and bivalves were exposed in separate tanks for each concentration. After the 96 h exposure period, surviving bivalves from the control, exposed were dissected to estimate protein content in different body tissues: mantle, foot, gill, gonad, hepatopancreas, and adductor muscle. The tissues were weighed and they were then kept in hot air oven at 92ºC till constant weights were obtained. The dried product was ground to obtain fine powder.

Lowry method was followed to determine the protein content (Lowry *et al.,* 1951). The absorbance of the samples was measured at 660 nm using a UV-Visible spectrophotometer. A standard calibration curve was prepared using Bovine Serum Albumin (BSA) and the protein content in the tissue samples was expressed as mg of protein per gram of tissue.

Data were statistically calculated by regression equation. A p-value < 0.05 was considered statistically significant. All experiments were performed in triplicate, and the results were expressed as mean ± standard deviation (SD).

RESULT

Lamellidens marginalis were exposed to cadmium chloride during different seasons for acute toxicity test. After completion of 24, 48, 72 and 96 h the protein content analyzed from different body parts of bivalves**.** The obtained LC0 values where no mortality occurred for cadmium exposure were 4, 7 and 1.5 mg/L in monsoon, winter and summer respectively. The calculated LC50 values for 96 h by Finney's method were 8.07, 11.39 and 3.54 mg/L in monsoon, winter and summer respectively. Meanwhile the experimental control group of bivalves runs through the exposed animals.

Results mentioned in Table 1-6 reveals that cadmium exposure leads to a significant reduction in protein content across various body parts (mantle, foot, gill, gonad, hepatopancreas, and adductor muscle) of bivalves as compared to body parts of control bivalves, with the most pronounced decreases observed during the summer, followed by the monsoon and winter seasons. By observing tables (1 to 6) the detailed comparative explanation is given below.

In monsoon, experimental control bivalves showed more protein in foot followed by mantle, gill, adductor muscle, gonad and hepatopancreas. In addition to this, the bivalves, when exposed to cadmium metal the protein content decreased in all body parts when it was compared to respective tissues of control group. During 24 h the content was decreased in mantle followed by foot, hepatopancreas, gill, gonad and adductor muscle. In 48 h more protein was decreased in gill followed by foot, hepatopancreas, mantle, gonad and adductor muscle In 72 h the protein content was more decreased from foot followed by mantle, gill, hepatopancreas, gonad and adductor muscle During 96 h exposure period, content was decreased more in foot followed by mantle, gonad, gill, adductor muscle and hepatopancreas.

In winter, the protein content in control group of bivalves was more in mantle followed by foot, gill, adductor muscle, hepatopancreas and gonad In addition to this, the bivalves, when exposed to metal the protein content decreased in all body parts when it was compared to respective tissues of control group of bivalves. During 24 h the content was decreased in foot followed by hepatopancreas, gill, gonad, adductor muscle and mantle. In 48 h it was decreased in mantle, followed by hepatopancreas, foot, gonad, adductor muscle and gill. During 72 h the content was decreased in gill followed by mantle, gonad, hepatopancreas, foot and adductor muscle. During 96 h the content was decreased from gill followed by foot, hepatopancreas, mantle, gonad and adductor muscle.

In summer, the content in control group of bivalves was more in mantle followed by gonad, foot, adductor muscle, hepatopancreas, and gill. When the bivalves compared with control the protein content was decreased in all body parts. During 24 h the protein content was decreased from gonad followed by hepatopancreas, foot, adductor muscle, gill, and mantle. In 48 h content was decreased in gill followed by gonad, hepatopancreas, foot, adductor muscle, and mantle. During 72 h it was decreased in hepatopancreas followed by foot, adductor muscle, gill, gonad, and mantle. In 96 h, protein content was more decreased in gonad followed by gill, foot, mantle, hepatopancreas, and adductor muscle.

On the other hand when the protein content compared with monsoon season of respective group of bivalves, in 24 h of winter the content was more increased in adductor muscle followed by mantle, hepatopancreas, gonad, gill, and foot while in summer the content was decreased from gill followed by foot, mantle, hepatopancreas, adductor muscle and gonad. Under 48 h of winter the content was more increased from adductor muscle followed by hepatopancreas, gill, gonad, mantle and foot while in summer the content was more decreased from gill followed by foot mantle, hepatopancreas, adductor muscle, and gonad. In 72 h of winter more content was increased in hepatopancreas followed by mantle, adductor muscle, foot, gonad, and gill further in summer content decreased from gill followed by foot, adductor muscle, hepatopancreas, mantle, and gonad. In 96 h content of winter was increased from adductor muscle followed by mantle, gonad, hepatopancreas, foot and gill while in summer content was decreased with gill, foot, mantle, hepatopancreas, gonad, and adductor muscle.

When the protein content compared with winter season of respective group of bivalves, in 24 h of summer the content was more decreased in gill followed by foot, mantle, hepatopancreas, adductor muscle and gonad. During 48 h the content was more in decreased in gill followed by foot, hepatopancreas, adductor muscle, mantle, and gonad. In 72 h, the content was more decreased from gill followed by foot hepatopancreas adductor muscle, mantle and gonad. During 96 h significant decrease in protein content observed like gill followed by foot, mantle, hepatopancreas, adductor muscle and gonad.

DISCUSSION

The present study provides insights into the effects of cadmium (Cd) exposure on the protein content of various tissues in the freshwater. The results of this study were clearly demonstrating a correlation between the progressive decrease in the protein content and the increased exposure period. Our results revealed significant differences in protein content between the different tissues and across the seasons, highlighting the complex interaction between heavy metal stress, tissue-specific responses, and environmental factors.

Proteins are crucial in cellular responses to environmental stress, including exposure to toxic metals like Cd. The decrease in the protein content across the tissues in the LC50 groups, particularly in the hepatopancreas, mantle, gill and gonad were observed which indicates a significant metabolic disruption under cadmium stress. The hepatopancreas, being a major site of detoxification and metabolism in bivalves which often leads to protein degradation or inhibition of protein synthesis as the organism attempts to detoxify and eliminate cadmium (Humbe *et al.,* 2016; Khandekar and Muley 2018). The gills, being the primary site of pollutant uptake from water (Bhamre and Deoray 2010, Bouquegneau 1973) and play a critical role in the initial detoxification response by producing metal-binding proteins such as metallothioneins (MTs) (Gagné *et al.,* 2007). MTs are induced in response to metal exposure and bind to cadmium, facilitating its sequestration and detoxification (Li *et al.,* 2015). The gonads also exhibited significant protein alterations in control which could have implications for reproductive function (Siddique *et al.,* 2020). The protein depletion observed in exposed gonads, particularly in the summer which may be due to increased proteolysis and potential metabolic utilization of degradation products, could be results from enhanced catabolism and reduced anabolism during pollutant exposure (Deshmukh and Lomte 1998; Merad and Soltani 2017). Cadmium is known to disrupt the endocrine system, impairing reproductive proteins and enzymes, leading to reduced fecundity and altered gametogenesis in aquatic organisms (Ansari *et al.,* 2004). Moreover, the foot and mantle tissues particularly in monsoon season showed high protein depletion which may be due to both are responsible for mobility and protection, highlighting their role in the organism's adaptive mechanisms under environmental stress (Ghosh *et al.,* 2020; Lvanina *et al.,*2008).

Seasonal Variation in Protein Content: The seasonal differences in protein content across the control and cadmium-exposed groups underscore the importance of environmental factors such as temperature, photoperiod, and metabolic rate in modulating the organism's response to metal toxicity. In our study, the highest reduction in protein content was observed during the summer season, coinciding with higher water temperatures. This result aligns with previous studies showing that elevated temperatures increase metabolic activity and cadmium uptake in aquatic organisms, intensifying the toxic effects (Dallinger *et al.,* 1997; Uma, 1996).

During winter, the reduction in protein content was less pronounced, suggesting that lower metabolic rates reduce the bioavailability and uptake of cadmium. Bivalves generally exhibit seasonal metabolic plasticity, where metabolic activities, including protein synthesis and degradation, are down regulated in colder conditions, thereby mitigating the impact of metal exposure (Baudrimont *et al*., 2003). The detoxification pathways involving MTs and other stress-related proteins may also be less active in winter, reducing the overall protein loss (El-Gendy *et al.,* 2019). One of the key mechanisms by which bivalves combat cadmium toxicity is through the upregulation of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx). These enzymes work synergistically to neutralize reactive oxygen species (ROS) generated by cadmium-induced oxidative stress (Cossu *et al.,* 2000; Shi *et al.,* 2011).

The results of this study align with previous research showing reduced protein levels in various organisms exposed to metals. The decrease in tissue protein may be due excessive proteolysis to manage metabolic stress, allowing cytoplasmic proteins to compensate for losses during physiological stress (Patil, 2011). Mestry and Bhosale (2017) showed gills and hepatopancreas are target organs to assess the genotoxic effect as exposed to mercury chloride. Andhale and Zambare (2011) showed that biochemical Alterations in Freshwater Bivalve, *Lamellidens marginalis* after chronic exposure to nickel chloride. Suryawanshi and Deshpande (2016) studied the decrease in the protein content of the bivalve *L. marginalis* after acute exposure of zinc chloride, copper sulphate and mercury chloride.

Table 1: Protein contents from Mantle of *L. marginalis* after acute exposure to cadmium chloride in different seasons.

Season	Control	24 h	48 h	72 h	96 h
Monsoon	46.87±2.831	45.74 ±2.83 (2.41%)	44.99 ±2.976 (4.01%)	40.49±2.976 (13.61%)*	38.99±0.649 (16.81%)***
Winter	56.24±1.948	55.49±2.831 (1.33%) (21.32%) ΔΔ	51.37±2.341 (8.65%)* (14.18%)ΔΔ	48.74±0.649 (13.33%) *** (20.37%)ΔΔΔ	46.87±2.341 (16.66%) ** (20.21%)ΔΔ
Summer	39.74 ±1.299	38.99±2.598 (1.88%) (14.75%)Δ (29.73%) □□□	37.49±1.718 (5.66%) (16.67%)ΔΔ (27.01%) □□□	33.74 ±1.124 (15.09%) *** (16.67%)ΔΔΔ (30.77%) □□□	24.74 ±2.976 (36.13%) *** (36.54%)ΔΔ (47.21%) □□□

(Bracket values represent percentage differences) (*, Δ, □- p-<0.05, **, ΔΔ, □□-p<0.01 and ***, ΔΔΔ, □□□-p<0.001.
*- compared to control, Δ- compared to monsoon, □- compared to winter).

Table 2: Protein contents from Foot of *L. marginalis* after acute exposure to cadmium chloride in different seasons.

Season	Control	24 h	48 h	72 h	96 h
Monsoon	51.74 ±1.124	50.62 ±1.124 (2.16%)	48.37 ±2.976 (6.51%)	42.37 ±1.718 (18.10%)***	37.49 ±2.341 (27.54%)***
Winter	53.62 ±1.718	52.12 ±0.649 (2.79%)* (2.96%)Δ	50.99 ±1.718 (4.90%)* (5.41%)	48.74 ±1.718 (9.10%) ** (15.03%) ΔΔ	44.24 ±1.718 (17.49%)*** (18.00%)ΔΔ
Summer	37.49 ±1.718	36.37 ± 2.831 (2.98%) (28.15%)ΔΔΔ (30.21%) □□□	34.12 ± 1.299 (8.98%) * (29.46%)ΔΔΔ (33.08%) □□□	30.37 ± 2.249 (18.99%) ** (28.32%)ΔΔΔ (37.68%) □□□	23.24 ±1.299 (38.01%) *** (38.01%) ΔΔΔ (47.46%) □□□

(Bracket values represent percentage differences) (*, Δ, □- p-<0.05, **, ΔΔ, □□-p<0.01 and ***, ΔΔΔ, □□□-p<0.001.
*- compared to control, Δ- compared to monsoon, □- compared to winter).

Table 3: Protein contents from Gill of *L. marginalis* after acute exposure to cadmium chloride in different seasons.

Season	Control	24 h	48 h	72 h	96 h
Monsoon	43.49 ±1.718	42.74±1.948 (1.72%)	40.49±1.948 (6.89%)*	38.24±1.124 (12.07%)	36.74±0.64 (15.52%)***
Winter	50.24 ±1.718	49.12±1.299 (2.22%) (14.93%) ΔΔ	48.74±1.718 (2.98%) (20.37%)ΔΔ	43.12±2.341 (14.17%) ** (12.76%) ΔΔ	38.24±1.948 (23.88%)*** (4.08%)
Summer	30.74 ±0.649	29.99±1.718 (2.43%) (29.83%)ΔΔΔ (38.94%) □□□	27.37±1.718 (10.96%) * (32.40%)ΔΔΔ (43.84%) □□□	25.12±2.831 (18.28%) * (34.30%)ΔΔ (41.74%) □□□	18.74±2.341 (39.03%) *** (48.99%) ΔΔΔ (50.99%) □□□

(Bracket values represent percentage differences) (*, Δ, □- p-<0.05, **, ΔΔ, □□-p<0.01 and ***,ΔΔΔ, □□□-p<0.001.
*- compared to control, Δ- compared to monsoon, □- compared to winter

Table 4: Protein contents from Gonad of *L. Marginalis* after acute exposure to cadmium chloride in different seasons.

Season	Control	24 h	48 h	72 h	96 h
Monsoon	39.37 ±1.124	38.99 ±2.598 (0.96%)	37.87 ±2.341 (3.81%)	35.99 ±1.948 (8.58%)*	32.24 ±0.649 (16.20%)***
Winter	46.12 ±1.948	45.37 ±2.831 (1.62%) (16.36%)Δ	44.24±0.649 (4.07%) ** (16.82%)ΔΔΔ	41.24±2.341 (10.58%) * (14.59%) ΔΔ	39.37±2.976 (14.63%) * (19.33%) Δ
Summer	39.74 ±1.718	37.87±0.649 (4.70%) ** (2.87%)Δ (16.53%) □□□	35.62±2.341 (10.36%) * (5.94%) (19.48%) □□	32.62±1.124 (17.91%) *** (9.36%)ΔΔ (20.90%) □□□	23.99±2.341 (39.63%) *** (27.28%) ΔΔ (39.06%) □□□

(Bracket values represent percentage differences) (*, Δ, □- p-<0.05, **, ΔΔ, □□-p<0.01 and ***,ΔΔΔ, □□□-p<0.001.
*- compared to control, Δ- compared to monsoon, □- compared to winter).

Table 5: Protein contents from Hepatopancreas of *L. marginalis* after acute exposure to cadmium chloride in different seasons.

Season	Control	24 h	48 h	72 h	96 h
Monsoon	38.62 ±1.299	37.87 ± 1.299 (1.94%)	36.74 ± 0.649 (4.86%) **	34.49 ± 2.341 (10.69%)*	32.99 ± 2.341 (14.57%)**
Winter	46.87 ±1.299	45.74 ± 0.649 (2.41%)* (20.78%)ΔΔΔ	44.24 ± 1.299 (5.61%) * (20.41%)ΔΔΔ	41.99 ± 1.718 (10.41%) ** (21.75%) ΔΔ	38.99 ± 2.598 (16.81%) ** (18.18%) Δ
Summer	34.12 ±2.831	32.62 ± 1.948 (4.39%) (13.86%) ΔΔ (28.68%) □□□	30.74 ± 1.299 (9.90%) * (16.33%)ΔΔ (30.51%) □□□	27.37 ± 1.718 (19.78%) ** (20.64%)ΔΔ (34.81%) □□□	22.49 ± 2.976 (34.08%) ** (31.82%) ΔΔ (42.31%) □□□

(Bracket values represent percentage differences) (*, Δ, □- p-<0.05, **, ΔΔ, □□-p<0.01 and ***,ΔΔΔ, □□□-p<0.001.
*- compared to control, Δ- compared to monsoon, □- compared to winter).

Table 6: Protein contents from Adductor muscle of *L. marginalis* after acute exposure to cadmium chloride in different seasons.

Season	Control	24 h	48 h	72 h	96 h
Monsoon	40.12 ±1.299	39.74 ±1.718 (0.94%)	38.99±1.718 (2.81%)	38.62±1.299 (3.73%)	34.12±0.649 (14.95%)***
Winter	49.49 ±1.124	48.74±0.649 (1.51%) (22.65%)ΔΔΔ	47.99±1.299 (3.03%) (23.08%)ΔΔΔ	45.37±0.649 (8.32%) *** (17.47%)ΔΔΔ	44.24±2.34 (10.60%) * (29.66%)ΔΔ
Summer	36.37 ±2.341	35.62±1.718 (2.06%) (10.36%)Δ (26.91%) □□□	33.37±1.718 (8.24%) * (14.41%)ΔΔ (30.46%) □□□	29.62±2.341 (18.55%) ** (23.30%)ΔΔ (34.71%) □□□	25.87±1.948 (28.86%) *** (24.17%) ΔΔ (41.52%) □□□

(Bracket values represent percentage differences) (*, Δ, □- p-<0.05, **, ΔΔ, □□-p<0.01 and ***,ΔΔΔ, □□□-p<0.001.
*- compared to control, Δ- compared to monsoon, □- compared to winter).

CONCLUSIONS

This study demonstrates that cadmium chloride exposure significantly affects the protein content of various body parts in *Lamellidens marginalis*, with the extent of the impact varying with the seasons and exposure duration. The results indicate that the toxicity of cadmium is exacerbated during the summer season, where higher temperatures likely contribute to increased metabolic stress and greater protein depletion. The findings highlight the critical need for considering seasonal variations when assessing the ecological risks of heavy metal pollution in aquatic environments. Further research is recommended to develop strategies for protecting freshwater ecosystem from metal stress with the help of freshwater bivalve.

FUTURE SCOPE

This study “Seasonal Variation in the Protein Content in Different Body Parts of *Lamellidens marginalis* due to Exposure of Heavy Metal” helps in understanding how different seasons changes tissue specific capacity of facing heavy metal stress by observing the protein content alternation in *L. marginalis*. The findings of this research have important implications for contributing valuable insights to the international community in environmental toxicology and aquatic biology.

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Conflicts of Interest. None.

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