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Biomarker-Based Assessment of Stress Responses among Cage-Cultured Fish Species in Lagos State, Nigeria

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Abstract: Cage culture has become a prominent method of aquaculture production in Nigeria, particularly in Lagos State, where extensive water bodies provide ideal conditions for large-scale fish farming. However, concerns over metal accumulation and oxidative stress in cultured fish remain underexplored. This study aimed to evaluate the levels of arsenic, boron, selenium, silicon, and sulfur in three fish species (*Clarias gariepinus*, *Clarias* hybrid,, and *Oreochromis niloticus*) from cage culture systems in Lagos, Nigeria, and their relationships with oxidative stress markers (CAT, SOD, MDA, GSH). Results showed species-specific differences in metalloid/non-metal, with *Clarias* hybrid, exhibiting the highest arsenic levels and *C. gariepinus* showing elevated silicon and boron concentrations. Oxidative stress markers varied across species, with *Clarias* hybrid, displaying robust antioxidant defenses and *O. niloticus* showing susceptibility to oxidative damage. Correlation analysis revealed that arsenic was strongly associated with increased oxidative stress, while selenium exhibited a dual role—enhancing antioxidant defenses at low concentrations but contributing to oxidative stress at elevated levels, enhancing CAT, SOD, and MDA activities, while boron and sulfur inhibited key antioxidant defenses. Silicon exhibited a potential protective role, possibly mitigating oxidative damage. These findings highlight the need for regular monitoring of metal accumulation in cage-cultured fish to mitigate oxidative stress risks. Further research should explore safe exposure limits and potential dietary interventions to enhance fish resilience in aquaculture systems.

1. Introduction

Aquaculture plays a pivotal role in global food security, providing a reliable source of high-quality protein and sustaining livelihoods for millions of people worldwide (Pradeepkiran, 2019). The rapid expansion of the aquaculture industry has been instrumental in addressing the growing demand for fish products, particularly in developing nations. In Nigeria, cage culture has emerged as one of the most efficient methods of aquaculture production. This practice has been particularly successful in regions like Lagos State, where extensive water bodies such as lagoons and estuaries provide suitable environments for large-scale fish farming operations (Oluwatobi *et al.*, 2017). By enabling efficient use of aquatic resources, cage culture has significantly boosted fish supply, contributing to the national economy and improving food security for local populations.

However, the intensification of cage culture practices is not without challenges. Increased stocking densities and prolonged confinement within cage systems often create a range of environmental and physiological stressors for farmed fish. Overcrowding, deteriorating water quality, and frequent disease outbreaks are among the key issues that negatively impact fish health and overall productivity (Paredes-Trujillo and Mendoza-Carranza, 2022; Nasri *et al.*, 2024). These stressors can compromise immune responses, impair growth, and reduce survival rates, ultimately undermining the sustainability of aquaculture operations. Addressing these challenges requires a comprehensive understanding of the stressors and their impacts on fish species, particularly in high-intensity farming systems like those in Lagos State. Such insights are crucial for developing effective management strategies that promote fish welfare and support the long-term viability of cage culture as a sustainable practice.

Biomarkers have emerged as powerful tools for assessing physiological stress responses and environmental health in aquaculture systems. These molecular and biochemical indicators help in evaluating the effects of environmental stressors, including pollutants, temperature fluctuations, and handling stress, on fish health. Biomarkers are widely used to assess the environmental status of aquatic ecosystems and to investigate the relationships between contaminants and biological responses in fish from polluted coastal waters (Ugwu *et al.*, 2021; Errich *et al.*, 2023). As noted, the use of biomarkers for pollution in fish is an effective strategy for monitoring the aquatic environment and diagnosing of negative impact (Porras-Rivera *et al.*, 2024). When these compensatory responses are activated, the survival potential of the organism may already have begun to decline because the ability of the organism to mount compensatory responses to new environmental challenges may have been compromised (Lawal-Are *et al.*, 2019). The most compelling reason for using biomarkers is that they can give information on the biological effects of pollutants rather than a mere quantification of their environmental levels. Commonly studied biomarkers include enzymes such as superoxide dismutase (SOD) and catalase, which indicate oxidative stress, and cortisol levels, which reflect primary stress responses (Usese *et al.*, 2019).

Lagos State, a major hub for aquaculture in Nigeria, faces unique challenges due to its dense population, industrial activities, and urban runoff, which further exacerbate water quality issues in fish farming environments (Amaeze and Otabor, 2024). Despite the recognized impact of these stressors, limited studies have employed biomarkers to assess stress responses in farmed fish species within the region. The lack of localized data on stress biomarkers in Lagos State's cage culture systems poses a significant gap in managing aquaculture sustainably.

The rapid expansion of aquaculture highlights the need for robust monitoring strategies to maintain fish health and ensure sustainable production (Jolly *et al.*, 2023). Stress responses in farmed fish, particularly under cage culture conditions in brackish and freshwater systems, are not well-documented in Nigeria, despite their critical role in aquaculture management. Understanding these responses is essential for reducing sublethal stress impacts, improving fish welfare, and optimizing farm productivity. This study evaluates physiological and biochemical stress biomarkers in cultured Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*) from cage farms in Lagos State. Findings will support the development of evidence-based management strategies that enhance fish resilience, promote sustainable aquaculture, and improve long-term productivity in Nigerian aquaculture systems.

2. Methodology

2.1 Study area

The fish cages utilized in Epe and Badagry Lagoons are predominantly floating structures constructed from materials such as plastic pipes, metal frames, and netting. These cages are anchored using mooring systems attached to the lagoon bed to prevent drifting caused by water currents. The sizes of the cages vary, with small-scale fish farmers employing smaller cages (e.g., 4–16 cubic meters), while larger commercial farms adopt bigger and more advanced cage systems. The mesh size is selected based on the cultured species' size and growth stage, ensuring proper water exchange, oxygenation, and minimizing biofouling while reducing fish escapes and intrusion of predatory species.

Epe Lagoon covers a surface area of 243 km^2, with depth varying between 1.8 and 4 meters, influenced by seasonal fluctuations and tidal exchanges. It is located between the Lagos Lagoon (brackish water) to the west and Lekki Lagoon (freshwater) to the east (Uwadiae, 2017). In contrast, Badagry Lagoon is part of an interconnected network of lagoons and creeks extending along Nigeria's coast from the Republic of Benin to the Niger Delta. It measures about 60 km in length, 3 km in width, and has a water depth ranging from 1 to 3 meters (Okunade *et al*., 2020).

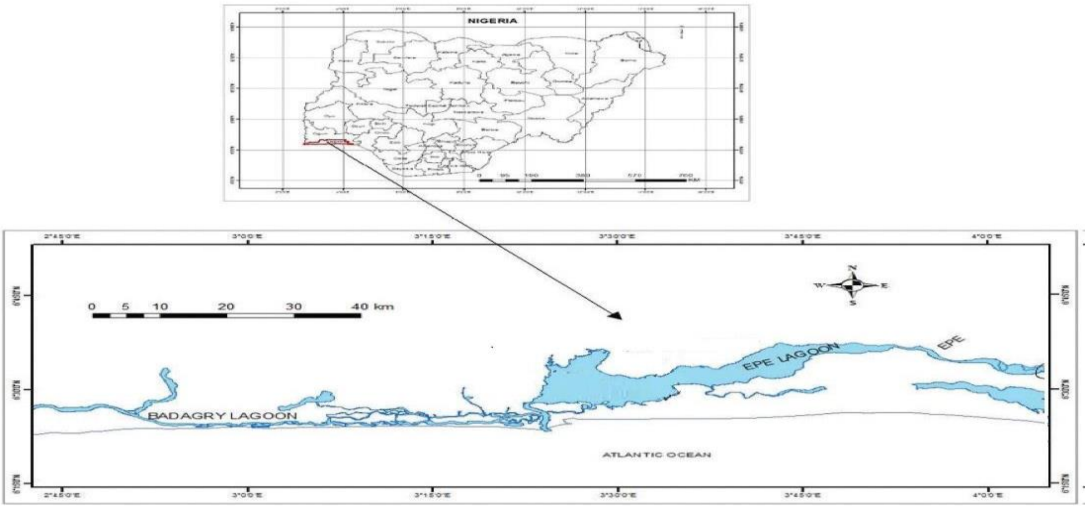

Figure 1. Map of Badagry and Epe Lagoons (Moruf, 2022)

2.2 *Sampling and sample preparation*

Fish samples, including *Clarias gariepinus*, *Oreochromis niloticus* and *Clarias* hybrid, were collected monthly over a two-year period from May 2022 to April 2024. Immediately after collection, the fish samples were placed in styrofoam boxes without water to maintain their integrity during transport. These boxes were then transported to the Aquatic Toxicology and Ecophysiology Laboratory, located within the Department of Marine Sciences at the University of Lagos, where the samples underwent further processing and analysis.

2.3 Laboratory analysis

To determine heavy metal levels, the muscle tissues of the fish samples were oven-dried at 70°C for 1 hour, ground into a fine powder using ceramic mortars, and 0.5 g of each sample was mixed with double-distilled water to form a paste. The paste was then digested with 5 ml of 1 M HNO_3 under mild heat until brown fumes were observed. The samples were allowed to cool, diluted to 50 ml in acid-washed standard volumetric flasks to eliminate residual metal contamination, and then filtered prior to analysis. The processed samples were subsequently analyzed using an Atomic Absorption Spectrophotometer (Perkin Elmer series) to quantify the levels of selected heavy metals.

To evaluate oxidative responses, samples of excised muscle tissues of fish stored at −20 °C were later thawed and homogenized for the assays of reduced glutathione, catalase, superoxide dismutase, levels of proteins, and lipid peroxidation (TBARS) following the protocol described by Lushchaks *et al.* (2005) and Bertholdo-Vargas *et al.* (2009). Lipid peroxidation estimation was carried out through the determination of thiobarbituric acid reactive substance (TBARS) which are indices of membrane lipid peroxidation.

2.4 Data analysis

Descriptive statistics were employed to analyze and present the results of the study. Data were analyzed using SPSS (version 22) software package and Microsoft Excel 2013. Statistical tests of significance were performed using Multifactor ANOVA. Pearson's correlation analysis/post-hoc mean comparisons based on Duncan Multiple Range Test (DMRT) were used to relate metals and biomarker responses.

3. Results and Discussion

3.1 Levels of Metalloids and Non-metals in cage-cultured fish

In Tables 1, the concentrations of arsenic showed moderate variability across species, with *Clarias* hybrid, exhibiting the highest levels (0.2390 ± 0.0902 µg/g) and *O. niloticus* the lowest (0.0749 ± 0.0271 µg/g), though differences were not statistically significant ($p > 0.05$). This trend may reflect variations in feeding ecology or bioaccumulation mechanisms, aligning with the findings of Rehman *et al.* (2021), who reported that arsenic accumulation in fish may be influenced by dietary sources and habitat contamination. Boron (B) levels varied significantly, with *C. gariepinus* (0.0475 ± 0.0239 µg/g) showing the highest concentrations, followed by *O. niloticus* (0.0129 ± 0.0051 µg/g) and *Clarias* hybrid (0.0038 ± 0.0008 µg/g). This aligns with Resgalla *et al.* (2022), who observed higher boron levels in benthic species like *C. gariepinus*, while the low levels in *Clarias* hybrid may reflect its hybrid nature and associated metabolic differences.

Selenium concentrations were generally low, with *O. niloticus* (0.0136 ± 0.0069 µg/g) significantly higher than *C. gariepinus* (0.0008 ± 0.0003 µg/g) and *Clarias* hybrid (0.0015 ± 0.0006 µg/g), potentially influenced by its herbivorous diet and selenium bioavailability in its habitat (Xu *et al.*, 2021). Silicon was highest in *C. gariepinus* (6.1168 ± 1.8976 µg/g), followed by *Clarias* hybrid (2.0699 ± 0.6158 µg/g) and *O. niloticus* (0.1374 ± 0.0371 µg/g), a pattern attributed to sediment exposure and benthic feeding habits (Usese *et al.*, 2018). Sulfur levels were relatively uniform across species, with *C. gariepinus* (0.0014 ± 0.0006 µg/g) slightly higher than *Clarias* hybrid and *O. niloticus* (both at 0.0006 ± 0.0004 µg/g), consistent with Bradford *et al.* (2024), who noted that sulfur bioaccumulation often correlates with environmental availability rather than species-specific factors.

Table 1. Concentrations of metalloids and non-metals in cage-cultured fish from Epe Lagoon

	Clarias gariepinus	*Clarias* hybrid	*Oreochromis niloticus*
Arsenic	0.1594 ± 0.0765^{a} (0.0244-0.5241)	0.2390 ± 0.0902^{a} (0.0359-0.5702)	0.0749 ± 0.0271^{a} (0.0141-0.1595)
Boron	0.0475 ± 0.0239^{ab} (0.0005-0.1372)	0.0038 ± 0.0008^{a} (0.0013-0.0065)	0.0129 ± 0.0051^{a} (0.0015-0.0327)
Selenium	0.0008 ± 0.0003^{a} (0.0002-0.0021)	0.0015 ± 0.0006^{a} (0.0003-0.0042)	0.0136 ± 0.0069^{a} (0.0012-0.0446)
Silicon	6.1168 ± 1.8976^{a} (1.4248-11.6919)	2.0699 ± 0.6158^{a} (0.2746-4.7177)	0.1374 ± 0.0371^{a} (0.0222-0.2726)
Sulfur	0.0014 ± 0.0006^{ab} (0.0000-0.0032)	0.0006 ± 0.0004^{a} (0.000-0.0018)	0.0006 ± 0.0004^{a} (0.0000-0.0019)

Keys: Mean±Standard Dev.; values with different superscripts across row are significantly different ($P < 0.05$)

In Tables 2, the concentrations of metalloids and non-metals in cage-cultured fish from Badagry Lagoon reveal species-specific differences influenced by environmental factors and feeding habits. Arsenic levels were significantly higher in *Clarias* hybrid (0.3001 ± 0.0589 µg/g) compared to *C.*

gariepinus (0.2093 ± 0.0569 µg/g) and *O. niloticus* (0.0789 ± 0.0211 µg/g). This pattern suggests a greater tendency for arsenic bioaccumulation in *Clarias* hybrid, potentially due to its hybrid physiology, as noted by Rehman *et al.* (2021), who emphasized habitat and dietary sources as key factors. Boron levels were highest in *C. gariepinus* (0.0506 ± 0.0224 µg/g), aligning with Resgalla *et al.* (2022), who reported higher boron accumulation in benthic feeders due to sediment interaction. By contrast, *O. niloticus* (0.0139 ± 0.0041 µg/g) and *Clarias* hybrid (0.0047 ± 0.0007 µg/g) had significantly lower boron levels, reflecting their less sediment-reliant feeding strategies.

Selenium was markedly elevated in *O. niloticus* (0.0132 ± 0.0093 µg/g), consistent with Xu *et al.* (2021), who observed higher selenium levels in herbivorous fish due to their plant-rich diet. Silicon concentrations varied significantly, with *C. gariepinus* showing exceptionally high levels (16.7392 ± 8.6947 µg/g) compared to *Clarias* hybrid (4.8635 ± 1.4987 µg/g) and *O. niloticus* (0.3820 ± 0.0976 µg/g). The elevated silicon levels in *C. gariepinus* are likely due to its benthic feeding behavior, which increases sediment exposure, as highlighted by Usese *et al.* (2018). Sulfur levels were relatively low across all species, with *C. gariepinus* exhibiting a wide variability (0.3260 ± 0.3238 µg/g), possibly influenced by environmental sulfur availability rather than species-specific factors, as suggested by Bradford *et al.* (2024). These findings emphasize the complex interplay between environmental conditions, feeding habits, and elemental bioaccumulation in fish species.

Table 2. Concentrations of metalloids and non-metals in cage-cultured fish from Badagry Lagoon

Elements	*Clarias gariepinus*	*Clarias* hybrid	*Oreochromis niloticus*
Arsenic	0.2093 ± 0.0569^b (0.1071-0.4576)	0.3001 ± 0.0589^b (0.0819-0.4977)	0.0789 ± 0.0211^a (0.0148-0.1509)
Boron	0.0506 ± 0.0224^a (0.0010-0.1174)	0.0047 ± 0.0007^a (0.0027-0.0075)	0.0139 ± 0.0041^a (0.0031-0.0267)
Selenium	0.0005 ± 0.0002^a (0.0002-0.0014)	0.0008 ± 0.0003^a (0.0003-0.0021)	0.0132 ± 0.0093^b (0.0009-0.0593)
Silicon	16.7392 ± 8.6947^c (5.2521-59.9234)	4.8635 ± 1.4987^a (1.0123-11.550)	0.3820 ± 0.0976^a (0.0556-0.6344)
Sulfur	0.3260 ± 0.3238^a (0.0009-1.9448)	0.0012 ± 0.0004^a (0.0000-0.0018)	0.0011 ± 0.0004^a (0.0000-0.0019)

Keys: Mean±Standard Dev.; values with different superscripts across row are significantly different ($P < 0.05$)

3.2 Assessment of oxidative stress in cage-cultured fish

Figures 2 to 6 present the antioxidant properties of different parts of fish species from caged-culture systems in Lagos, Nigeria. Holistically, *Clarias* hybrid consistently exhibited high antioxidant defense: CAT (13.68-15.72 min/mg pro), SOD (543.53-603.02 min/mg pro) and GSH (6.60925-6.635917 µmol/ml) in both locations, suggesting a robust ability to counteract oxidative stress. C. gariepinus had relatively high MDA (3.082917-3.13925 µmol/ml), suggesting that although they counteract oxidative stress effectively, they still experience significant lipid peroxidation. Tilapia (*O. niloticus*) had lowest antioxidant enzyme activity, especially CAT (0.950875-1.921 min/mg pro) and SOD (400.95-488.51 min/mg pro) in both locations, indicating that this species might be more susceptible to oxidative damage.

The antioxidant properties observed in the current study align with findings from previous literature on fish species in aquaculture systems. For instance, *Clarias* hybrid' robust antioxidant defense, as indicated by elevated CAT, SOD, and GSH activities, is consistent with reports by Ugwu *et al.* (2021), who highlighted the species' adaptive oxidative stress mechanisms in polluted environments. Similarly, the high MDA levels in *C. gariepinus* reflect findings by Demirci-Cekic *et al.* (2022), suggesting that while the species exhibits notable antioxidant activity, it remains prone to lipid peroxidation under stress. Tilapia's low antioxidant enzyme activity mirrors observations by Lawal-Are *et al.* (2021), who noted its susceptibility to oxidative damage, particularly in environments with high oxidative stress. These comparisons emphasize species-specific variations in oxidative stress responses within aquaculture systems.

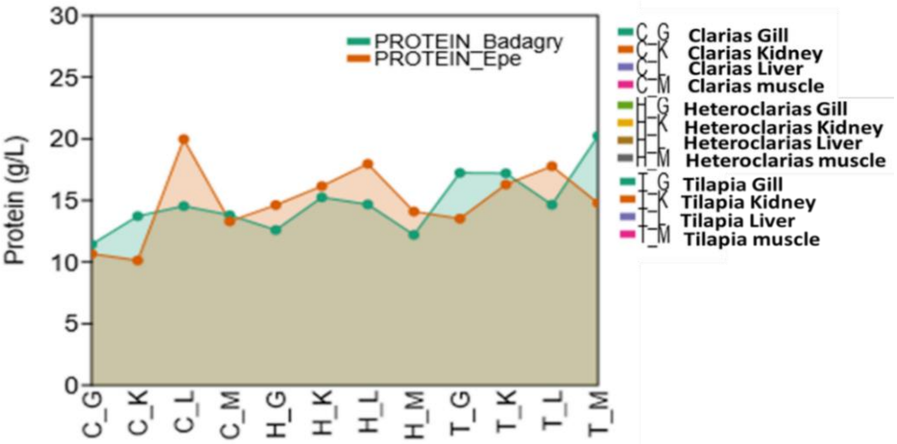

Figure 2. Mean variations of Protein (g/L) in cage-cultured fish species in Lagos, Nigeria

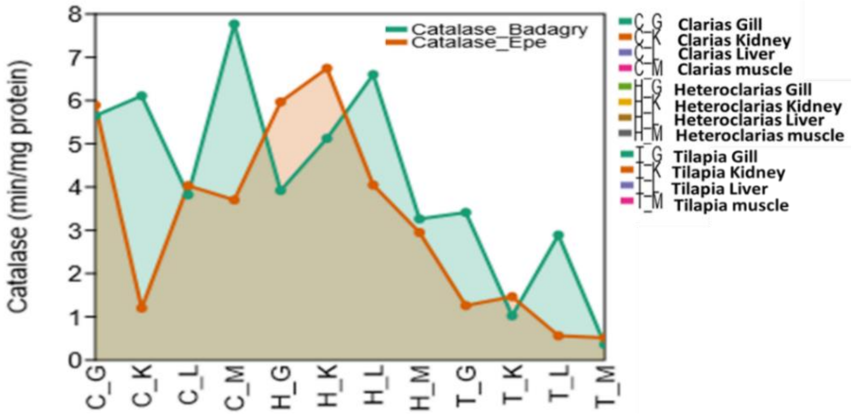

Figure 3. Mean variations of Catalase (CAT) (min/mg protein) in cage-cultured fish species in Lagos, Nigeria

Figure 4. Mean Variations of Superoxide Dismutase (SOD) (min/mg protein) in cage-cultured fish species in Lagos, Nigeria

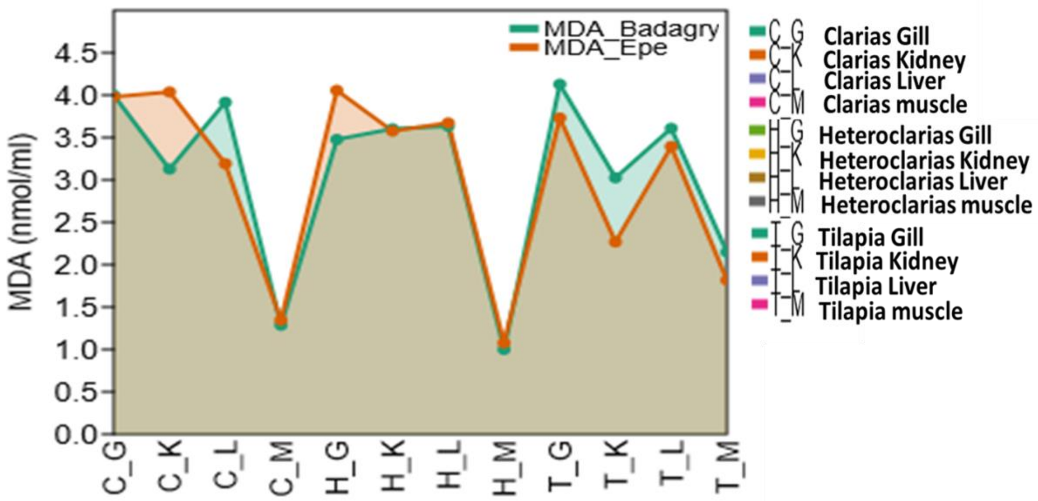

Figure 5. Mean Variations of Malondialdehyde (MDA) (nmol/ml) in cage-cultured fish species in Lagos, Nigeria

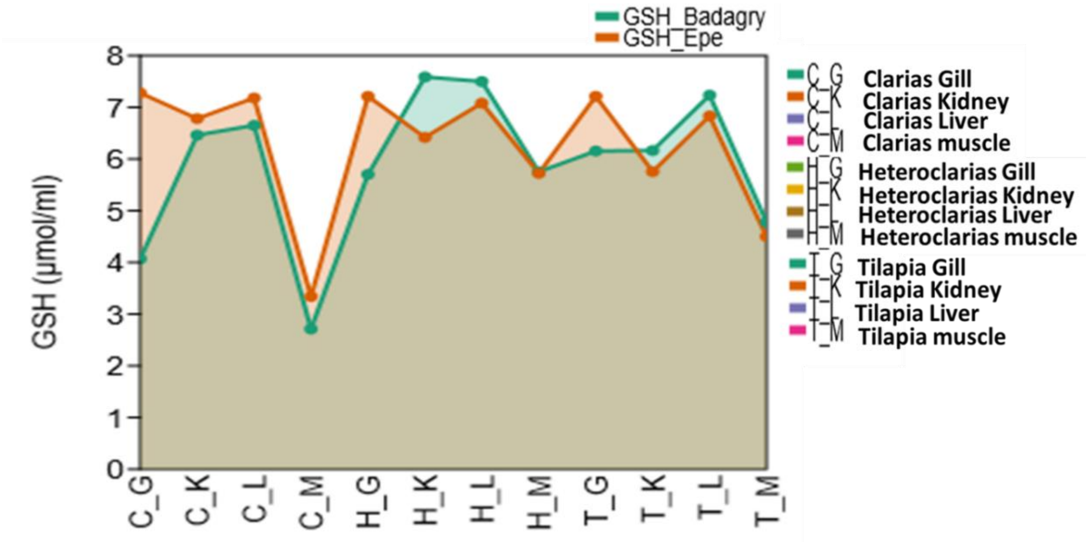

Figure 6. Mean Variations of Glutathione (GSH) (µmol/ml) iin cage-cultured fish species in Lagos, Nigeria

3.3 Relationship between elements and oxidative stress markers

Tables 3 and 4 present the relationships between metal concentrations (arsenic, boron, selenium, silicon, sulfur) and oxidative stress markers (PRO, CAT, SOD, MDA, GSH) in *C. gariepinus* from caged culture systems in Epe and Badagry, respectively. In Epe, CAT exhibited strong positive correlations with arsenic (0.658) and selenium (0.673), suggesting these metals enhance catalase activity, but strong negative correlations with boron (-0.920) and sulfur (-0.919), indicating inhibitory effects. Similarly, SOD showed strong positive correlations with arsenic (0.983) and selenium (0.979), highlighting their role in increasing superoxide dismutase activity, while MDA had strong positive correlations with arsenic (0.623) and selenium (0.608), linking these metals to elevated lipid peroxidation. GSH had strong negative correlations with boron (-0.983) and sulfur (-0.982), implying reduced antioxidant defense in their presence. In Badagry, CAT positively correlated with silicon (0.600), sulfur (0.659), and arsenic (0.522), indicating these metals may improve antioxidant enzyme activity. SOD had strong positive correlations with arsenic (0.973) and selenium (0.900), while GSH showed negative correlations with arsenic (-0.564) and selenium (-0.370), suggesting a suppression of glutathione levels. Across both locations, arsenic and selenium are associated with increased oxidative stress (elevated CAT, SOD, and MDA), while boron and sulfur inhibit key antioxidant defenses, and silicon demonstrates a protective role by reducing oxidative damage.

The observed relationships between metal concentrations and oxidative stress markers align with findings from earlier studies. Elevated CAT and SOD activities in response to arsenic and selenium are consistent with Usese *et al.* (2017), who reported that these metals stimulate antioxidant enzymes as part of the oxidative stress response in fish. Similarly, the suppression of GSH by arsenic and selenium reflects the findings of Ghasemi *et al.* (2023), who noted that prolonged exposure to these metals depletes glutathione reserves, weakening antioxidant defenses. The inhibitory effects of boron and sulfur on CAT and GSH are comparable to the results of Zhang *et al.* (2020), which highlighted their negative impact on antioxidant enzyme efficiency. Furthermore, the protective role of silicon, demonstrated by its positive correlation with GSH and negative correlation with MDA, aligns with findings by Mahboub *et al.* (2022), who emphasized silicon's antioxidative properties in mitigating oxidative stress in aquatic organisms. These comparisons underscore the complex interplay between metals and oxidative stress in aquaculture systems.

Table 3. Pearson's correlation tests for contaminants and oxidative response of caged-culture *Clarias gariepinus* in Epe, Lagos, Nigeria

	Arsenic	*Boron*	*Selenium*	*Silicon*	*Sulfur*	*PRO*	*CAT*	*SOD*	*MDA*	*GSH*
Arsenic	1									
Boron	-0.311	1								
Selenium	1.000	-0.330	1							
Silicon	0.171	-0.990	0.190	1						
Sulfur	-0.309	1.000	-0.327	-0.990	1					
PRO	-0.632	-0.540	-0.617	0.655	-0.542	1				
CAT	0.658	-0.920	0.673	0.854	-0.919	0.167	1			
SOD	0.983	-0.131	0.979	-0.013	-0.129	-0.764	0.509	1		
MDA	0.623	0.549	0.608	-0.664	0.551	-1.000	-0.178	0.756	1	
GSH	0.482	-0.983	0.500	0.946	-0.982	0.373	0.977	0.313	-0.384	1

Table 4. Pearson's correlation tests for contaminants and oxidative response of caged-culture *Clarias gariepinus* in Badagry, Lagos Nigeria

	Arsenic	*Boron*	*Selenium*	*Silicon*	*Sulfur*	*PRO*	*CAT*	*SOD*	*MDA*	*GSH*
Arsenic	1									
Boron	0.978	1								
Selenium	0.976	1.000	1							
Silicon	-0.369	-0.554	-0.563	1						
Sulfur	-0.298	-0.490	-0.499	0.997	1					
PRO	-0.717	-0.556	-0.548	-0.383	-0.452	1				
CAT	0.522	0.333	0.323	0.600	0.659	-0.969	1			
SOD	0.973	0.904	0.900	-0.146	-0.071	-0.858	0.704	1		
MDA	-0.273	-0.067	-0.056	-0.794	-0.837	0.866	-0.963	-0.486	1	
GSH	-0.564	-0.379	-0.370	-0.560	-0.621	0.980	-0.999	-0.738	0.948	1

Tables 5 and 6 present the relationships between metal concentrations (arsenic, boron, selenium, silicon, sulfur) and oxidative stress markers (PRO, CAT, SOD, MDA, GSH) in *Clarias* hybrid from caged culture systems in Epe and Badagry, respectively. In Epe, CAT exhibited moderate positive correlations with selenium (0.692), silicon (0.693), and sulfur (0.722), suggesting these elements enhance catalase activity to reduce oxidative stress. SOD showed strong positive correlations with silicon (0.732) and sulfur (0.759), indicating a collaborative role in counteracting oxidative stress. MDA had a strong positive correlation with arsenic (0.992), linking it to increased lipid peroxidation, while negative correlations with silicon (-0.685), sulfur (-0.654), and boron (-0.860) suggested these elements mitigate oxidative damage. GSH demonstrated strong negative correlations with boron (-0.986) and sulfur (-0.988), indicating reduced glutathione levels in their presence. In Badagry, CAT showed a strong positive correlation with arsenic (0.956) but a strong negative correlation with selenium (-0.993), suggesting arsenic promotes, while selenium inhibits, catalase activity. SOD exhibited a very strong positive correlation with selenium (0.996), signifying its role in enhancing SOD activity, but had negative correlations with arsenic (-0.873) and CAT (-0.977), highlighting interplay between these factors. MDA correlated positively with selenium (0.906) and sulfur (0.847) but negatively with arsenic (-0.656) and boron (-0.409), linking these elements to lipid peroxidation regulation. GSH showed strong negative correlations with boron (-0.956), silicon (-0.863), and sulfur (-0.958), indicating that these metals reduce glutathione levels and potentially weaken antioxidant defenses.

The findings align with prior studies examining metal-induced oxidative stress in aquatic species. The stimulation of CAT and SOD by selenium, silicon, and sulfur, as observed in Epe, is consistent with reports by Çiçek and Özoğul (2022), who highlighted these metals' roles in enhancing antioxidant enzyme activity. Similarly, the link between arsenic and increased MDA levels, reflecting lipid peroxidation, aligns with Usese *et al.* (2017), who noted arsenic's oxidative stress-inducing properties. Negative correlations between GSH and boron or sulfur mirror observations by Zhang *et al.* (2020), emphasizing their suppressive effects on glutathione levels. Contrarily, in Badagry, selenium's inhibitory effect on CAT activity is consistent with Ghasemi *et al.* (2023), who observed selenium's dual role depending on concentration. The protective role of silicon and sulfur, evidenced by their negative correlations with MDA, supports findings by Moruf *et al.* (2022), which highlighted their antioxidative properties. These results underscore the nuanced interplay between metals and oxidative stress markers, with location-specific variations likely influenced by environmental and physiological factors.

Table 5. Pearson's correlation tests for contaminants and oxidative response of caged-culture *Clarias* hybrid in Epe, Lagos Nigeria

	Arsenic	*Boron*	*Selenium*	*Silicon*	*Sulfur*	*PRO*	*CAT*	*SOD*	*MDA*	*GSH*
Arsenic	1									
Boron	-0.787	1								
Selenium	0.834	-0.316	1							
Silicon	-0.585	0.961	-0.041	1						
Sulfur	-0.552	0.949	0.000	0.999	1					
PRO	-0.806	0.270	-0.999	-0.007	-0.048	1				
CAT	0.178	0.467	0.692	0.693	0.722	-0.726	1			
SOD	0.124	0.515	0.651	0.732	0.759	-0.686	0.998	1		
MDA	0.992	-0.860	0.756	-0.685	-0.654	-0.724	0.050	-0.005	1	
GSH	0.674	-0.986	0.155	-0.993	-0.988	-0.107	-0.606	-0.649	0.764	1

Table 6. Pearson's correlation tests for contaminants and oxidative response of caged-culture *Clarias* hybrid in Badagry, Lagos Nigeria

	Arsenic	*Boron*	*Selenium*	*Silicon*	*Sulfur*	*PRO*	*CAT*	*SOD*	*MDA*	*GSH*
Arsenic	1									
Boron	0.420	1								
Selenium	-0.914	-0.016	1							
Silicon	0.617	0.973	-0.245	1						
Sulfur	-0.154	0.832	0.542	0.682	1					
PRO	-0.293	-0.991	-0.120	-0.933	-0.899	1				
CAT	0.956	0.137	-0.993	0.361	-0.436	-0.002	1			
SOD	-0.873	0.075	0.996	-0.156	0.616	-0.209	-0.977	1		
MDA	-0.656	0.409	0.906	0.188	0.847	-0.529	-0.848	0.941	1	
GSH	-0.136	-0.956	-0.278	-0.863	-0.958	0.987	0.160	-0.364	-0.658	1

Tables 7 and 8 present the relationships between metal concentrations (arsenic, boron, selenium, silicon, sulfur) and oxidative stress markers in *O. niloticus* from caged culture systems in Epe and Badagry, respectively. In Epe, CAT exhibited a strong positive correlation with arsenic (0.958) and negative correlations with silicon (-0.804) and sulfur (-0.749), indicating that arsenic enhances catalase activity while silicon and sulfur inhibit it. SOD had a very strong positive correlation with arsenic (0.991), linking arsenic exposure to increased superoxide dismutase activity. MDA showed strong positive correlations with selenium (0.929) and sulfur (0.638), suggesting that these metals contribute to lipid peroxidation and oxidative stress. GSH displayed a strong positive correlation with selenium (0.985), highlighting selenium's role in boosting glutathione levels. In Badagry, CAT showed a negative correlation with sulfur (-0.920) but a weaker positive correlation with arsenic (0.288), suggesting a less pronounced response to arsenic-induced oxidative stress. SOD exhibited negative correlations with silicon (-0.989) and sulfur (-0.836), indicating a reduction in SOD activity in their presence. MDA had strong positive correlations with selenium (0.711) and arsenic (0.454), reflecting their role in oxidative stress, while showing a negative correlation with sulfur (-0.975). GSH had a strong positive correlation with sulfur (0.995), indicating that sulfur enhances glutathione levels, which are critical for oxidative stress defense. Across both locations, arsenic and selenium consistently correlate with increased oxidative stress (higher MDA, CAT, and SOD), while sulfur exhibits dual roles, enhancing GSH but inhibiting SOD and CAT.

The results are consistent with previous studies on metal-induced oxidative stress in *O. niloticus*. The positive correlation of arsenic with CAT and SOD aligns with the findings of Usese *et al.* (2022), who reported that arsenic exposure enhances antioxidant enzyme activities to counter oxidative stress. Selenium's association with increased MDA and GSH levels supports Ghasemi *et al.* (2023), who highlighted selenium’s dual role in promoting lipid peroxidation while boosting glutathione synthesis. The inhibitory effect of silicon and sulfur on CAT and SOD activity observed in this study parallels the findings of Guo *et al.* (2020), which noted that excessive levels of these elements can suppress enzymatic antioxidant defenses. Conversely, the strong positive correlation of sulfur with GSH reflects in the report of Çiçek and Özoğul (2022), who emphasized sulfur's role in bolstering glutathione-dependent antioxidant mechanisms. These findings underscore the complex interplay between metals and oxidative stress markers in *O. niloticus*, with variations influenced by environmental conditions and metal concentrations.

Table 7. Pearson's correlation tests for contaminants and oxidative response of caged-culture *Oreochromis niloticus* in Epe, Lagos, Nigeria

	Arsenic	*Boron*	*Selenium*	*Silicon*	*Sulfur*	*PRO*	*CAT*	*SOD*	*MDA*	*GSH*
Arsenic	1									
Boron	-0.560	1								
Selenium	-0.056	0.859	1							
Silicon	-0.601	0.999	0.831	1						
Sulfur	-0.529	0.999	0.877	0.996	1					
PRO	-0.989	0.428	-0.095	0.474	0.395	1				
CAT	0.958	-0.773	-0.339	-0.804	-0.749	-0.904	1			
SOD	0.991	-0.444	0.079	-0.489	-0.410	-1.000	0.911	1		
MDA	0.316	0.609	0.929	0.568	0.638	-0.456	0.032	0.441	1	
GSH	0.117	0.758	0.985	0.723	0.781	-0.265	-0.172	0.249	0.979	1

Table 8. Pearson's correlation tests for metal contaminants and oxidative response of caged-culture *Oreochromis niloticus* in Badagry, Lagos Nigeria

	Arsenic	*Boron*	*Selenium*	*Silicon*	*Sulfur*	*PRO*	*CAT*	*SOD*	*MDA*	*GSH*
Arsenic	1									
Boron	-0.879	1								
Selenium	0.949	-0.984	1							
Silicon	0.034	0.447	-0.283	1						
Sulfur	-0.641	0.930	-0.850	0.745	1					
PRO	-0.337	-0.153	-0.023	-0.952	-0.506	1				
CAT	0.288	-0.710	0.575	-0.947	-0.920	0.804	1			
SOD	0.114	-0.574	0.422	-0.989	-0.836	0.897	0.984	1		
MDA	0.454	-0.824	0.711	-0.875	-0.975	0.686	0.984	0.937	1	
GSH	-0.559	0.887	-0.792	0.810	0.995	-0.592	-0.955	-0.888	-0.993	1

Conclusion

This study highlights significant variations in metal concentrations and oxidative stress responses among *Clarias gariepinus*, *Clarias* hybrid and *Oreochromis niloticus* from caged culture systems in Lagos, Nigeria. Arsenic and selenium were identified as key drivers of oxidative stress, stimulating enzymatic antioxidant activities (CAT and SOD) while promoting lipid peroxidation. In contrast, boron and sulfur exhibited concentration-dependent effects, where excessive levels suppressed antioxidant defenses, while moderate levels may play physiological roles in cellular function. Sulfur, in particular, influenced glutathione metabolism, necessitating further investigation into its dual role in oxidative stress modulation. Silicon showed a protective effect, potentially mitigating oxidative stress in Heteroclarias, likely through its role in reducing reactive oxygen species (ROS). These findings underscore the need for regular monitoring of metal bioaccumulation in aquaculture systems to maintain optimal fish health, ensuring food safety and environmental sustainability. To enhance fisheries management, further studies should assess long-term bioaccumulation patterns, threshold toxicity levels, and adaptive responses in various aquaculture settings, including earthen ponds and recirculating systems. Identifying safe exposure limits for essential and non-essential elements will aid in developing best practices for water quality management in fish farming.

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