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Impacts of Mining-Induced Pollution on Water Quality and Morphological Development of the African Catfish (*Clarias gariepinus*) and the Nile Tilapia (*Oreochromis niloticus*) in the Ankobra River Basin, Ghana

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ABSTRACT
Mining in Ghana's Ankobra River basin has severely impacted aquatic ecosystems. This study examined the effects on *Clarias gariepinus* (African catfish) and *Oreochromis niloticus* (Nile tilapia) by comparing morphometric features and water quality in two tributaries: Kawre (mined) and Okyeadea (unmined). Data were collected from June to August, measuring key morphometric traits and analyzing water for physicochemical parameters, nutrients, and heavy metals.The mined Kawre stream showed high pollution, with mean Hg and As levels at 3.543 and 0.154mg/ L, compared to 0.001mg/ L in the unmined Okyeadea. Turbidity in Kawre ranged from 4,023 to 4,116 NTU, far exceeding Okyeadea's 16.5–21.2 NTU, indicating severe sediment and contaminant influx. Fish in Kawre exhibited reduced growth in critical features for survival, such as fins and snout size, likely due to energy diverted to detoxification and stress response. The condition factor for both species between mined and unmined sampling factors was significantly different ($P < 0.05$). This study highlights the urgent need for stringent regulations and sustainable mining to protect aquatic ecosystems essential for biodiversity and the livelihoods of communities reliant on fishing.

INTRODUCTION

The global expansion of mining operations has significantly raised environmental concerns worldwide **(Carvalho, 2017)**. Mining industries provide essential materials for infrastructure development, energy production, and agricultural fertilizers. However, the escalating demand for metal ores has led to both legal and illegal mining operations, many of which lack adequate regulatory supervision **(Carvalho, 2017)**. This has resulted in long-term negative impacts on the environment and public health **(Fashola *et al.*, 2016)**.

One of the major issues associated with mining activities is the improper disposal of mining tailings and acid mine drainage. Tailings, the waste materials left after extracting valuable minerals, often contain hazardous substances **(Nordstrom, 2011; Jain *et al.*, 2016)**. When these tailings come into contact with water and oxygen, they can generate acid mine drainage **(Carvalho, 2017)**. This process releases harmful chemical elements into the environment, contaminating water sources, aquatic organisms, and food chains. Elevated concentrations of heavy metals—such as mercury, lead, and cadmium—pose significant health risks to both ecosystems and human populations **(Fashola *et al.*, 2016)**.

Numerous studies **(Osman & Kloas, 2010; Fashola *et al.*, 2016; Carvalho, 2017; Greenfield *et al.*, 2018)** have explored the impact of mining on aquatic environments. Heavy metals from mining activities contaminate surface and groundwater, affecting aquatic life and human water supplies **(Akcil & Koldas, 2006; Mudd, 2010; Canton *et al.*, 2020)** and can accumulate in the tissues of aquatic organisms, leading to toxicity and death **(Osman & Kloas, 2010)**. Acid mine drainage from sulfide minerals generates acidic runoff, lowering pH levels and mobilizing toxic metals that harm aquatic ecosystems **(Vane *et al.*, 2017; Ponder *et al.*, 2020)**. Erosion and sedimentation caused by surface mining clog aquatic habitats and disrupt species reproduction **(Palmer *et al.*, 2010; Richardson *et al.*, 2017)**. Mining activities distort the ecological balance of water bodies and their dependent organisms **(Sidle *et al.*, 2006; Boulton *et al.*, 2010)**. Groundwater depletion also poses risks, as deep extraction reduces aquifer reserves while introducing contaminants that compromise water quality **(Barton *et al.*, 2007; Wang *et al.*, 2018)**.

The effects of mining pollution extend to aquatic organisms, significantly impacting biodiversity and ecosystem functions. Fish species such as *Oreochromis niloticus* (the Nile tilapia) and *Clarias gariepinus* (African catfish) are particularly vulnerable to these pollutants. Exposure to heavy metals has been linked to various morphological deformities, including skeletal abnormalities, gill and fin erosion, and changes in body shape **(El-Khayat *et al.*, 2018)**. These alterations compromise health, survival, and reproductive success, ultimately reducing species diversity and disrupting food chains—especially for communities that rely on aquatic ecosystems for their livelihoods **(Ouma, 2017)**.

The consumption of fish contaminated with heavy metals poses serious health risks to humans, including neurotoxicity and developmental disorders **(Erasmus *et al.*, 2022)**. This not only affects public health but also has economic consequences. In many developing regions, fishing is a vital source of food security, providing essential protein and micronutrients **(Greenfield *et al.*, 2018)**. The decline in fish diversity due to mining pollution jeopardizes this food source, leading to malnutrition and increased vulnerability to food insecurity—thus impeding progress toward achieving SDG 2 (Zero Hunger).

This research focuses on the impact of mining on the morphological formation of *Oreochromis niloticus* and *Clarias gariepinus*, emphasizing the urgent need for comprehensive supervision of mining operations to mitigate adverse effects on aquatic ecosystems. Key objectives of this study include, but are not limited to, assessing the impact of mining on nutrient levels and heavy metal concentrations in water bodies, and quantifying key morphometric parameters such as weight, length, and specific anatomical features to evaluate morphological variations induced by mining activities.

Understanding these impacts is essential for environmental conservation and the development of effective mitigation strategies. The physiological responses of *Oreochromis* *niloticus* and *Clarias gariepinus* to mining-induced stressors can serve as bioindicators of aquatic ecosystem health. Moreover, the findings of this research have direct implications for communities dependent on these fish species for food, income, and cultural identity **(Balogun, 2006)**. By elucidating the specific effects of mining on these species, this study aimed to contribute valuable insights into sustainable resource management and the protection of aquatic biodiversity.

MATERIALS AND METHODS

1. Study area

The study was conducted in the Tarkwa-Nsuaem Municipal District (TMA), located in the Western Region of Ghana. TMA has the highest concentration of mines within a single area in Africa and holds nearly a century-long history of gold mining, predominantly through surface mining operations. The district is situated between latitudes 4°00′ N and 5°40′ N and longitudes 1°45′ W and 2°01′ W, covering a land area of approximately 954.8km² **(CityPopulation.de, 2021)**. As of 2021, the estimated population of the entire area is 219,109 **(Ghana Statistical Service, 2023)**.

TMA lies within the South-Western Equatorial Climatic Zone, experiencing temperatures ranging from 24 to 32°C throughout the year. The average annual rainfall is approximately 190cm, with the wettest months occurring from May to October.

This research focused on two communities located along two named tributaries—Okyeadea and Kawre—of the Ankobra River, within the mining catchment area of the AngloGold Ashanti Iduapriem mines. Both streams are part of the same interconnected drainage network. Sampling was conducted at Timber Road community (for the Okyeadea stream) and Wangra community (for the Kawre stream). The Wangra community has an estimated population of about 1,000, while Okyeadea has approximately 500 residents.

The primary occupation in both communities is small-scale mining. Other common livelihoods include trading, farming, and fish farming. The water bodies serve multiple essential functions, providing sources of drinking water and irrigation for agricultural activities.

Water and fish samples were collected from both the Okyeadea and Kawre streams (Picture 1 and 2). The exact sampling locations were recorded using GPS. Table (1) presents the sampling points along with their GPS coordinates.

Table 1. Sampling points and GPS coordinates

Sampling Point	GPS location
Okyeadea stream	**5˚16'58 2˚5'12**
Kawre stream	**5˚17'52 2˚4'28**

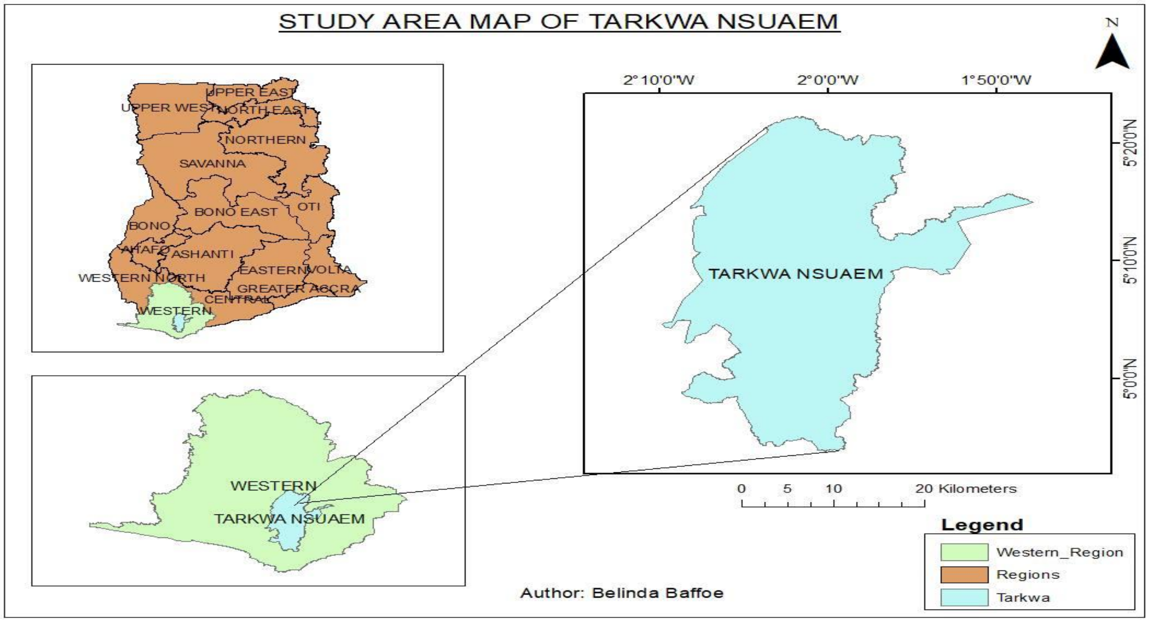

Fig. 1. Map showing the areas where data were collected

Picture 1. Okyeadea (Unmined Stream)

Picture 2. Kawre (Mined Stream)

2. Water sampling

Water samples were collected from upstream, midstream, and downstream sections of each stream. These zones were defined by a clear upstream starting point, a midstream central section, and a downstream endpoint where the stream merged into another waterbody. Water and fish samples were gathered simultaneously from randomly selected locations within these sections.

The study followed the United States Environmental Protection Agency (US EPA) Method 1669 for water sampling. Sampling bottles were sterilized, rinsed with deionized water, and air-dried for 24 hours prior to use. At each site, bottles were rinsed three times with the stream water before sample collection to minimize contamination. After collection, samples were sealed, stored in coolers at 4°C, and transported to the laboratory within 24 hours.

Some physicochemical parameters—including color, turbidity, pH, dissolved oxygen (DO), and total dissolved solids (TDS)—were measured *in situ* using a multi-parameter probe. Additional parameters such as nitrite, cyanide, and sulfate were analyzed using a HACH DR/900 portable spectrophotometer. Heavy metals, nutrients, and trace elements were quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

2.1 Fish sampling

Fish samples were collected monthly from May to July 2024 at three designated points (upstream, midstream, and downstream) along each stream. Kawre Stream, which has active gold mining within its bed, represented the mining-impacted site, while Okyeadea Stream served as the unmined control site. Fish were sampled from the same sections where water samples were collected.

Over the three-month study, a total of 42 fish (21 from each stream) were captured using cast and set nets by local fishermen. Each fish's total length and body weight were recorded on-site. Length was measured to the nearest millimeter, and weight to the nearest gram using calibrated equipment. Samples were labeled with waterproof tags and stored in ice coolers for laboratory analysis.

In the laboratory, frozen fish samples were thawed and re-measured following the same procedures to maintain consistency. Additional observations, including external morphology and gut condition, were recorded.

2.2 Morphometric measurements

Morphometric characteristics were recorded for each fish sample from both the mined (Kawre) and unmined (Okyeadea) streams. Measurements included snout length, anal fin length, pectoral fin length, pelvic fin length, dorsal fin length, tail fin length, and head length. All measurements were taken to the nearest 0.1cm using a graduated measuring tape.

2.3 Condition factor

The condition factor (K) of *Oreochromis niloticus* and *Clarias gariepinus* was calculated using the formula by **Anderson and Neumann (1996)**:

$$K=(W/L^3)\times 100$$

Where:

- K = condition factor
- W = weight of the fish (g)
- L = total length of the fish (cm)

This metric provides insights into the health and well-being of the fish.

3. Data analysis

A two-sample t-test was conducted to assess significant differences in variables such as water quality parameters, morphometric measurements, and condition factors between the mined and unmined sites. The coefficient of determination (R^2) was also calculated to evaluate the strength of the relationship between fish length and weight for both species.

Statistical significance was determined at a *P*-value < 0.05 with a 95% confidence interval. All data were analyzed using Microsoft Excel's Data Analysis ToolPak, and the results were presented in tables and graphs for clarity and interpretation.

RESULTS

1. Water quality parameters

The pH levels of water samples from both mined and unmined streams exhibited slight variation, ranging from 6.12 to 6.36. The mined streams recorded a higher mean pH of 6.31, while the unmined streams had a mean of 6.13. Although pH values in mined streams were consistently higher (6.27–6.36) than those in unmined streams (6.12–6.14), a t-test revealed a statistically significant difference between the two groups (*P*= 0.023) (Fig. 2).

Total Suspended Solids (TSS) levels were markedly elevated in mined streams, ranging from 2,350 to 3,543mg/ L, with a mean value of 2,920mg/ L. In contrast, unmined streams had significantly lower TSS levels, ranging from 10 to 15mg/ L, with a mean of 12.33mg/ L. A t-test showed a statistically significant difference in TSS between mined and unmined streams (*P*= 0.01382) (Fig. 3).

Turbidity levels showed an inverse trend, with mined streams having a lower mean turbidity of 0.059mg/ L compared to 0.079mg/ L in unmined streams. Despite this apparent difference, the t-test indicated no statistically significant variance in turbidity between the two stream types (*P*= 0.4607) (Fig. 4).

The mean values of other physicochemical parameters that showed no significant differences between mined and unmined sampling locations are summarized in Table (2).

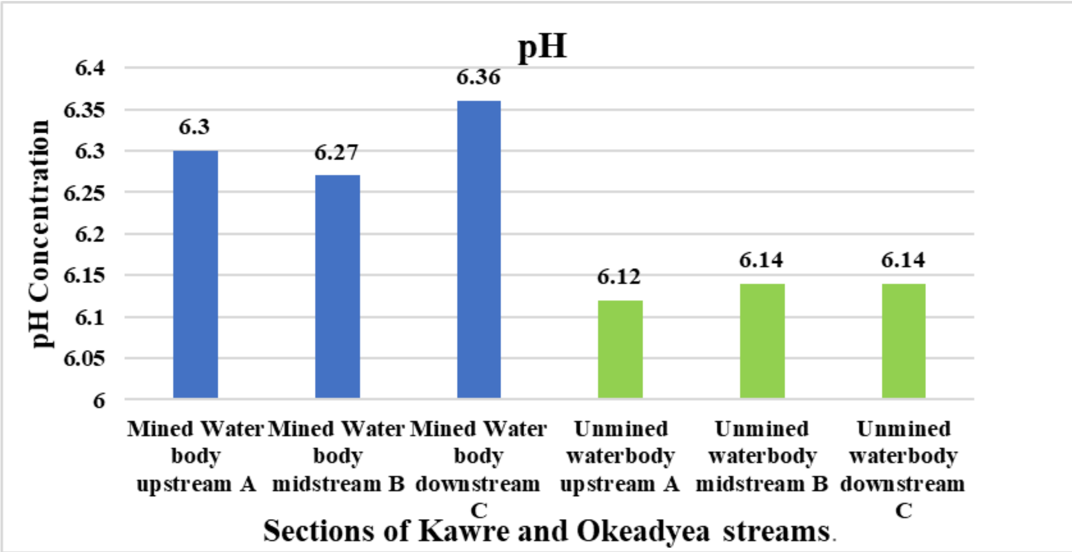

Fig. 2. pH concentration of mined and unmined streams (Kawre and Okyeadea)

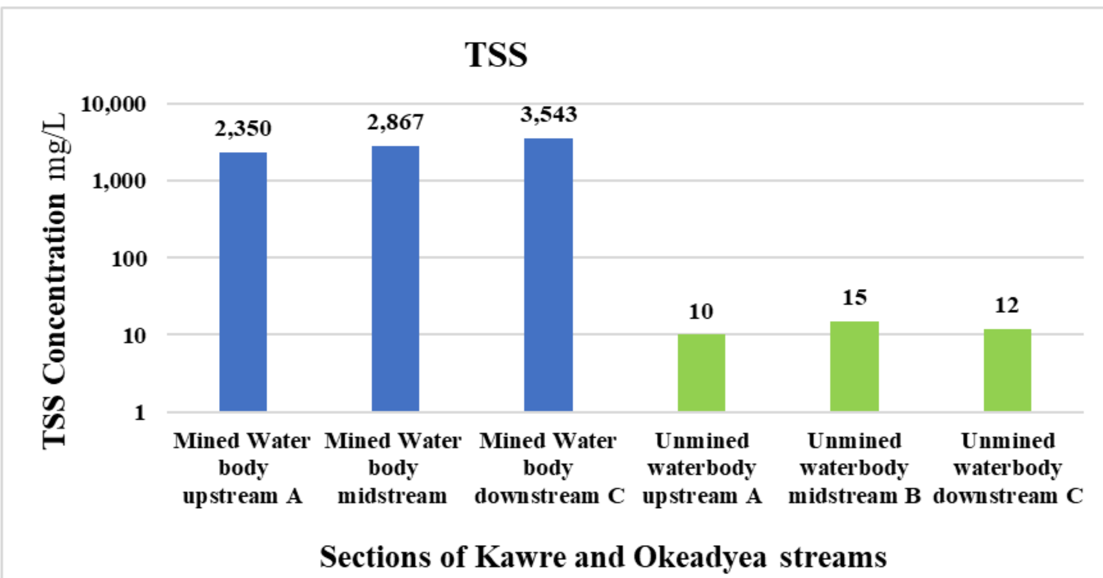

Fig. 3. TSS concentration of mined and unmined streams (Kawre and Okyeadea)

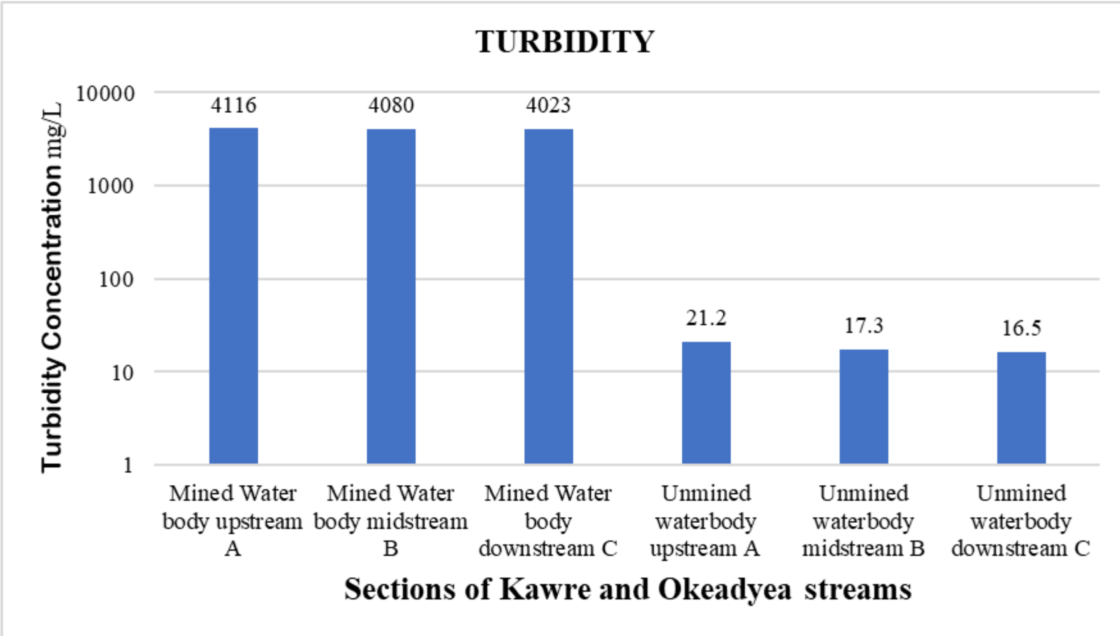

Fig. 4. Turbidity concentration of mined and unmined streams (Kawre and Okyeadea)

Potassium concentrations ranged from 1.39 to 2.96mg/ L in both stream types, with mined streams averaging a higher concentration (2.68mg/ L) compared to unmined streams (1.69mg/ L). A t-test, however, found no significant difference in potassium levels (P= 0.0413), although mined values were consistently higher (Fig. 5).

Sodium levels were also elevated in mined streams, with values between 5.82 and 11.13 mg/L, and a mean concentration of 10.27 mg/L, in contrast to unmined streams which averaged 6.73 mg/L. The difference was statistically insignificant (P= 0.0314) (Fig. 6).

The mean values of nutrients that indicated no significant difference between mined and unmined sampling locations are presented in Table (2).

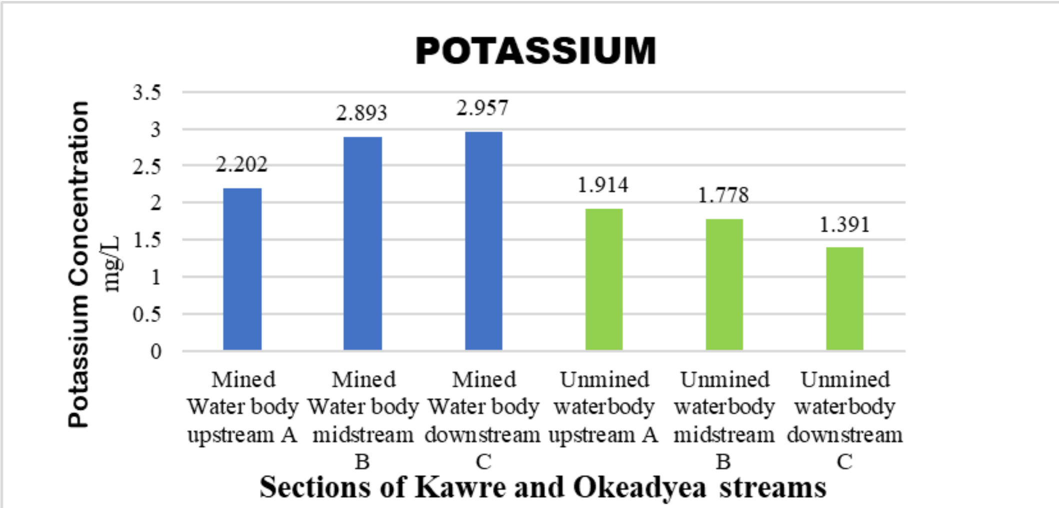

Fig. 5. Potassium concentration of mined and unmined streams (Kawre and Okyeadea)

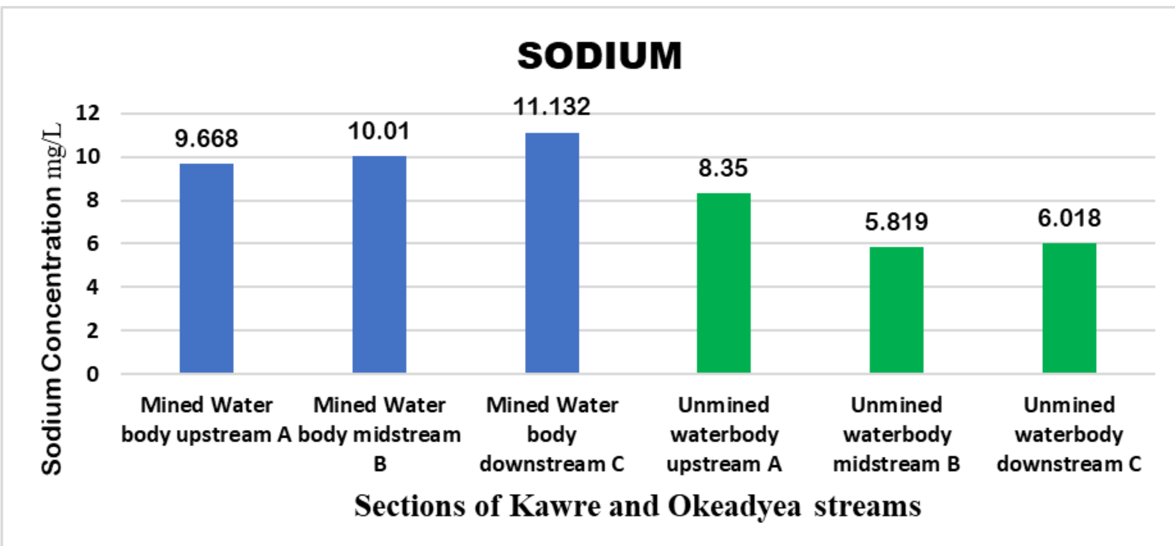

Fig. 6. Sodium concentration of mined and unmined streams (Kawre and Okyeadea)

Mercury concentrations displayed a considerable range, with mined streams reaching a mean of 3.54mg/ L compared to the unmined stream's mean of 0.00089mg/ L. This variance was prominent, with statistical analysis showing significant difference (*P*= 0.0403) (Fig. 7).

Arsenic levels in mined samples reached a mean concentration of 0.152mg/ L, significantly exceeding the unmined stream's mean of 0.00087mg/ L. T-test results confirmed significant difference (*P*= 0.0232) (Fig. 8). The mean values of heavy metals that showed no significant difference between mined and unmined sampling locations are presented in Table (2).

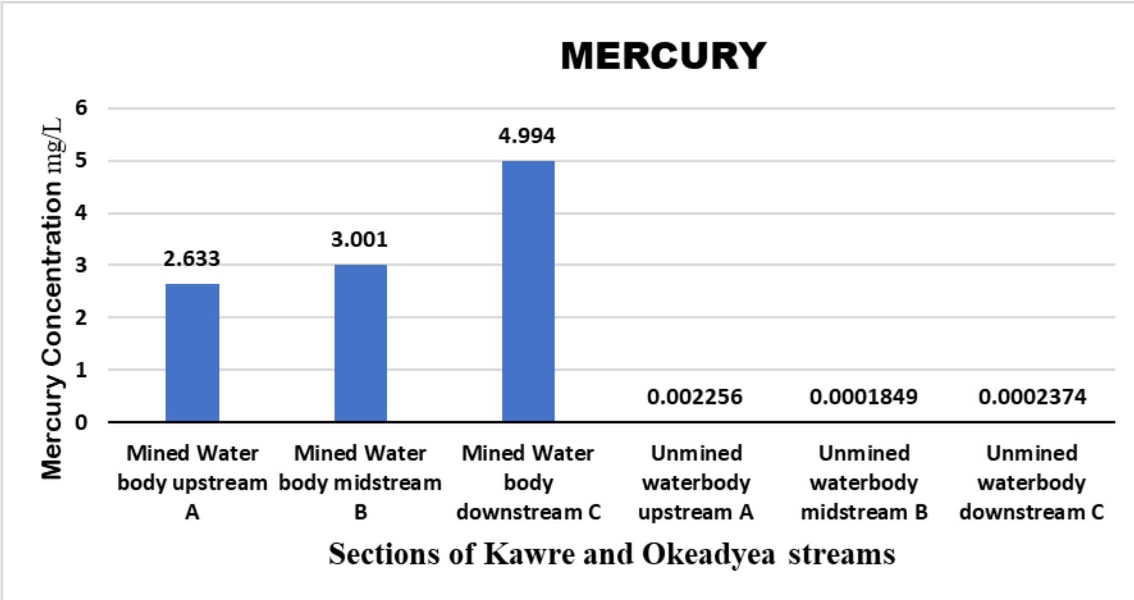

Fig. 7. Mercury concentration of mined and unmined streams (Kawre and Okyeadea)

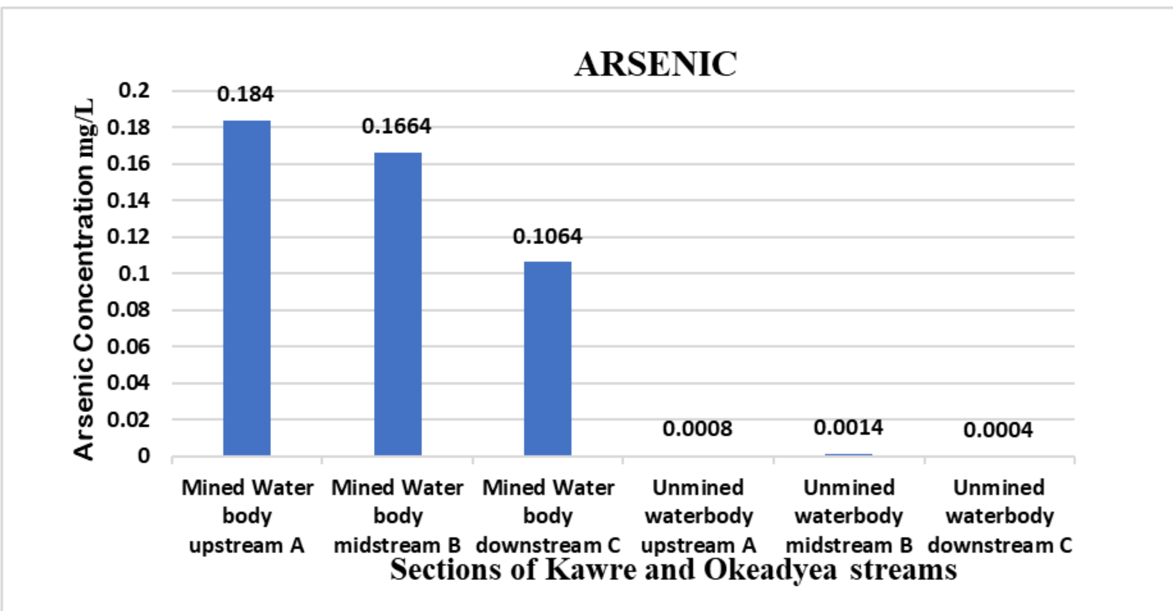

Fig. 8. Arsenic concentration of mined and unmined strea]ms (Kawre and Okyeadea)

Table 2. Descriptive summary of water quality parameters

SAMPLES MEAN	PHYSICO-CHEMICAL					NUTRIENTS					HEAVY METALS						TOXICANT
	DO	TDS	NTU	COLOR	SO_4^{2-}	NH_3-N	NO_2^-	P	Ca	Mg	Co	Cu	Cd	Mn	Ld.	Zn	CN^-
MINED	11.85	0.06	4073.00	20782.00	3.33	0.32	0.05	0.16	21.66	6.76	0.00	0.38	0.03	0.24	0.02	0.02	0.01
UNMINED	11.76	0.08	18.33	217.67	0.98	0.17	0.02	0.11	8.36	1.60	0.00	0.07	0.04	0.03	0.00	0.02	0.00
***P*-VALUE**	0.90	0.46	0.00	0.02	0.22	0.34	0.24	0.09	0.10	0.07	0.90	0.00	0.79	0.08	0.14	0.36	0.26

3.2 Condition factor of sampled fish species

The mean condition factor of tilapia species from the mined and unmined species was 2.3 ± 0.25 and 3.3 ± 0.37. The condition factor for both species between mined and unmined sampling factors was significant different ($P< 0.05$). For the catfish species, the condition factor from the mined and unmined species was 3.5 ± 0.41 and 0.7 ± 0.04 (Fig. 9).

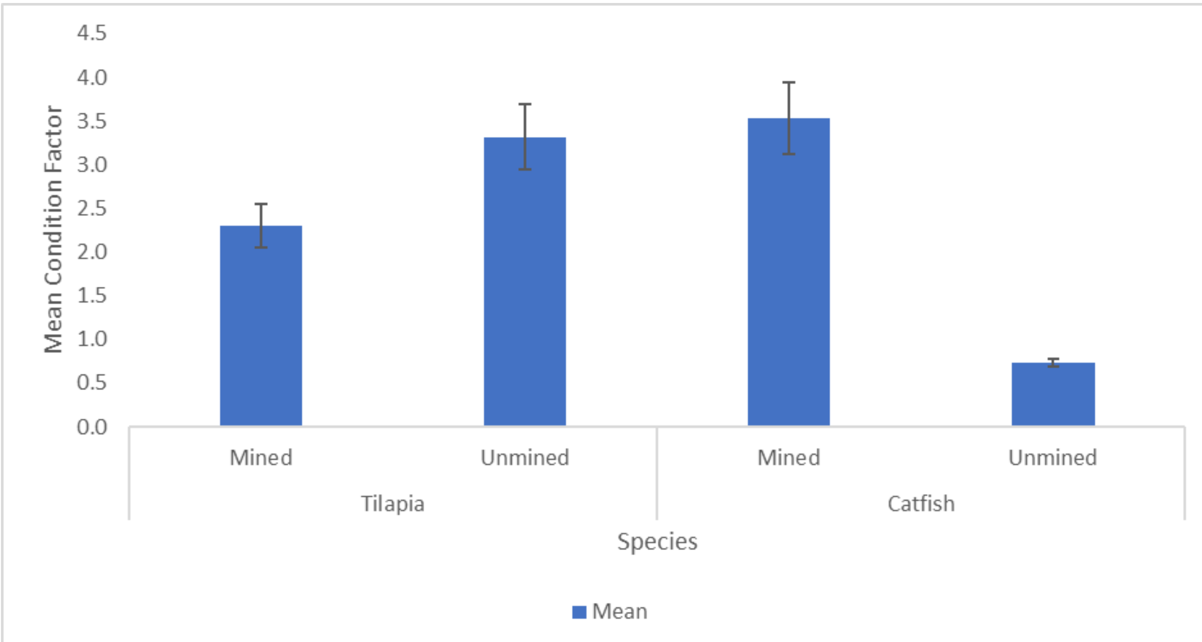

Fig. 9. Condition factor of sampled fish species from mined and unmined sampling locations

3.3 Morphometric comparison between catfish from mined and unmined streams

The average head length, tail fin, dorsal fin, pelvic fin, pectoral fin, anal fin and snout length of catfish species from the mined sampling locations was 2.0, 1.8, 9.1, 1.0, 1.8, 6.9 and 1.0mm, respectively (Fig. 10). From the unmined sampling locations, the average head length, tail fin, dorsal fin, pelvic fin, pectoral fin, anal fin and snout length of catfish species was 74.1, 78.4, 160. 2, 54.8, 66.8, 162.5, and 40.4mm, respectively (Fig. 10). Sample t-test analysis showed significant difference in morphometric measurement of catfish species from both mined and unmined sampling locations ($P< 0.05$).

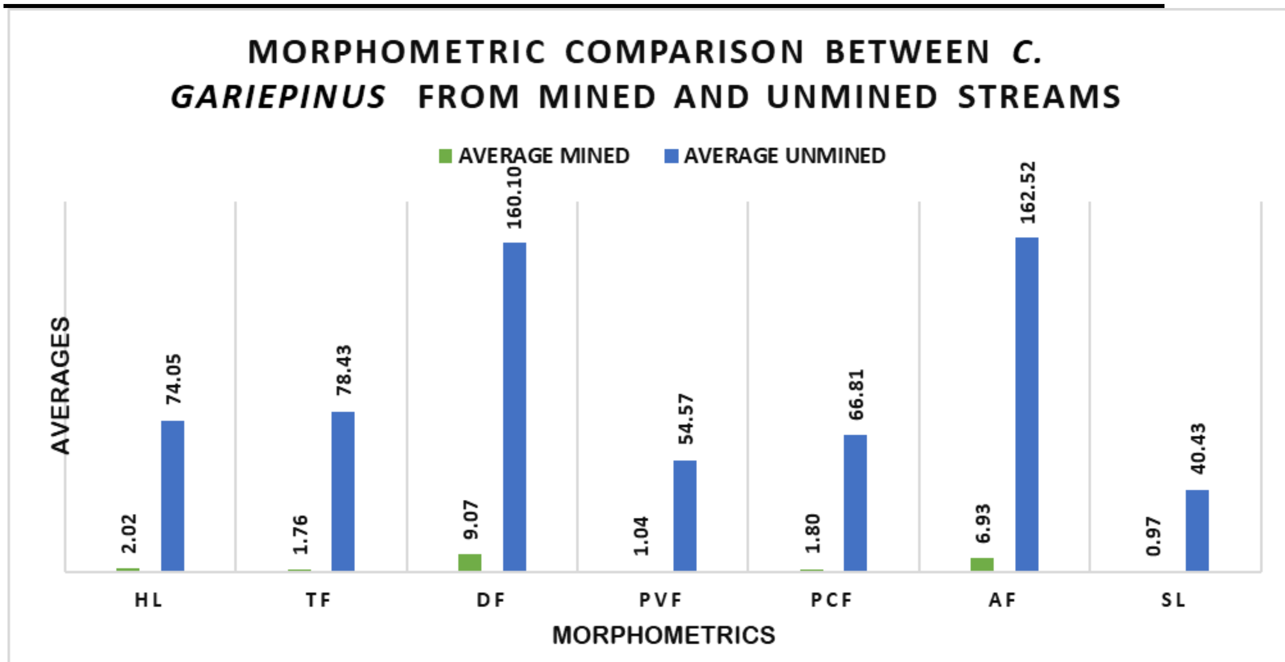

Fig. 1. Morphometric commparison between *C. gariepinus* from mined and unmined streams. *SL* = **SNOUT LENGTH; AF= ANAL FIN; PcF = PECTORIAL FIN; PvF = PELVIC FIN; DF = DORSAL FIN; TF = TAIL FIN; HL = HEAD LENGTH**

3.4 Morphometric comparison between Oreochromis niloticus from mined and unmined streams

The average head length of tilapias species from the mined and unmined sampling locations was 53. 2 and 54.3mm, respectively (Fig. 11). The average tail fin of tilapias species from the mined and unmined sampling locations was 41.9 and 43.9mm, respectively (Fig. 11). The average dorsal fin of tilapias species from the mined and unmined sampling locations was 122.9 and 128.3mm, respectively (Fig. 11). The average pelvic fin of tilapias species from the mined and unmined sampling locations was 52.3 and 55.5mm, respectively (Fig. 11). The average pectoral fin of tilapias species from the mined and unmined sampling locations was 50.2 and 51.5mm, respectively (Fig. 11). The average anal fin of tilapias species from the mined and unmined sampling locations was 57.0 and 60.0mm, respectively (Fig. 11). The average snout length of tilapias species from the mined and unmined sampling locations was 27.2 and 31.4mm, respectively (Fig. 11). Sample t-test analysis showed no significant difference in morphometric measurement of tilapia species from both mined and unmined sampling locations ($P < 0.05$).

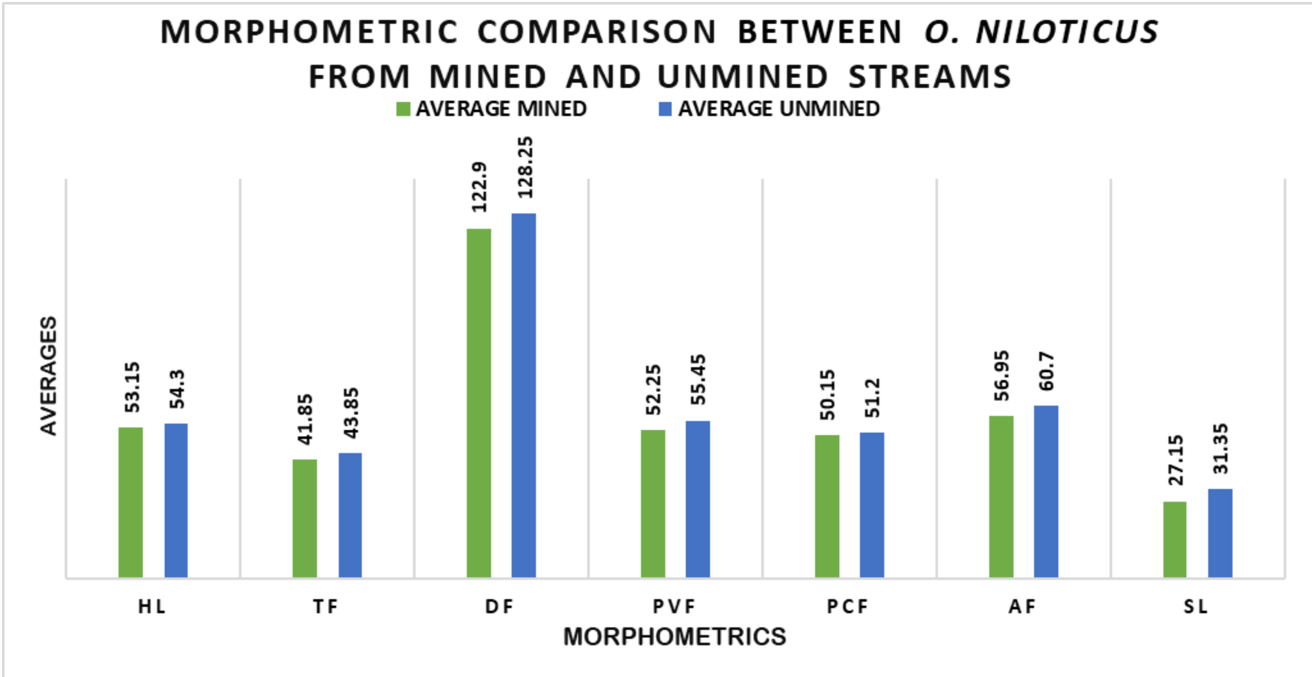

Fig. 11. Morphometric comparison between *Oreochromis niloticus* from mined and unmined streams. **SL = SNOUT LENGTH; AF= ANAL FIN; PcF = PECTORIAL FIN; PvF = PELVIC FIN; DF = DORSAL FIN; TF = TAIL FIN; HL = HEAD LENGTH**.

DISCUSSION

1. Physicochemical parameters

Water pH levels in both mined and unmined streams were slightly acidic, ranging from 6.12 to 6.36. The mined stream consistently recorded higher pH values, which may be attributed to reduced organic matter input following vegetation removal. In contrast, the slightly lower pH values in the unmined stream could result from agricultural activities, such as cocoa farming, which contribute to soil acidification through fertilizer runoff **(Wang *et al.*, 2019)**. Although these values fall within the tolerance range for *Oreochromis niloticus* and *Clarias gariepinus*, chronic exposure may still induce metabolic stress in fish **(Huang *et al.*, 2018)**.

Dissolved oxygen (DO) concentrations were relatively high in both streams, ranging between 10.63 and 12.72 mg/L. Despite active mining, DO levels in the mined stream remained above optimal thresholds, likely due to the reduced input of organic material, which minimizes oxygen depletion **(Jackson, 2007)**. Elevated DO in the unmined stream may be attributed to the presence of tree canopy cover, which lowers water temperature and enhances oxygen retention **(Kolditz *et al.*, 2008)**. These observations suggest that, in this instance, mining activities have not critically impaired oxygen availability required for fish survival.

Total suspended solids (TSS) levels were significantly elevated in mined streams (2,350 to 3,543mg/ L) compared to the unmined streams (10 to 15mg/ L). This increase is likely due to sediment runoff from disturbed soils during mining. High TSS can reduce light penetration, impair aquatic photosynthesis, and clog fish gills, leading to respiratory stress and reduced growth **(Bilotta & Brazier, 2008)**. In contrast, vegetation in unmined areas acts as a natural buffer, filtering sediment and stabilizing TSS levels **(Lee *et al.*, 2015)**.

Mining also influenced total dissolved solids (TDS) levels, introducing dissolved metals and salts into the water. Elevated TDS in mined streams is commonly linked to runoff and leaching from mining activities **(Nguyen *et al.*, 2018)**. High TDS disrupts osmotic balance, which affects ion regulation critical to the growth and metabolic function of fish species such as tilapia and catfish **(Mohamed & Abo-State, 2017)**.

Turbidity levels were markedly higher in mined streams (4,023 to 4,116 NTU) compared to unmined streams (16.5 to 21.2 NTU). This is attributed to sediment-heavy runoff from mining operations **(Simate *et al.*, 2011)**. Although high turbidity can block sunlight and inhibit aquatic photosynthesis—potentially reducing oxygen levels—DO concentrations in this study remained high. This contradiction may be explained by surrounding forest cover, which helps moderate temperature and oxygen levels **(Li *et al.*, 2020)**.

Both potassium and sodium concentrations were elevated in mined streams, likely due to soil disturbance and mineral release during mining operations **(Adamu *et al.*, 2018)**. High levels of these ions disrupt osmotic regulation and impose stress on fish physiology **(Griffiths *et al.*, 2017)**. In contrast, the lower nutrient levels in unmined streams reflect a more stable and undisturbed ecosystem with intact riparian zones.

Ammonia concentrations were also significantly higher in mined streams, likely due to runoff containing explosives and other mining chemicals. Elevated ammonia impairs gill function and reduces respiratory efficiency in fish **(Jensen, 2017)**. Similarly, nitrite levels increased downstream of mined areas, where mining effluents enter the stream system **(Balistrieri *et al.*, 2020)**. High nitrite levels interfere with oxygen transport in fish blood, leading to reduced growth and survival **(Zhou *et al.*, 2022)**.

Mercury and arsenic levels were substantially higher in mined streams due to soil disruption during extraction. These heavy metals bioaccumulate in fish tissue, leading to neurological and reproductive impairments **(Monteiro *et al.*, 2019)**. Mercury toxicity can cause motor dysfunction and behavioral abnormalities, affecting fish survival **(Clarkson & Magos, 2018)**.

Lead and cadmium also showed significant increases in mined waters, interfering with bone formation and reducing survival rates in fish **(Wu *et al.*, 2020)**. Elevated copper and zinc concentrations were also observed. While essential in trace amounts, excessive copper induces oxidative stress and developmental deformities **(Zhang & Wang, 2018)**. These findings confirm that mining activities significantly increase the risk of heavy metal toxicity in aquatic ecosystems.

Cyanide levels were higher in mined streams, primarily from leaching during gold extraction. Even low concentrations of cyanide impair cellular respiration, causing developmental deformities in fish **(Benson *et al.*, 2018)**. Lower cyanide concentrations in unmined streams reflect a more favorable aquatic environment conducive to healthy fish growth and metabolism **(Shokrzadeh *et al.*, 2020)**.

2. Condition factor of fish species

According to **LeCren (1951)**, a condition factor (K) greater than 1 indicates that a fish is in sound physiological condition. In this study, *O. niloticus* (tilapia) from both mined and unmined streams recorded condition factors above 1, suggesting general physiological well-being. However, for *C. gariepinus* (catfish), only individuals from the mined streams recorded K values above 1, while those from unmined streams recorded values below 1.

This disparity may be attributed to increased competition for food among larger individuals in the unmined stream, which can reduce nutritional uptake and affect condition factors **(Rueda *et al.*, 2015; Andrades *et al.*, 2023)**. Such competition is known to negatively affect fish condition in resource-limited environments **(Stoner, 2004; Koehnken *et al.*, 2020)**.

3. Morphometric comparisons between mined and unmined streams

Fish from mined streams exhibited notable morphological changes. *C. gariepinus* (catfish) showed significant reductions in head length, fin size, and overall body proportions. These reductions are likely due to energy reallocation in response to toxic exposure, particularly from heavy metals like mercury and lead, which impair growth and development **(Nguyen *et al.*, 2019)**. Reduced fin sizes can limit mobility and foraging capacity, decreasing survival potential.

Similarly, *O. niloticus* (tilapia) from mined areas displayed smaller morphometric features, including head length, fins, and total body dimensions. These reductions point to impaired growth due to bioaccumulation of toxins and related metabolic stress **(Mohamed & Abo-State, 2017)**. The degree of morphometric reduction in tilapia was less severe than that observed in catfish, indicating species-specific tolerance or response mechanisms.

CONCLUSION

This study highlights the significant impact of mining activities on the health, growth, and morphology of *Clarias gariepinus* (African catfish) and *Oreochromis niloticus* (The Nile tilapia) in mined versus unmined stream environments. Fish from mined streams exhibited notably reduced growth in morphometric features, such as head length, tail fin, dorsal fin, and other key fin structures, which are essential for swimming, foraging, and predator evasion. These findings suggest that exposure to mining-related pollutants, particularly heavy metals, is linked to stunted growth and impaired physiological development in fish species.

The study's results indicate that heavy metal contamination in mined streams likely diverts energy from growth and reproduction toward detoxification and managing oxidative stress. Smaller pectoral and pelvic fins observed in fish from mined streams suggest limited mobility, impacting their feeding efficiency, adaptability, and overall fitness. In contrast, fish from unmined streams displayed healthier growth patterns, with larger morphometric measurements and robust physiological health, indicating a more stable and supportive environment for development.

The findings underline the broader ecological consequences of mining on aquatic ecosystems, demonstrating how pollutants disrupt growth and morphology, ultimately compromising the long-term survival of fish populations. This study provides essential insights into the vulnerabilities of aquatic ecosystems in mining regions, reinforcing the need for interventions to protect these habitats from degradation.

Recommendations

To further understand and mitigate the adverse effects of mining on aquatic ecosystems, the following actions are recommended:

- Further Research on Gill Health: Future studies should focus on examining the impact of heavy metals and other mining contaminants on the gill structures of catfish and tilapia, as gill health directly influences respiratory efficiency and overall fish health.

- Analysis of Heavy Metal Concentrations in Fish Tissues: Research should investigate the specific concentrations of mining-induced heavy metals within fish tissues, which would provide critical data on bioaccumulation risks and potential health implications for consumers.

- Community Education: Initiatives to educate community members in mining regions about the risks associated with consuming fish from polluted environments should be implemented. Awareness programs can help reduce health risks by informing communities of the potential dangers of heavy metal exposure through diet.

- Investigation into Sustainable Land Use Practices: Continued research into alternative land use practices, such as reforestation, agroforestry, and establishing riparian buffers, can be effective in reducing the environmental impact of mining. These practices could help stabilize soil, filter pollutants, and improve water quality, ultimately supporting healthier aquatic ecosystems.

These recommendations are critical for enhancing the understanding of mining impacts on aquatic life and informing policies and practices to protect the health of both ecosystems and human populations reliant on these resources.

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