THE IRAQI JOURNAL OF
VETERINARY MEDICINE
eISSN:2410-7409
pISSN: 1609-5693

OPEN ACCESS

Heavy Metals Contamination and Biometric Characteristics of Marine Fish in The Industrial Waters of Aceh Province, Indonesia

Muliari Muliari*[1,2], Muchammad Yunus[3], Epy M Luqman[3], Mahdaliana Mahdaliana[4], Irfannur Irfannur[5], Yusrizal Akmal[5], Akmal Izwar[5], Muhammad Radhi[5], Agung S Batubara[6]

[1]Sains Veterinary Doctoral Program, Faculty of Veterinary Medicine, Universitas Airlangga, Surabaya, Indonesia, [2]Department of Marine Science, Faculty of Agriculture, Universitas Malikussaleh, Aceh Utara, Indonesia, [3]Department of Veterinary Science, Faculty of Veterinary Medicine, Universitas Airlangga, Surabaya, Indonesia, [4]Department of Aquaculture, Faculty of Agriculture, Universitas Malikussaleh, Aceh Utara, Indonesia, [5]Department of Aquaculture, Faculty of Agriculture, Universitas Almuslim, Bireuen, Indonesia, [6]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Negeri Medan, North Sumatra, Indonesia

***Correspondence**:
muliari@unimal.ac.id
Received: 16.October 2025
Revised: 28.November 2025
Accepted:12.April 2026
Published:28 June 2026

DOI:
https://doi.org/10.30539/e8s7zg43

Cite:
Muliari M, Yunus M, Luqman EM, Mahdaliana M, Irfannur I, Akmal Y, Izwar A, Radhi M, Batubara AS. Heavy metals contamination and biometric characteristics of marine fish in the industrial waters of Aceh province, Indonesia. Iraqi J. Vet. Med. 2026;50(1):28-34.

ABSTRACT

Trevally (*Caranx ignobilis*), mackerel (*Rastrelliger* sp.), and grouper (*Epinephelus fuscoguttatus*) are commercially important species, and their habitats in the waters of North Aceh and Lhokseumawe Regency are potentially disturbed by industrial activities. This study was conducted to evaluate heavy metals contamination, fish biometrics and growth patterns. Data and samples were collected using the purposive sampling method. The data collection points were at four locations including station 1 PT Pupuk Iskandar Muda, station 2 PT ASEAN Aceh Fertilizer, station 3 PT Kertas Kraft Aceh, and station 4 PT Arun Natural Gas Liquefaction. The results of biometric analysis including GiSI (Gill Somatic Index), GSI (Gonado Somatic Index), GaSI (Gastro Somatic Index), ISI (Intestine Somatic Index), RGL (Relative Gut Lengths), and RIL (Relative Intestine Lengths) showed significant differences in trevally, mackerel, and grouper fish based on four research locations. The growth pattern of trevally and mackerel fish is negative allometric ($b < 3$), while grouper is positive allometric ($b > 3$). The condition factors of trevally, mackerel and grouper fish at the four stations indicated the good condition. Based on research results, the heavy metal (Pb, Cd, and Hg) content in the meat of trevally, mackerel and grouper fish, with the average content was still below quality standards.

Keywords: allometric, condition factors, heavy metal, industrial area, marine fishes

INTRODUCTION

North Aceh and Lhokseumawe Regency are potential areas in the field of marine and fisheries, such as large and small pelagic fish. The production of small pelagic fish includes mackerel, snapper, grouper, scad, yellowfin, spanish mackerel, and sardines (**1**), while large pelagic fish includes tuna (**2**). Pelagic fish are an export commodity and play a crucial role in global food security (**3-5**). The resources of pelagic fish are limited, thus requiring management for sustainability (**6**).

North Aceh and Lhokseumawe Regency are also one of the industrial areas in Aceh Province based on several industries that operate there, such as PT Pupuk Iskandar

Muda, PT ASEAN Aceh Fertilizer, PT Kertas Kraft Aceh, and PT Arun Natural Gas Liquefaction, which is now part of the Arun Lhokseumawe Special Economic Zone. The massive development of industrial areas can increase pollution caused by industrial waste disposal (**7**). Heavy metals are found in aquatic environments due to contamination from industrial waste, agriculture, and household product waste (**8**). Heavy metal pollution is a serious problem for the environment (**9**).

The waters of North Aceh and Lhokseumawe Regency contain several economically important fish that are utilized by the local community, such as mackerel, scad, and grouper. Scad is classified as an economic resource derived from coastal waters. The mackerel has become one of the target catches for fishermen (**10**). Grouper (*Epinephelus* spp.) is an economically important fish and is widely consumed by the community (**11**). However, industrial activities in the regions of North Aceh and Lhokseumawe Regency are predicted to pollute fish resources, such as heavy metal contamination in fish. The presence of heavy metals in aquatic environments can include Fe, Zn, Cu, Mn, Cd, Pb, Cr, Ni, Hg, and As (**12**), with Pb, Cd, Hg, As, and Cr being the five most toxic heavy metals found in fish flesh (**13,14**). Monitoring of toxic heavy metals in fish samples is very important from the perspectives of nutrition and toxicology (15). This monitoring is aimed at avoiding health hazards caused by toxic heavy metals through fish consumption (**16,17**).

This research aims to determine the population structure and growth patterns, as well as the heavy metal content of Pb, Cd, and Hg in three economically important fish species, namely the trevally (*Caranx ignobilis*), mackerel (*Rastrelliger* sp.), and grouper (*Epinephelus fuscoguttatus*) in the waters of the industrial area of North Aceh and Lhokseumawe Regency. The structure of the population and growth patterns of important fish species are essential for resource management and conservation (**18**). Fish stock assessment is measured based on biological population and fishing catch patterns (**19**), where studies are conducted on biometry, condition factors, and the length-weight relationship of fish (**20**). Population information aims for fisheries management (**21**), providing accurate assessment and objective management of fishery resources (**22,23**).

Materials And Methods

Site and Time

This study was conducted from June to August 2024. Data collection and sampling were conducted using the purposive sampling method. The data collection points during the research were located at four stations around the industrial area: the station I at PT Pupuk Iskandar Muda, the station II at PT ASEAN Aceh Fertilizer, the station III at PT Kertas Kraft Aceh, and the station IV at PT Arun Natural Gas Liquefaction (**Figure 1**). All sampling procedures were reviewed and approved by the Committee of Ethics for animals used in the Department of Marine Science, Faculty of Agriculture, Universitas Malikussaleh (ref: 39/UN45.2.5/KP.10.00/2024), which confirmed that the study fulfilled all ethical feasibility requirements.

Samples were collected from catches made directly by fishermen and landed in fresh condition. The capture technique was carried out using gillnets and fishing gear. As the samples were wild-caught, details regarding housing and husbandry conditions were not applicable. The primary species sampled were trevally (*C. ignobilis*), mackerel (*Rastrelliger* sp.), and grouper (*E. fuscoguttatus*). A total of 40 samples were collected for each species. The mean body length and weight (± SD) for *C. ignobilis* were 28 ± 8.96 cm and 133 ± 33.34 g, respectively. Rastrelliger sp. samples averaged 21 ± 1.62 cm and 128 ± 26.58 g, while *E. fuscoguttatus* samples averaged 26 ± 5.05 cm and 238 ± 20.87 g.

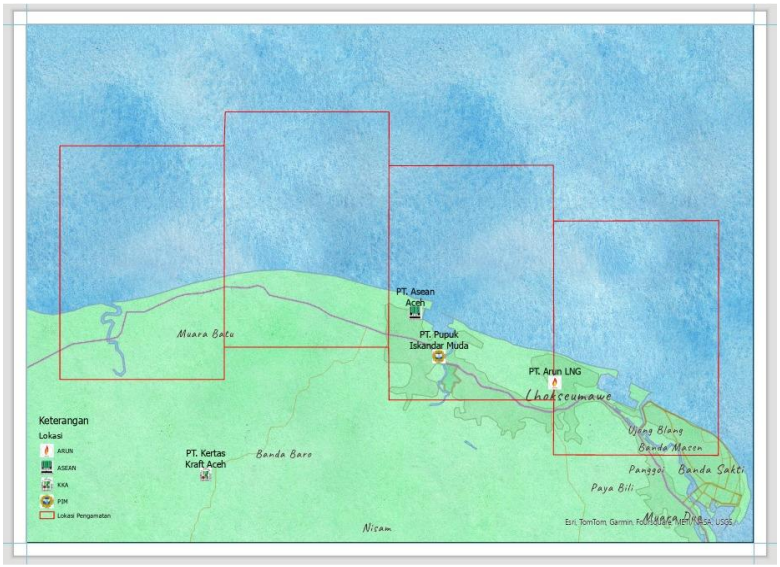

Figure 1. Four research stations are located within the industrial area of North Aceh and Lhokseumawe Regency, with details as follows: Station I is PT Pupuk Iskandar Muda, Station II is PT ASEAN Aceh Fertilizer, Station III is PT Kertas Kraft Aceh, and Station IV is PT Arun Natural Gas Liquefaction

Analysis of Biometric, Length-Weight Relationship, and Condition Factors

The observed biometric parameters include Gill Somatic Index (GiSI), Gonadosomatic Index (GSI), Gastrosomatic Index (GaSI), Hepatosomatic Index (HSI), Intestinal Somatic Index (ISI), Relative Gut Length (RGL), and Relative Intestinal Length (RIL). The formulas used in the analysis of GiSI, GSI, GaSI, and RGL are based on (**24**), ISI, and RIL are based on the formula by (**25**). In this analysis, 10 fish samples per species were measured at each location.

iSI =Gill weight gTotal body weight of fish g×100

$$GSI = \frac{Gonad\ weight\ (g)}{Total\ body\ weight\ of\ fish\ (g)} \times 100$$

$$GaSI = \frac{Stomach\ weight\ (g)}{Total\ body\ weight\ of\ fish\ (g)} \times 100$$

$$ISI = \frac{Intestinal\ weight\ (g)}{Total\ body\ weight\ of\ fish\ (g)} \times 100$$

$$HSI = \frac{Liver\ weight\ (g)}{Total\ body\ weight\ of\ fish\ (g)} \times 100$$

$$RGL = \frac{Stomach\ length\ (cm)}{Total\ length\ of\ fish\ (cm)} \times 100$$

$$RIL = \frac{Intestinal\ length\ (cm)}{Total\ length\ of\ fish\ (cm)} \times 100$$

The analysis of the length-weight relationship of fish is determined using the functional equation as described by (26): $W = aL^b$, where: W is body weight in grams (g), L is total length in millimetres (mm), a is the regression intercept (which indicates the initial growth index or condition factor), and b is the regression slope which represents the allometric growth coefficient. To characterize the growth pattern, the allometric growth coefficient (b) was statistically tested against the theoretical isometric value of 3 using the Student's t-test.

The physiological condition and relative fatness level (plumpness) of fish are assessed using the condition factor (K). This index was calculated utilizing the parameters derived from the length-weight relationship, with K as the condition factor, W as the observed body weight (g), L as the total length (mm), and a and b as the computed constants from the LWR equation: $K = \frac{W}{aL^b}$.

Analysis of Heavy Metals Content Pb, Cd, and Hg

Analysis of heavy metals contamination in fish was carried out using the atomic absorption spectrophotometry (AAS) method (Shimadzu AA-7000, Japan). Three samples per species were tested at each location. Fish tissue (fish muscle tissue) was washed using distilled water. The ashing process was carried out using a furnace at a temperature of 500°C until all samples became ash. The samples were then destroyed with nitric acid (HNO_3, 65% Suprapur®, Merck, Germany) and hydrochloric acid (HCl, 37% ACS reagent, Indonesia) solvents. Destruction is carried out to break down the form of metal compounds into inorganic metals so that they can be analyzed (**27**). The fish ash sample was then dissolved using nitric acid in a ratio of 1:1 and transferred into a 100 mL measuring flask homogenized with distilled water. The sample was filtered using Whatman filter paper (no. 42, Whatman plc, UK) into a test tube. After that, the AAS reading process begins when the fire button is pressed and the tool will work (this process lasts around 5-10 min) until the results can be seen on the monitor layer (**28**).

Statistical Analysis

The resultant data on heavy metals concentrations (Pb, Cd, and Hg) and biometric indices were subjected to statistical analysis, specifically an Analysis of Variance (ANOVA), utilizing SPSS software (Version 22). Parameters that showed significant differences were then further tested by Duncan post-hoc test. This study was limited by samples collected at four research sites and did not involve control samples.

RESULTS

Biometric Parameters of Gills, Gonads, Stomach and Intestines

The analysis of biometric parameters for trevally, summarized in **Table 1**, revealed that only the GiSI and HSI exhibited statistically significant differences ($P < 0.05$) among the four sampling stations. Conversely, the GSI, GaSI, ISI, RGL, and RIL showed no significant variations ($P > 0.05$) across the locations. For the parameters with significant differences, the mean GiSI was highest at Station 2 (46.4±10.6), which was significantly greater than the mean value at Station 3 (22.2±17.2). The mean HSI was highest at Station 1 (14.7±3.42), a value significantly elevated compared to that of Station 3 (7.25±6.50). Although not showing statistical significance, the highest average values for other indices were observed at Station 4 for GSI (19.3±10.7), Station 2 for GaSI (20.7±4.52) and ISI (5.01±0.55), Station 1 for RGL (24.7±3.76), and Station 3 for RIL (46.8±6.60).

Table 1. Biometric parameters of trevally fish at four research locations in the industrial area of North Aceh and Lhokseumawe Regency, Indonesia

Biometrics	Station 1	Station 2	Station 3	Station 4
GiSI	40.9±10.7 ^{ab}	46.4±10.6 ^{b}	22.2±7.21 ^{a}	37.4±9.06 ^{ab}
GSI	16.8±11.8 ^{a}	10.2±5.82 ^{a}	4.98±2.30 ^{a}	19.3±10.7 ^{a}
GaSI	18.3±3.96 ^{a}	20.7±4.52 ^{a}	17.0±6.15 ^{a}	18.4±4.09 ^{a}
ISI	4.82±0.80 ^{a}	5.01±0.55 ^{a}	3.76±2.53 ^{a}	4.55±0.49 ^{a}
HSI	14.7±3.42 ^{b}	14.0±1.67 ^{ab}	7.25±6.50 ^{a}	14.1±2.09 ^{ab}
RGL	24.7±3.76 ^{a}	22.1±3.55 ^{a}	18.6±5.40 ^{a}	23.9±4.05 ^{a}
RIL	35.9±10.5 ^{a}	44.1±3.99 ^{a}	46.8±6.60 ^{a}	39.4±10.5 ^{a}

Values are mean±SEM. Different superscripts indicate significant differences in the same row. GiSI: Gill Somatic Index, GSI: Gonadosomatic Index, GaSI: Gastrosomatic Index , HIS: Hepatosomatic Index, ISI: Intestinal Somatic Index, RGL: Relative Gut Length, RIL: Relative Intestinal Length

Different biometric analysis results were shown in mackerel (*Rastrelliger* sp.), where wide statistical differences were observed across sampling sites (**Table 2**). Six of the seven parameters tested (GiSI, GSI, GaSI, ISI, RGL, and RIL) showed significant differences ($P < 0.05$), while HSI was the only parameter that was not statistically significantly different ($P > 0.05$) across the four research stations. The highest mean values for several indices were recorded at Station 1, including GiSI (3.67±0.23), GSI (3.77±1.09), and ISI (1.04±0.07). Post-hoc analysis showed these values were significantly higher than at one or more of the other stations. Conversely, Station 4 showed the highest mean values for GaSI (5.19±3.1) and RGL (18.68±1.54), both of which were significantly higher compared to the other locations. Finally, the highest mean RIL value was observed at Station 2 (48.87±8.16), while the results in station 4 were significantly higher.

Table 2. Biometric parameters of mackerel fish at four research locations in the industrial area of North Aceh and Lhokseumawe Regency, Indonesia

Biometrics	Station 1	Station 2	Station 3	Station 4
GiSI	3.67±0.23 ^{b}	3.20±0.18 ^{ab}	2.82±0.34 ^{a}	2.94±0.60 ^{a}
GSI	3.77±1.09 ^{b}	1.91±1.45 ^{a}	2.26±0.44 ^{a}	1.88±1.08 ^{a}
GaSI	0.85±0.13 ^{a}	2.28±3.21 ^{ab}	0.75±0.23 ^{a}	5.19±3.10 ^{b}
ISI	1.04±0.07 ^{b}	0.95±0.12 ^{ab}	0.87±0.48 ^{ab}	0.66±0.14 ^{a}
HSI	1.16±0.33 ^{a}	1.33±0.48 ^{a}	1.23±0.22 ^{a}	1.18±0.24 ^{a}
RGL	10.8±0.48 ^{a}	13.7±4.95 ^{a}	12.9±0.49 ^{a}	18.7±1.54 ^{b}
RIL	44.6±3.11 ^{b}	48.9±8.16 ^{b}	44.1±8.89 ^{b}	26.6±6.82 ^{a}

Values are mean±SEM. Different superscripts indicate significant differences in the same row. GiSI: Gill Somatic Index, GSI: Gonadosomatic Index, GaSI: Gastrosomatic Index , HIS: Hepatosomatic Index, ISI: Intestinal Somatic Index, RGL: Relative Gut Length, RIL: Relative Intestinal Length

Statistical analysis of biometric parameters for grouper, presented in **Table 3**, shows that most indices are homogeneous across the four sampling stations. Only two parameters, GiSI and HSI, showed statistically significant differences ($p < 0.05$). The other five parameters (GSI, GaSI, ISI, RGL, and RIL) did not show significant variation ($p > 0.05$) among the locations. For the parameters showing significant differences, the mean GiSI was highest at Station 1 (4.14±1.27), a value significantly greater than those recorded at Station 2 (2.72±0.34) and Station 3 (2.94±0.59). The HSI was highest at Station 2 (1.40±0.23), which was significantly higher than the mean values at Station 1 (0.96±0.26) and Station 4 (0.89±0.29). Although no statistically significant differences were found for the other indices, the highest mean numerical values were observed at Station 2 for GSI (0.82±0.94), GaSI (1.78±1.18), and RIL (88.2±10.8); at Station 4 for ISI (1.14±0.23); and at Station 3 for RGL (15.0±5.84).

Table 3. Biometric parameters of grouper fish at four research locations in the industrial area of North Aceh and Lhokseumawe Indonesia

Biometrics	Station 1	Station 2	Station 3	Station 4
GiSI	4.14±1.27 ^{a}	2.72±0.34 ^{b}	2.94±0.59 ^{b}	3.57±0.66 ^{ab}
GSI	0.50±0.77 ^{a}	0.82±0.94 ^{a}	0.80±0.96 ^{a}	0.43±0.81 ^{a}
GaSI	1.50±0.63 ^{a}	1.78±1.18 ^{a}	1.45±1.07 ^{a}	1.32±0.46 ^{a}
ISI	0.73±0.35 ^{a}	1.10±0.21 ^{a}	0.74±0.27 ^{a}	1.14±0.23 ^{a}
HSI	0.96±0.26 ^{b}	1.40±0.23 ^{a}	1.26±0.35 ^{a}	0.89±0.29 ^{b}
RGL	14.1±2.82 ^{a}	13.9±3.78 ^{a}	15.0±5.84 ^{a}	13.6±1.85 ^{a}
RIL	73.6±9.48 ^{a}	88.2±10.8 ^{a}	78.2±4.88 ^{a}	84.9±18.9 ^{a}

Values are mean±SEM. Different superscripts indicate significant differences in the same row

Analysis of Allometric Growth and Condition Factors

The results of the analysis of the length-weight relationship and condition factors in trevally, mackerel, and grouper were carried out on 40 fish/species, respectively. The growth pattern of trevally and mackerel is negative allometric ($b < 3$), while grouper is positive allometric ($b > 3$) (**Table 4 and Figure 2**). The condition factors of trevally, mackerel and grouper at the four stations indicate the good condition of the fish when viewed in terms of physical capacity for survival and reproduction. The condition factors of the three species of fish at the four stations are trevally reach of 1.03±0.10, mackerel reach of 1.02±0.08, and grouper reach of 0.96±0.19.

Table 4. Length-weight relationship, condition factors, and growth patterns of trevally, mackerel, and grouper

Parameters	Species		
	Trevally	Mackerel	Grouper
n	40	40	40
a	0.0396	0.0446	0.0079
b	2.6879	2.58	3.1607
R^2	0.942	0.775	0.9327
Growth pattern	Negative allometric	Negative allometric	Positive allometric
Condition factors	1.03±0.10 ^{a}	1.02±0.08 ^{a}	0.96±0.19 ^{b}

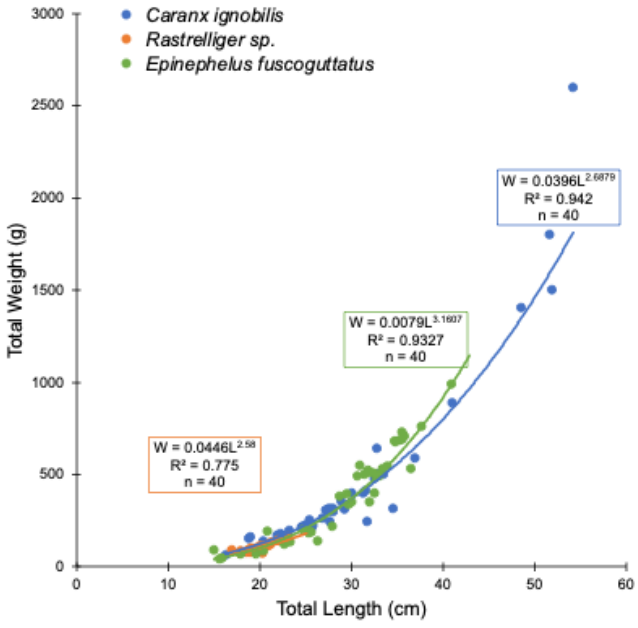

Figure 2. Linear allometric model analysis (LAM) of trevally (blue line), mackerel (orange line), and grouper (green line)

Heavy Metals Content of Fish Muscle Tissue

Based on research results, the heavy metals content in the muscle tissue of trevally, mackerel and grouper fish, with the average content still below quality standards. The content of the heavy metals trevally fish was highest at station 2 reach of 0.17±0.10, with a Pb quality standard of

0.30. Furthermore, the highest heavy metal Cd content was found at station 1 at 0.05 ± 0.01, with a Cd quality standard of 0.10. The highest Hg heavy metal content was found at station 3 at 0.08 ± 0.02, with an Hg quality standard of 0.50 (**Table 5**).

The results of the analysis of the heavy metal content in mackerel muscle tissue were the highest heavy metal Pb at station 4 reach of 0.17±0.02, with a Pb quality standard of 0.30. Furthermore, the highest heavy metal Cd content was found at stations 2 and 4 at 0.05±0.01, with a Cd quality standard of 0.10. The highest Hg heavy metal content was found at stations 1 and 3 at 0.07±0.02, with an Hg quality standard of 0.50 (**Table 5**).

The results of the analysis of the heavy metals content in the flesh of grouper fish were that the highest heavy metal Pb was at station 1 reach of 0.12±0.01, and station 3 was 0.12±0.01, with a Pb quality standard of 0.30. Furthermore, the highest heavy metal Cd content was found at station 4 reach of 0.05±0.01, with a Cd quality standard of 0.10. The highest Hg heavy metal content was found at stations 1, 3, and 4 reach of 0.07±0.03, with an Hg quality standard of 0.50 (**Table 5**).

Based on the research results, the content of heavy metals Pb, Cd, and Hg in trevally fish, mackerel fish, and grouper fish were not significantly different ($P < 0.05$). The highest concentration of the heavy metal Pb was in trevally reaching 0.121 ± 0.05, then the highest heavy metal content Cd was in mackerel reaching 0.043±0.01, and the highest heavy metal content Hg was in grouper reaching 0.068±0.02 (**Table 5**).

Table 5. Heavy metal content in muscle tissue of trevally fish, mackerel fish, and grouper fish

		Heavy metal concentration (mg/kg)		
Fish species	**Research location**	**Pb**	**Cd**	**Hg**
Trevally fish	Station 1	0.13±0.04 [b]	0.05±0.01 [a]	0.07±0.02 [a]
	Station 2	0.17±0.01 [a]	0.03±0.01 [c]	0.05±0.02 [a]
	Station 3	0.06±0.04 [c]	0.03±0.01 [c]	0.08±0.02 [a]
	Station 4	0.12±0.01 [b]	0.04±0.01 [b]	0.06±0.03 [a]
	Quality standard	0.3	0.1	0.5
Mackerel fish	Station 1	0.08±0.04 [b]	0.04±0.01 [b]	0.07±0.01 [a]
	Station 2	0.10±0.04 [b]	0.05±0.01 [a]	0.06±0.03 [a]
	Station 3	0.09±0.03 [b]	0.03±0.01 [b]	0.07±0.02 [a]
	Station 4	0.17±0.02 [a]	0.05±0.01 [a]	0.06±0.03 [a]
	Quality standard	0.3	0.1	0.5
Grouper fish	Station 1	0.12±0.01 [a]	0.04±0.01 [b]	0.07±0.03 [a]
	Station 2	0.10±0.04 [a]	0.04±0.01 [b]	0.06±0.02 [a]
	Station 3	0.12±0.03 [a]	0.04±0.01 [b]	0.07±0.03 [a]
	Station 4	0.05±0.03 [b]	0.05±0.01 [a]	0.07±0.03 [a]
	Quality standard	0.3	0.1	0.5

Values are mean±SEM. Different superscripts indicate significant differences in the same column

DISCUSSION

Biometric analysis is important in providing information about fish population growth (**29,30**). Biometric analysis, namely the length-weight relationship, shape, and condition factors (**31**). Fish biometric data for fisheries management such as identifying fish population structure (**32**). Fish species taken at the research location are economically important resources in the waters of North Aceh and Lhokseumawe Regency.

The growth pattern of fish in the research location in the industrial area of North Aceh and Lhokseumawe Regency reveal that the trevally and mackerel is negative allometric, while grouper is positive allometric. In the waters of the Sape Strait, Bima Regency, the growth pattern of trevally is negative allometric (**33**), in the waters of Labu Deli Serdang the growth pattern of mackerel is negative allometric (**34**). The growth pattern of Rastrelliger spp. is negative allometric at each location (**35**). In contrast to grouper fish (*Cephalopolis sonnerati*) which are landed in the waters of Lhok Peukan Bada, Aceh Besar Regency, their growth pattern is negative allometric (**36**). In the waters of Wayaban, Misool, Raja Ampat, grouper fish that are landed, such as *Cephalopholis sexmaculata*, *Cephalopholis argus*, and *Plectropomus leopardus* are isometric (**37**).

The condition factor of the fish at the 4 stations consisted of PT Pupuk Iskandar Muda, PT ASEAN Aceh Fertilizer, PT Kertas Kraft Aceh, and PT Arun Natural Gas Liquefaction where the type of trevally fish with a total of 1.03±0.10, concluding that the condition of the fish was healthy. Mackerel with a total of 1.02±0.08, and grouper with a total of 0.96±0.19. The condition factor value for the condition of trevally is an average of 1.3, indicating that the overall biological condition of the fish is in good health (**38**). The average value of 1.41 indicates that the grouper's body is less flat and fleshy and is still growing. This study provides information about population structure that can be useful in fisheries management and conservation efforts (**39**).

So far, there is a lack of information regarding the quality of fish meat during fishing in waters. The content of heavy metals in the meat found at the research locations of the four stations, namely trevally, mackerel, and grouper, varies, with the average content still below quality standards. The highest content of the heavy metal Pb is found in trevally fish, namely 0.121 ± 0.05, one of the heavy

metal accumulations in the flesh of trevally fish (*C. ignobilis*) is Pb (**40**), while the highest heavy metal content Cd is found in mackerel fish, namely 0.043 ± 0.01, cadmium (Cd) is the most common pollutant heavy metal that can be discharged into the marine environment (**41**). The highest content of the heavy metal Hg was found in grouper fish, namely 0.068 ± 0.02. The levels of heavy metals in the fish species studied did not pose any risk to fish and human health (**42**).

The biological analyses confirmed that although population biometrics (including GiSI, GSI, GaSI, ISI, RGL, and RIL) showed significant differences across sites, overall fish health remained good, as indicated by their condition factors. Species-specific growth dynamics were also quantified: trevally and mackerel exhibited negative allometric growth ($b < 3$), while grouper exhibited positive allometric growth ($b > 3$). Second, toxicological analyses indicated that average heavy metal (Pb, Cd, and Hg) levels in edible muscle tissue of all three species remained well below established quality standards. In conclusion, these findings indicate that despite measurable biometric variations across industrial sites, these economically important fish populations are currently in good physiological condition and remain safe for human consumption.

ACKNOWLEDGEMENTS

The author would like to thank the Ministry of Education, Culture, Research, and Technology, Malikussaleh University, and all those who have helped and supported this research.

FUNDING

This research was financially supported by the Ministry of Education, Culture, Research, and Technology under the 2024 "Penelitian Fundamental–Reguler" Scheme (Grant Nos: 058/E5/PG.02.00.PL/2024 and 195/UN45.3.1/AL.04/VI/2024.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization, Investigation (data acquisition): M.M.; Formal Analysis: M.M., M.M., I.I., A.I., M.R., A.S.B.; Methodology, Supervision: M.Y., E.M.L., Y.A.; Writing – Original Draft: M.M., M.Y., E.M.L., Y.A., M.M., I.I., A.I., M.R., A.S.B.; Writing – Review & Editing: M.Y., E.M.L., Y.A. All authors have read and approved the final version of the manuscript.

ARTIFICIAL INTELLIGENT DECLARATION

The authors declare that they are responsible for the accuracy and integrity of all content of the manuscript, including part generated by AI, and it is not used as a co-author.

REFERENCES

1. Shadiqin I, Yusfiandayani R, Imron, M. Productivity of hand line on portable fads in the water of north Aceh district. J Fish Mar Technol. 2018;9:105-113. 10.24319/jtpk.9.105-113
2. Jamilah J, Nurmala N, Sullaida S, Nisa SN, Novita D. Processed product diversification based cottle fish for coastal fishing communities. Inter Rev Pract Innov Technol Green Ener. 2022;2(1):1-6. 10.54443/irpitage.v2i1.59
3. Peck MA, Alheit J, Bertrand A, Catalán I A, Garrido S, Moyano M, van Der Lingen CD. Small pelagic fish in the new millennium: a bottom-up view of global research effort. Progr Oceanograph. 2021;91:102494. 10.1016/j.pocean.2020.102494
4. Deme M, Failler P. Small pelagic fish in Senegal: a multi-usage resource. Mar Pol. 2022;141:105083. 10.1016/j.marpol.2022.105083
5. Peck M A, Catalán IA, Garrido S, Rykaczewski RR, Asch RG, McDowell JR, Kaplan IC. Small pelagic fish: new frontiers in ecological research. Mar Ecol Progr Ser. 2024;741:1-6. 10.3354/meps14648
6. Fréon P, Cury P, Shannon L, Roy C. Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: a review. Bull Mar Sci. 2005;76(2):385-462. https://www.documentation.ird.fr/hor/PAR00000210
7. Dirgapraja, VA, Poluan, RJ, Lakat, RS. The impact of industrial area development on settlements in Madidir District, Bitung City. Spasial. 2019; 6(2):282-290. 10.35793/sp.v6i2.25310
8. Agbugui, MO, Abe, GO. Heavy metals in fish: bioaccumulation and health. British J Earth Sci Res. 2022;10(1):47-66. 10.37745/bjesr.2013
9. Garai P, Banerjee P, Mondal P, Saha NC. Effect of heavy metals on fishes: Toxicity and bioaccumulation. J Clinic Toxicol. 2021;11:1-11. 10.35248/2161-0495.21.s18.001
10. Heriyanto T, Rosmasita R, Limbong I, Ariani F, Ghazali TM, Simanjuntak SA, et al . Identification of the utilization of female mackerel (*Rastrelliger brachysoma*) resources was assessed based on analysis of the length-weight relationship. J Enggano. 2020; 5(3): 404-415. 10.31186/jenggano.5.3.404-415
11. Magwa RJ, Gelis ERE, Yunita LH, Wulanda Y, Heltria S. Analysis of the length-weight relationship of grouper (*Epinephelus* sp) landed at Kaliadem and Muara Angke Fish Market, Jakarta. J Indo Trop Fish. 2023;6(2):174-184. 10.33096/joint-fish.v6i2.334
12. Yousif R, Choudhary MI, Ahmed S, Ahmed Q. Bioaccumulation of heavy metals in fish and other aquatic organisms from Karachi Coast, Pakistan. Nusantara Biosci. 2021;13(1):1-10. 10.13057/nusbiosci/n130111
13. Wang J, Shan Q, Liang X, Guan F, Zhang Z, Huang H, Fang H. Levels and human health risk assessments of heavy metals in fish tissue obtained from the agricultural heritage rice-fish-farming system in China. J Hazard Mater. 2020;386:121627. 10.1016/j.jhazmat.2019.121627
14. Ananda, SF, Redjeki, S, Widowati, I. The content of heavy metal lead (Pb) in water, sediment, and soft tissue of mussels (*Solen* sp.) in the waters of Rembang, Central Java and Gresik, East Java. J Mar Res. 2022;11(2):176-182. 10.14710/jmr.v11i2.29956
15. Bozorgzadeh E, Pasdaran A, Ebrahimi-Najafabadi, H. Determination of toxic heavy metals in fish samples using dispersive micro solid phase extraction combined with inductively coupled plasma optical emission spectroscopy. Food Chem. 2021;346:128916. 10.1016/j.foodchem.2020.128916
16. Rakib MRJ, Jolly YN, Enyoh CE, Khandaker MU, Hossain MB, Akther S, Bradley DA. Levels and health risk assessment of heavy metals in dried fish consumed in Bangladesh. Scient Rep. 2021;11(1):14642. 10.1038/s41598-021-93989-w
17. Töre Y, Ustaoğlu F, Tepe Y, Kalipci E. Levels of toxic metals in edible fish species of the Tigris River (Turkey); threat to public health. Ecolog Indicat. 2021;123:107361. 10.1016/j.ecolind.2021.107361
18. Huwae R, Yalindua FY,Rizki MP , Akbar N. Population structure and growth patterns of economically important fish in the seagrass beds of Tanjung Merah Waters. J Ilm Kel Kepul. 2024;7(1):966-980. 10.33387/jikk.v7i1.8344

19. Cadrin SX. Defining spatial structure for fishery stock assessment. Fish Res. 2020;221:105397. 10.1016/j.fishres.2019.105397
20. Famoofo OO, Abdul WO. Biometry, condition factors and length-weight relationships of sixteen fish species in Iwopin fresh-water ecotype of Lekki Lagoon, Ogun State, Southwest Nigeria. Heliyon. 2020;6(1):e02957. 10.1016/j.heliyon.2019.e02957
21. Wujdi A, Kim HJ, Oh CW. Population structure of Indian mackerel (*Rastrelliger kanagurta*) in Java and Bali Island, Indonesia inferred from otolith shape. Sains Malaysiana. 2022;51(1):39-50. 10.17576/jsm-2022-5101-04
22. Nikolic N, Montes I, Lalire M, Puech A, Bodin N, Arnaud-Haond S, Bonhommeau S. Connectivity and population structure of albacore tuna across southeast Atlantic and southwest Indian Oceans inferred from multidisciplinary methodology. Scient Rep. 2020;10(1):15657. 10.17882/61552
23. Baldé BS, Brehmer P, Faye S, Diop P. Population structure, age and growth of sardine (*Sardina pilchardus*, Walbaum, 1792) in an upwelling environment. Fishes. 2022;7(4):178. 10.3390/fishes7040178
24. Mogodan A, Metaxa I, Petrea SM, Simionov IA, Nica A, Cristea V. Evaluation of cyprinids condition reared in two Integrated Multi-Trophic Aquaculture (IMTA) systems based on a few somatic indices (VSI, HSI, GaSI AND RGL). Scient Pap Ser D Anim Sci. 2021;64:536-545. https://www.animalsciencejournal.usamv.ro/index.php/scientific-papers/past-issues?id=925
25. Wagner CE, McIntyre PB, Buels KS, Gilbert DM, Michel E. Diet predicts intestine length in Lake Tanganyika's cichlid fishes. Funct Ecol. 2009;23(6):1122-1131. 10.1111/j.1365-2435.2009.01589.x
26. Froese R. Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. J Appl Ichthyol. 2006;22(4):241-253. 10.1111/j.1439-0426.2006.00805.x
27. Ogan AC, Bob-Manuel FOG. Heavy metals concentration in some organs of tilapia (*Sarotherodon melanotheron*) and mullet (*Mugil cephalus*) harvested from Oginigba/Woji Creek, Port Harcourt, Nigeria. Fac Nat Appl Sci J Scient Innov. 2022;3:32–44. https://www.fnasjournals.com/index.php/FNAS-JSI/article/view/76
28. Anders N, Eide I, Lerfall J, Roth B, Breen M. Physiological and flesh quality consequences of pre-mortem crowding stress in Atlantic mackerel (*Scomber scombrus*). PLoS One. 2020;15(2):e0228454. 10.1371/journal.pone.0228454
29. Hasan MR, Mamun AA, Hossain MY. Biometric indices of eleven mangrove fish species from southwest Bangladesh. Egypt J Aqua Res. 2021; 47(2): 207-213. 10.1016/j.ejar.2020.11.002
30. Marsaoly R, Bataragoa N, Rondonuwu AB, Wantasen AS, Rembet U, Lalita J. Biometrics and reproduction of redbelly yellowtail fusilier *Caesio cuning* (Bloch, 1791) in Guraping Bay, Halmahera Island, Indonesia. J Ilm Platax. 2024;12(1):114-124. 10.35800/jip.v12i1.49322
31. Rahman MK, Rahman BS, Lima RA, Ali A, Mahmud Y. Biometric indices of eight fish species from the catchment area of Kaptai lake, Bangladesh. Ecol Front. 2024;44(5):1061-1068. 10.1016/j.ecofro.2024.05.007
32. Bravata N, Kelly D, Eickholt J, Bryan J, Miehls S, Zielinski D. Applications of deep convolutional neural networks to predict length, circumference, and weight from mostly dewatered images of fish. Ecol Evol. 2020;10(17):9313-9325. 10.1002/ece3.6618
33. Rabani D, Asrial E, Rahmawati A, Tarmizi A. Tonda demersal fisheries fishing profile in Sape Strait Waters, Bima Nusa Tenggara Barat District. Al-Qalbu. 2023;1(2):42-51. 10.59896/qalbu.v1i2.28
34. Pratam MF, Farhan MA. The length-weight relationship of mackerel (*Rastrelliger* sp.) at the Pantai Labu Fish Farm, Deli Serdang. J Agro Tolis. 2023;3(3):106-112. 10.56630/jago.v3i3.325
35. Wardiatno Y, Aziz A, Meilana L, Hakim AA. A morphometric approach into mackerel (*Rastrelliger* spp.) diversity in fisheries management area 711 as a management base. IOP Conf Ser Earth Environ Sci. 2021;744:012096. 10.1088/1755-1315/744/1/012096
36. Astuti R. Study of grouper (*Cephalopolis Sonnerati*) stocks based on the length-weight relationship landed at the Lhok Peukan Bada fish landing site, Aceh Besar District, Aceh Province. J Aceh Aqua Sci. 2017;1(1):1-11. 10.35308/.v1i1.397
37. Sala R, Tarigan RB, Dasmasela HY, Parenden D, Tururaja T, Manan J, Marsaoly DNR, Matulessy M, Bawole R. Catch structures, growth patterns and condition factor of grouper fish (Serranidae) caught in the waters near Wayaban, Misool, Raja Ampat. AACL Bioflux. 2022;15(1):240-250. http://bioflux.com.ro/docs/2022.240-250.pdf
38. Muchlisin ZA, Fransiska V, Muhammadar AA, Fauzi M, Batubara AS. Length-weight relationships and condition factors of the three dominant species of marine fishes caught by traditional beach trawl in Ulelhee Bay, Banda Aceh City, Indonesia. Croatian J Fish. 2017;75(3):142-54. 10.1515/cjf-2017-0014
39. Kasinath A, Kumar KA, Gauri P, Ayana B, Parveen PF, Raphael L, Thottappilly A, Ameen U, Bineesh KK, Tuset VM. Are Indian mackerel (*Rastrelliger kanagurta*) populations in the eastern Indian Ocean truly homogeneous? Insights from geometric morphometric analysis. Reg Stud Mar Sci. 2024;75:103555. 10.1016/j.rsma.2024.103555
40. Pertiwi RTA, Ariyanto D, Edward E, Lessy MR, Putri B. Significant metal buildup within the organs of Lethrinus sp. and Caranx ignobilis (Forsskål 1775) from Kao Bay waters, Indonesia. IOP Conf Ser Earth Environ Sci. 2023;1260:012046. 10.1088/1755-1315/1260/1/012046
41. Ture M, Kilic MB, Altinok I. Relationship between heavy metal accumulation in fish muscle and heavy metal resistance genes in bacteria isolated from fish. Biol Trac Elem Res. 2021;199(4):1595-1603. 10.1007/s12011-020-02246-0
42. Karayakar F, Işık U, Cicik B, Canli M. Heavy metal levels in economically important fish species sold by fishermen in Karatas (Adana/Turkey). J Food Comp Anal. 2022;106:104348. 10.1016/j.jfca.2021.104348