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A Biological and Reproduction Profile of the Blood Cockle (*Tegillarca granosa* Linnaeus, 1758) Captured by Fishermen in North Aceh

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ABSTRACT

Blood cockles (*Tegillarca granosa* Linnaeus, 1758) play a significant economic and ecological role in North Aceh's fisheries sector, serving as both a protein source and an environmental bioindicator due to their sensitivity to habitat changes. This study aimed to support sustainable management by examining morphology, reproductive status, water quality, and environmental influences. From May to June 2024, samples were collected from three coastal sites and analyzed for morphometric parameters, allometry, condition factor, meat yield, sex ratio, gonadal maturity, heavy metal concentrations (Pb and Zn), and water quality. Findings show relatively uniform shell length and body weight, with males generally larger than females. ANOVA revealed significant differences in total and flesh weight between sites, suggesting environmental influence. Growth efficiency varied: males at Station 1 showed positive allometry ($b = 2.56$), while females at Station 2 showed negative allometry ($b = 0.76$). The sex ratio was male-skewed, particularly at Station 2 (3.17:1), possibly due to ecological or reproductive factors. Most individuals were immature or in developmental stages, with no spawning observed, indicating seasonal or environmental constraints on reproduction. Heavy metal concentrations were within acceptable safety standards, though correlations between metal levels and weight suggest potential bioaccumulation. Water quality parameters (salinity, pH, and dissolved oxygen) met acceptable limits, although temperature fluctuations may induce stress. In conclusion, morphometric traits showed no significant differences between sexes or locations, condition factors remained stable, and reproductive stages were predominantly immature. Although heavy metal levels were safe, bioaccumulation remains a concern. Future research should expand spatial coverage, include additional contaminants, and assess broader environmental influences on cockle populations. Limitations of this study include restricted sampling areas, focus on only two heavy metals, and a limited reproductive observation period.

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INTRODUCTION

The blood cockle (*Tegillarca granosa* Linnaeus, 1758) is a bivalve species of high economic value in the fisheries sector, particularly in the coastal regions of North Aceh Regency, Indonesia. Beyond its role as a rich source of protein and nutrients, it is also utilized as raw material in the food and pharmaceutical industries and serves as an environmental bioindicator. According to data from **WWF-Indonesia (2015)**, Indonesia's annual blood cockle production reaches approximately 50,000 tons, reflecting strong market demand both domestically and internationally. Given its economic potential, the blood cockle is an essential commodity supporting the livelihoods of coastal communities **(Yulinda *et al.*, 2020; Prasetiyono *et al.*, 2022)**.

Blood cockles typically inhabit shallow waters with muddy or sandy substrates rich in organic material. Estuarine zones and river mouths—where freshwater and seawater mix—offer ideal conditions for their growth and reproduction. These habitats, however, are highly sensitive to environmental disturbances. According to **Mawardi and Sarjani (2021)**, such areas naturally support abundant blood cockle populations but are also vulnerable to rapid environmental change due to the species' benthic lifestyle and limited mobility. **Mawardi *et al.* (2024)** further noted that anthropogenic activities such as land reclamation, industrial waste discharge, pollution, and climate change can significantly disrupt habitat conditions, threatening the survival of blood cockles.

While previous studies have examined seasonal water quality fluctuations during the spawning period **(Khalil, 2013)** or focused on bivalve diversity in North Aceh's coastal areas **(Erniati *et al.*, 2024)**, there remains a lack of comprehensive research integrating the morphological, biological, and ecological aspects of blood cockles. This study aims to address that gap.

The species' vulnerability to environmental stressors—such as pollution, declining water quality, industrial activity, and unsustainable harvesting—poses a serious threat to the sustainability of blood cockle populations. Studies by **Dinulislam *et al.* (2021)** and **Zhang *et al.* (2023a)** show that degradation of water quality from industrial waste and pesticide use can impair phytoplankton growth, which is the primary food source for blood cockles. Moreover, overexploitation without sustainable practices can drastically reduce population sizes **(Azmi *et al.*, 2022; Waliullah *et al.*, 2023)**.

As such, conservation efforts and sustainable management are essential to protect both the species and its habitat **(Mahary *et al.*, 2023)**. Environmental degradation and unsustainable harvesting have already been observed in North Aceh's coastal zones **(Erniati *et al.*, 2024)**. In response to these threats, this study aims to investigate the morphology, reproductive status, and environmental parameters of blood cockles. The results are expected to serve as a scientific basis for policy development and sustainable habitat management strategies.

MATERIALS AND METHODS

1. Time and place

This research was conducted from May 9th to June 24th, 2024, in the coastal areas of Krueng Geukuh, Lancok, and Meunasah Sagoe in North Aceh Regency. Subsequent observations were carried out at the Water Quality and Fish Nutrition Laboratory, Faculty of Agriculture, Malikussaleh University. Gonad histology analysis was performed at the Medan Veterinary Center Laboratory, while heavy metal testing was conducted at the BSPJI Banda Aceh Laboratory.

2. Research methodology

The method used in this study was direct observation through sample collection at three locations: the coastal areas of Krueng Geukuh, Lancok, and Meunasah Sagoe (Fig. 1). The data collection technique was conducted using purposive random sampling **(Oyarzún *et al*., 2020)**, while heavy metal analysis was performed using the Atomic Absorption Spectrophotometry (AAS) method.

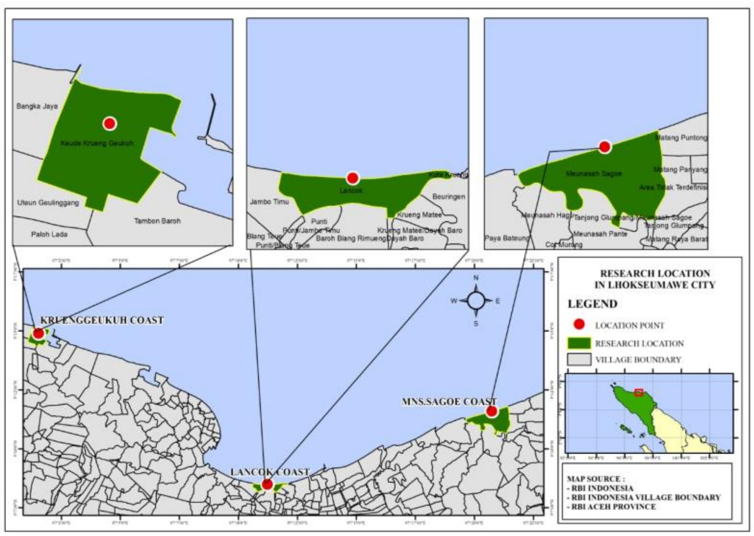


Fig. 1. Blood clam sampling location

3. Sampling and handling

The sample collection was conducted three times within one month (May – June 2024), with 50 blood cockle samples taken from each location, measuring 3–5 cm in size, totaling 450 individuals. The collected blood cockle samples were placed in a cool box for further laboratory analysis. Samples designated for testing were stored in labeled plastic sampling bags, corresponding to each collection site **(Alibon *et al*., 2020)**. Subsequently, the samples were preserved by keeping them in a cool box before undergoing further observations in the laboratory, focusing on sex determination, gonad analysis **(Le Cren, 1951)**, yield assessment **(Mahadev *et al*., 2015)**, morphometric measurements **(Meshram & Mohite, 2016)**, and the detection of heavy metals (Pb and Zn) in blood cockle meat **(Yulianto *et al*., 2020; Idris *et al*., 2023)**.

The histological preparation of blood cockle gonads followed the method described by **Koca *et al.* (2021)**. Samples for determining Gonadal Maturity Level (GML) were preserved in 10% formalin and fixed for 24–48 hours to prevent tissue degradation during slide preparation. After fixation, the samples were rinsed with water to eliminate residual fixative, then sectioned into the required organ parts.

These tissue sections were placed into labeled cassettes and processed in a tissue processor for 15 hours. Following this, the sections were embedded in paraffin by immersing the digestive organs in molten paraffin, which was then allowed to cool and harden for about one hour. Thin tissue sections were cut using a microtome, mounted on glass slides, and stained with hematoxylin and eosin. The prepared slides were sealed with coverslips, labeled for identification, and examined under a microscope.

4. Observation parameters

4.1. Morphometric measurements of blood cockles

Morphometric measurements were taken using digital calipers or a vernier caliper with an accuracy of 0.01 mm. Total body weight, including shell, was measured using a digital scale with 0.01 g precision **(Bahtiar *et al.*, 2023)**.

4.2. Calculation of allometry and condition factors

The length-weight relationship and condition factor were calculated following formulas from **Le Cren (1951)** and **Froese (2006)**:

Length-Weight Relationship: $W = a \times L^b$

Where:

- **W** = total weight of the cockle (g)
- **L** = shell length (mm)
- **a**, **b** = regression parameters
- **b > 1**: Positive allometry (weight increases faster than length)
- **b < 1**: Negative allometry (weight increases slower than length)
- **b = 1**: Isometric growth (weight and length increase proportionally)

For linear regression analysis, the equation is transformed into logarithmic form:

$$\log(W) = \log(a) + b \times \log(L)$$

Condition factor (K):

The condition factor assesses the general health and nutritional status of the organism. The formula is: $\mathbf{K = (W / L^3) \times 100}$

Where:

- **W** = total body weight (g)
- **L** = shell length (mm)

Interpretation:

- **K > 1**: Good physical condition
- **K ≈ 1**: Normal or average condition
- **K < 1**: Poor condition, possibly due to environmental stress or limited food

4.3. Calculation of meat yield and sex ratio

Meat Yield (R%) is a key parameter for evaluating commercial value. It is calculated by comparing meat weight to total body weight (or shell weight), using the formula **(Çelik *et al.*, 2012)**:

R (%) = (Meat Weight / Total Weight) × 100

Sex Determination was performed by dissection and visual inspection of the gonads:

- **Females**: orange to reddish gonads with visible egg granules
- **Males**: white or cream-colored gonads **(Efriyeldi & Effendi, 2022)**

To determine the sex ratio of male and female blood cockles, the following formula was used **(Oyarzún *et al*., 2020)**:

$$\text{Sex Ratio (\%)} = \frac{\text{Number of Males or Females}}{\text{Total Number of Individuals}} \times 100$$

This formula helps in assessing the population structure and reproductive dynamics in blood cockle populations.

4.4. Gonad observation

Gonads of blood cockles were observed through histological analysis to determine the stages of gonadal development in both male and female specimens. The histological slide preparation followed the procedure described by **Koca *et al.* (2021)** and included the following steps: preservation, fixation, grossing, tissue processing, labeling, impregnation, embedding, sectioning, floating, staining with hematoxylin-eosin, mounting, and microscopic examination. These steps ensure a detailed analysis of gonadal structures, providing insights into the reproductive status and maturity levels of the specimens.

4.5. Measurement of heavy metal content (Pb and Zn)

The concentration of heavy metals (lead and zinc) in blood cockle tissues was determined using Atomic Absorption Spectrophotometry (AAS). Only the soft tissues (meat) were analyzed, with a sample of 100 grams collected from each observation site, regardless of sex. The procedure followed the standard methodology described by **Idris *et al.* (2023)**.

4.6. Water quality parameters

Water quality assessments were carried out during each sampling event across all observation sites in North Aceh Regency. Parameters measured included salinity, temperature, pH, and dissolved oxygen (DO). These indicators provide essential information on the environmental suitability of blood cockle habitats and help interpret biological responses to environmental conditions **(Zhang *et al.*, 2023a)**.

5. Data analysis

All observed data are presented in tables and figures, followed by both statistical and descriptive analyses:

- Morphometric data, meat yield, and sex ratio were analyzed using Analysis of Variance (ANOVA) at a 95% confidence level.
- Gonadal maturity, heavy metal concentrations (Pb and Zn), and water quality parameters were analyzed descriptively.
- Regression analysis was applied to examine the relationship between shell length and body weight.
- Correlation analysis was used to explore the relationship between heavy metal concentration and the body weight of blood cockles.

RESULTS

1. Morphometric measurements of blood cockles

The results of the morphometric measurements of blood cockles at each station can be seen in the following table.

Table 1. Morphometric measurements data of blood cockles

Parameters	Station 1		Station 2		Station 3	
	Male	Female	Male	Female	Male	Female
Shell length (mm)	33.48±3.31	33.06±2.30	33.25±2.66	32.14±2,79	33.38±2.70	32.64±3.55
Shell height (mm)	31.49±3.06	30.84±1.99	31.24±2.49	30.37±2.64	31.33±2.48	31.04±3.47
Umbo height (mm)	11.57±1.51	11.58±1.06	11.65±1.34	11.42±1.55	12.02±1.51	12.04±2.59
Shell thickness (mm)	29.17±3.86	28.36±2.19	28.94±2.65	27.95±2.46	28.94±2.60	28.81±3.17
Ligament length (mm)	26.38±2.95	26.23±2.40	26.18±2.48	25.61±2.73	26.01±2.37	25.78±3.14
Total body weight (g)	17.89±5.70	16.87±3.49	16.55±3.48	16.01±2,88	17.05±3.82	16.81±3.63
Flesh weight (g)	4.02±1.45	3.78±0.96	3.74±1.00	3.51±1.28	3.83±1.00	3.83±1.06

The morphometric analysis of blood cockles across the three stations reveals slight variations in shell dimensions, umbo height, ligament length, and overall body weight between males and females. Males generally exhibit larger shell size, heavier body weight, and thicker shells compared to females, particularly at Station 1. The slight decrease in shell length and weight at Station 2 suggests potential environmental influences such as habitat conditions or food availability. Despite these differences, all morphometric parameters remain within comparable ranges across stations, indicating relatively uniform growth patterns within the studied population.

An ANOVA test was applied to assess significant differences in morphometric characteristics, meat yield, and sex ratio among the stations, with a confidence level of 95%. The results show statistically significant differences ($P< 0.05$) in total body weight and flesh weight, particularly between Station 1 and Station 2, highlighting possible environmental effects on growth and nutritional accumulation. Conversely, shell length and ligament length differences were not statistically significant ($P > 0.05$), indicating similar structural development across locations. Further regression analysis could explore the relationship between length-weight variation and environmental factors, providing deeper insights into blood cockle population dynamics.

2. Calculation of allometry and condition factors

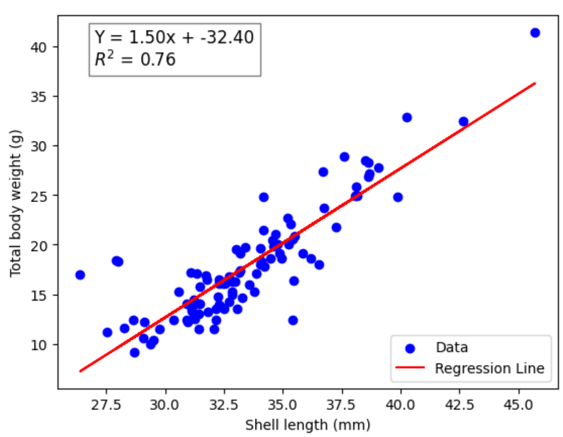
The results of allometric calculations and condition factors for male (Table 2) and female (Table 3) blood cockles are presented in the following table.

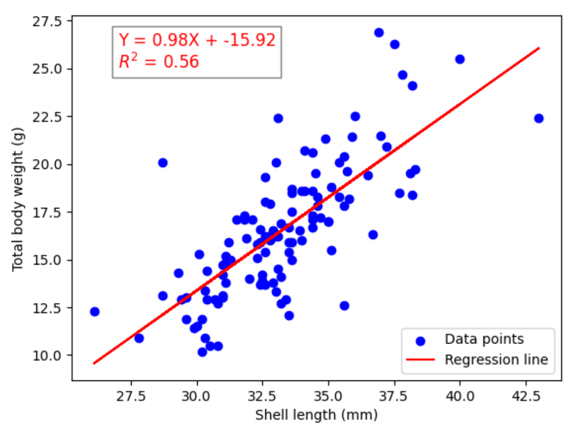
Table 2. Allometric and condition factors of length and weight of male blood cockles

Sampling location	Length (mm)	Weight (g)	Allometry	Condition factors
Station 1	33.48±3.31	17.89±5.70	2.56	1.00
Station 2	33.25±2.66	16.55±3.48	1.98	1.00
Station 3	33.38±2.70	17.05±3.82	2.14	1.00

The morphometric analysis of blood cockles at the three sampling locations shows relatively consistent shell lengths, ranging from 33.25 to 33.48 mm. However, body weight varies slightly across the stations, with cockles at Station 1 having the highest average weight (17.89 g) and those at Station 2 showing the lowest (16.55 g). The allometric coefficient (b) varies between stations, indicating different growth patterns. A b value above 1 suggests positive allometry, where weight increases faster than length. The highest b value (2.56) at Station 1 suggests favorable growth conditions, whereas Station 2 shows the lowest (b = 1.98), possibly reflecting environmental stress or lower food availability. Despite differences in weight and allometry, the condition factor (K) remains constant at 1.00 across all stations, indicating that the cockles are in stable physiological condition. This uniformity suggests that environmental conditions may support balanced development, but differences in b values highlight variations in growth efficiency across locations. The regression results are presented in Fig. (2).

The regression analysis between the length and weight of blood cockles at the three stations shows different levels of correlation. At Station 1, the R^2 value of 0.76 suggests a strong positive correlation between shell length and body weight. This indicates that length is a reliable predictor of weight in this location, meaning the cockles exhibit consistent growth patterns influenced by favorable environmental conditions or adequate food availability. The high R^2 value implies that a significant portion of the variations in weight can be explained by changes in shell length, reinforcing positive allometric growth in this population. Conversely, at Station 2 and Station 3, the R^2 values are 0.56 and 0.58, respectively, indicating a moderate correlation between length and weight. These lower values suggest that factors other than shell length may significantly affect weight variation, such as differences in water quality, food supply, or population density. The weaker correlation implies greater variability in growth patterns, potentially due to environmental stressors or inconsistent resource availability across these locations. Further analysis incorporating environmental parameters could help determine what influences growth rates and body mass fluctuations in blood cockles across stations.





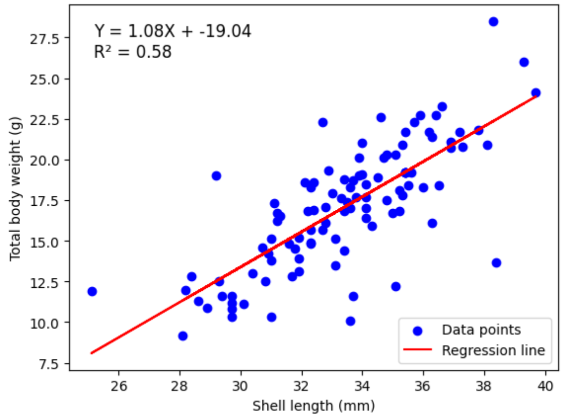


Fig. 2. Regression analysis of the length and weight of male blood cockles from each observation station

Table 3. Allometric and condition factors of length and weight of female blood cockles

Sampling location	Length (mm)	Weight (g)	Allometric	Condition factors
Station 1	33.06±2.30	16.87±3.49	2.11	1.00
Station 2	32.14±2,79	16.01±2,88	0.76	1.00
Station 3	32.64±3.55	16.81±3.63	0.94	1.00

The morphometric analysis of blood cockles across the three sampling stations indicates variations in length, weight, and growth patterns. The average shell length remains relatively similar, ranging from 32.14 to 33.06 mm, with Station 1 showing the highest values. The total body weight also fluctuates across stations, with Station 1 cockles being slightly heavier than those in Station 2 and Station 3, suggesting possible environmental influences on growth conditions. The allometric coefficient (b) varies significantly between stations. Station 1 exhibits positive allometry (b = 2.11), meaning weight increases at a faster rate than length, indicating favorable growth conditions. However, Station 2 and Station 3 show negative allometry (b = 0.76 and b = 0.94, respectively), suggesting restricted weight gain compared to shell length. Despite these differences, the condition factor (K) remains consistent at 1.00 across all stations, indicating stable physiological conditions for the cockles.

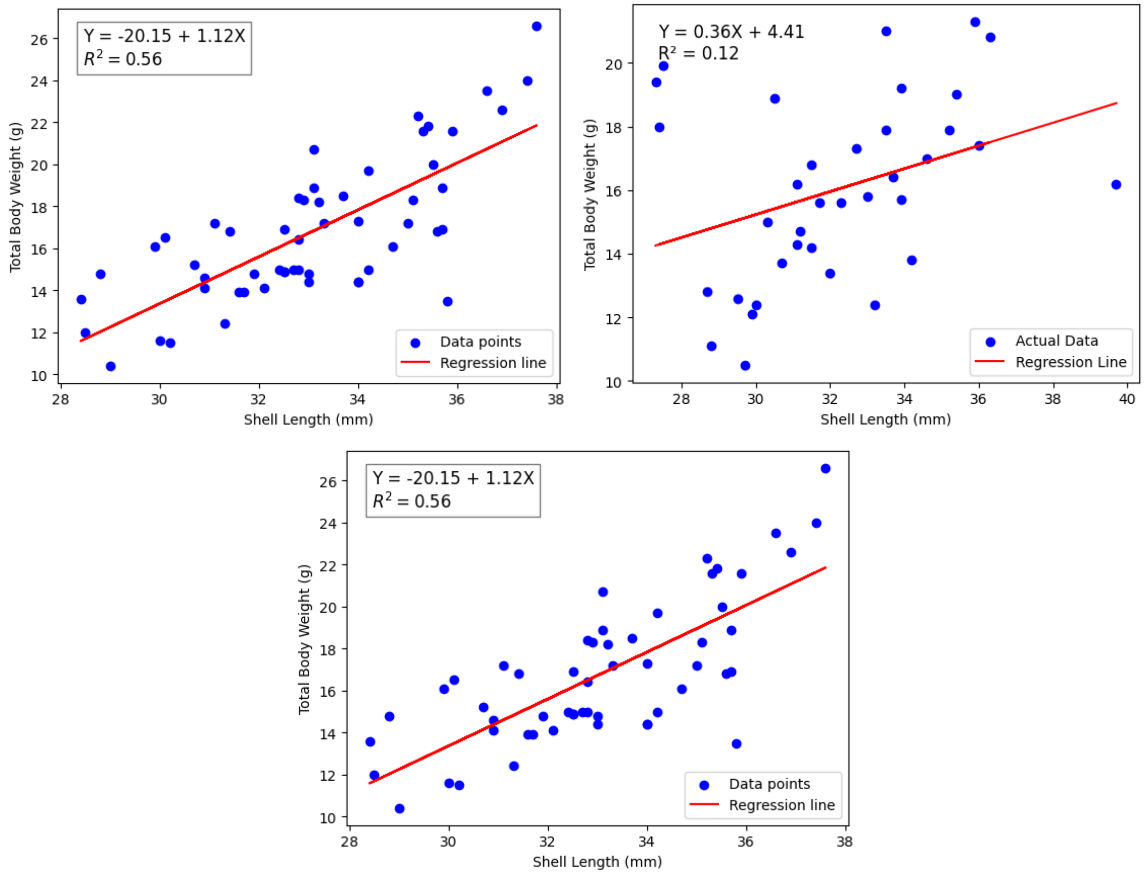


Fig. 3. Regression analysis of the length and weight of female blood cockles from each observation station

The regression analysis between length and weight of blood cockles at the three stations reveals varying degrees of correlation. At Station 1 and Station 3, the R^2 values of 0.56 suggest a moderate correlation, meaning that changes in shell length explain about 56% of the variations in body weight. This indicates that, while length is an important predictor of weight, other factors such as environmental conditions, food availability, or genetic differences also play a significant role in growth. The moderate correlation suggests that blood cockles at these stations follow a somewhat consistent growth pattern influenced by multiple factors. However, Station 2 presents a notably lower R^2 value of 0.12, indicating a weak correlation between length and weight. This suggests that shell length alone does not strongly determine weight at this location, implying possible environmental stressors or inconsistencies in food supply affecting growth patterns. The weak correlation could be due to factors such as water quality fluctuations, nutrient availability, or population density impacting individual development. Further analysis, incorporating habitat parameters, could help clarify what influences growth disparities across stations.

3. Calculation of yield and sex ratio

The following presents data on the yield and sex ratio of blood cockles at each research station.

Table 3. Percentage yield and sex ratio of blood cockles

Observation	Average meat yield (%)		Sex percentage (%)		Sex ratio	
	Male	Female	Male	Female	Male	Female
Station 1	22.78±5.49	22.39±3.06	65.33	34.67	1,88	1
Station 2	22.71±4.58	22.74±7.70	76.00	24.00	3,17	1
Station 3	22.57±3.53	22.91±4.21	70.00	30.00	2,33	1

The analysis of blood cockles across the three stations indicates a consistent average meat yield for males and females, with values ranging from 22.39 to 22.91%. This uniformity suggests that the cockles have similar growth efficiency, regardless of sex or location, potentially indicating stable environmental conditions that support balanced development. Small variations between stations could be influenced by factors such as food availability, water quality, or population density. The sex percentage data reveals a notable male dominance at all stations, with the highest male proportion recorded at Station 2 (76%), followed by Station 3 (70%), and Station 1 (65.33%). This skewed distribution suggests potential ecological or reproductive influences affecting population structure.

The sex ratio follows a similar trend, showing a higher prevalence of males, particularly at Station 2, where the ratio is 3.17 males per female. This suggests that males are significantly more abundant than females, possibly due to differences in reproductive cycles, survival rates, or habitat conditions. The ANOVA results indicate statistically significant differences ($P < 0.05$) in sex percentage and sex ratio across stations, highlighting variations in population composition that could be influenced by environmental or biological factors. However, the meat yield percentage does not show significant variation ($P > 0.05$), indicating that cockle growth efficiency remains stable across the study area.

4. Gonad observation

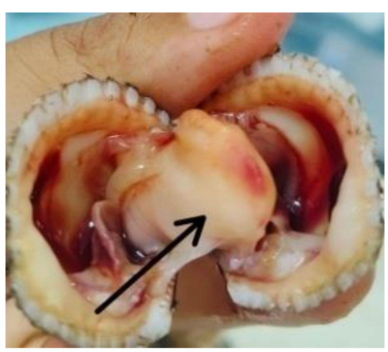
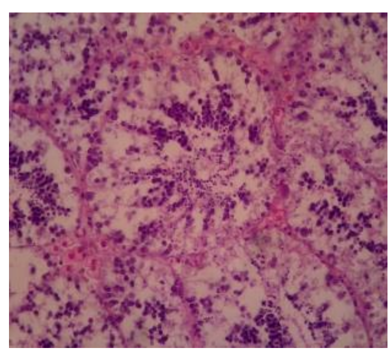
The observation results of gonad maturity levels at each station can be seen in the following table.

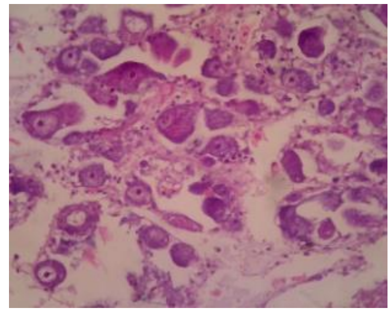
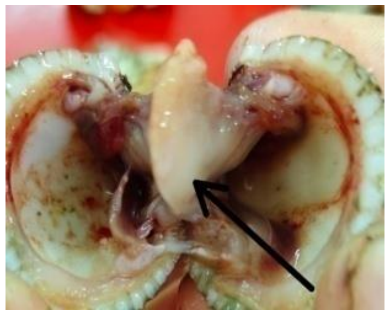
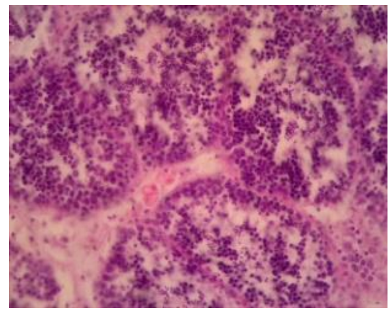
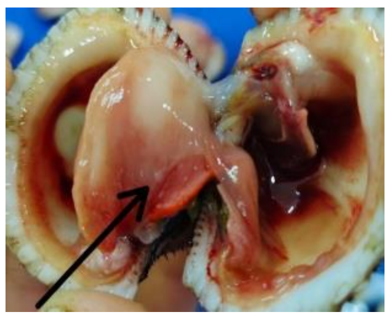
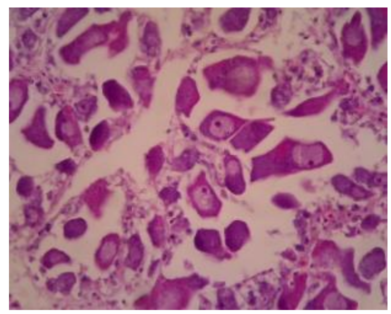
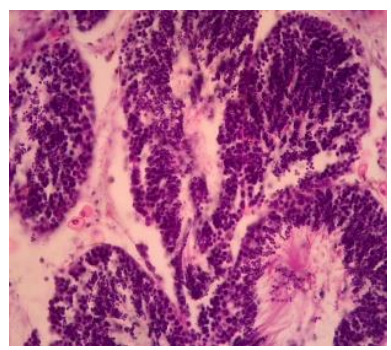
Table 3. The gonadal maturity level of blood cockles

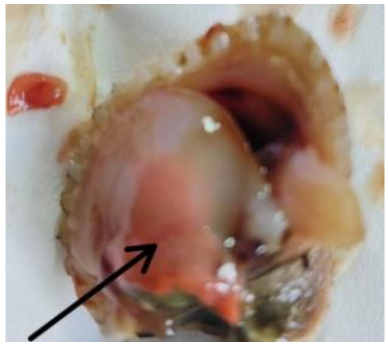
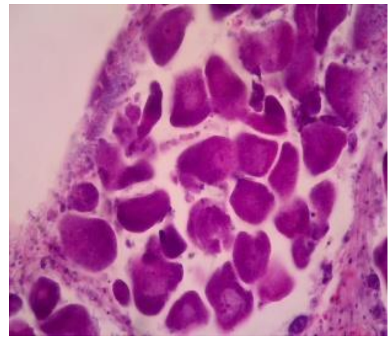
Gonadal maturity Level (GML)	Station 1		Station 2		Station 3	
	Male (%)	Female (%)	Male (%)	Female (%)	Male (%)	Female (%)
Level I (Immature)	42.00	16.67	50.67	16.67	51.33	17.33
Level II (Developing)	20.00	13.33	19.33	6.67	16.00	9.33
Level III (Mature)	3.33	4.67	6.00	0.67	2.67	3.33
Level IV (Spawning)	0.00	0.00	0.00	0.00	0.00	0.00

The gonadal maturity analysis of blood cockles across the three stations indicates that the majority of individuals are in Level I (Immature), with males showing significantly higher percentages compared to females. Station 3 records the highest percentage of immature males (51.33%), followed by Station 2 (50.67%) and Station 1 (42.00%), while females remain relatively stable across stations (16.67–17.33%). This suggests that most male blood cockles are still in early developmental stages, potentially influenced by environmental conditions or seasonal reproductive cycles. For Level II (Developing) individuals, males range from 16.00% to 20.00%, showing a slight decline at Station 3, while females exhibit lower percentages, particularly at Station 2 (6.67%). Meanwhile, Level III (Mature) blood cockles are less frequent, with only 2.67–6.00% of males and 0.67–4.67% of females reaching maturity, indicating that the population primarily consists of younger individuals. Notably, Level IV (Spawning) individuals are completely absent (0.00% across all stations), suggesting that the spawning period might not coincide with the observation time or that environmental factors are not yet favorable for reproductive activity. The ANOVA results likely show statistically significant differences ($P < 0.05$) in maturity levels among stations, especially for males, further reinforcing site-specific influences on gonadal development. The histological results of each gonad development are presented in Table (4) below.

Table 4. Observation of gonadal maturity levels in males and females

Station	Sex	Morphology	Histology	GML
Station 1	Male			I

	Female			I
Station 2	Male			II
	Female			II
Station 3	Male			III

Female			III

The analysis results indicate that at Gonadal Maturity Level (GML) I, male gonads have begun forming several follicles, with most follicles being small and showing spaces between them. At GML II, the follicles have started to enlarge, although some remain small, and the spaces between follicles are still visible. This stage represents gonadal development but has not yet reached maturity. At GML III, most follicles are large, densely packed, and closely arranged, eliminating the spaces between them. The spermatozoa structure predominantly exhibits distinct channels, suggesting that the gonads have begun to reach maturity.

At Gonadal Maturity Level (GML) I, female gonads have formed small to medium-sized follicles, with spaces between them and the presence of connective tissue. Most of the internal follicular space is occupied by oogonia, indicating an early developmental stage. At GML II, follicle size increases, and their number becomes more prominent compared to GML I. However, spaces between follicles and connective tissue remain visible, suggesting that the gonads are still in the developmental phase and have not yet fully matured. At GML III, the presence of developing oocytes is still observed, with an increasing number of mature oocytes, although they do not yet completely fill the follicular space. This suggests that the gonads are transitioning into the maturation stage, preparing for further reproductive processes. A deeper histological examination could provide insights into hormonal influences and environmental factors affecting female gonadal development.

5. Content of Pb and Zn in blood cockles

The results of heavy metal content measurements in the study for each observation station can be seen in Table (5) below.

Table 5. Results of heavy metal measurements in blood cockle meat

Heavy metal	Station 1	Station 2	Station 3	Acceptable limit
Lead (Pb)	1.62	1.72	1.64	2.0 mg/kg*
Zinc (Zn)	1.11	1.28	1.17	40 mg/kg*

*. The Indonesian National Agency of Drug and Food Control (BPOM) No 9/2022.

The analysis of heavy metal concentrations in blood cockles across the three stations reveals that lead (Pb) and zinc (Zn) levels remain within the acceptable limits set at 2.0 mg/kg for Pb and 40 mg/kg for Zn. The lead concentrations range from 1.62 mg/kg to 1.72 mg/kg, with Station 2 showing the highest Pb level. While still within safe limits, this slight increase may indicate localized sources of contamination, such as industrial discharge or sediment accumulation affecting Pb uptake. Similarly, zinc concentrations are relatively low across all stations, ranging from 1.11 to 1.28 mg/kg, far below the 40 mg/kg threshold. The highest Zn concentration is observed at Station 2 (1.28 mg/kg), which may suggest variations in nutrient availability or environmental exposure affecting metal accumulation. The ANOVA results likely indicate no statistically significant differences ($P > 0.05$) in Pb and Zn levels across stations, reinforcing that heavy metal accumulation remains consistent across locations. The results of the regression analysis between the content of heavy metal lead (Pb) and the body weight of blood cockles can be seen in the following image.

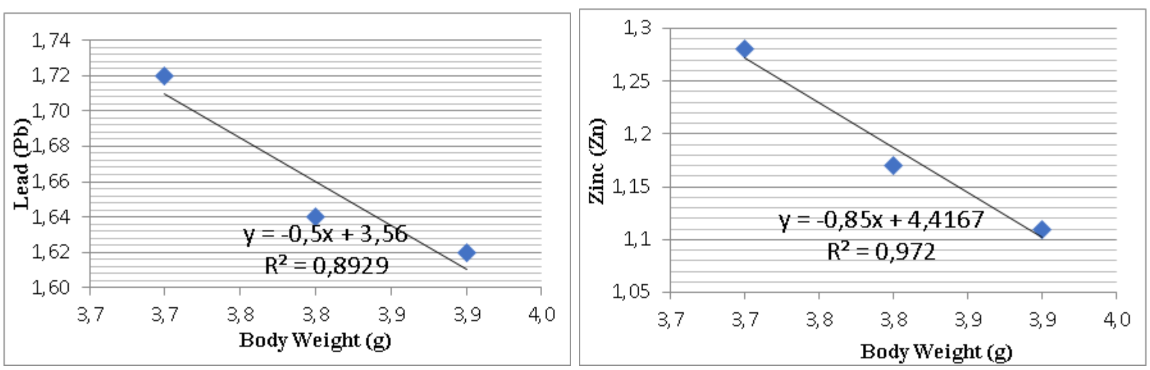


Fig. 4. Graph of the relationship between Pb and Zn content and body weight of blood cockles

The regression analysis between heavy metal concentration (Pb and Zn) and blood cockle weight indicates a strong correlation, suggesting that metal accumulation is closely linked to body weight. For lead (Pb), the R^2 value of 0.7876 demonstrates a high correlation, meaning approximately 78.76% of the variation in cockle weight can be explained by changes in Pb concentration. This suggests that as Pb levels increase, there is a proportional effect on weight, potentially due to bioaccumulation processes or environmental exposure influencing growth. Such a strong correlation indicates that Pb uptake is a significant factor in cockle physiology, warranting further investigation into its effects on health and sustainability.

For zinc (Zn), the R^2 value of 0.9048 reveals an even stronger correlation, implying that 90.480% of the variation in weight is associated with Zn concentration. This exceptionally high correlation suggests that Zn plays a crucial role in metabolic processes or structural development in blood cockles. Since Zn is an essential trace element, its bioavailability might directly affect growth efficiency, leading to a clear weight-dependent accumulation pattern. Overall, these high R^2 values indicate that heavy metal levels significantly influence cockle weight, likely due to environmental exposure, feeding habits, or physiological uptake mechanisms.

6. Water quality parameters

The following are the results of coastal water quality measurements in North Aceh from all observation stations.

Table 6. Water quality measurement results

Parameter	Values			Quality standards*
	Station 1	Station 2	Station 3	
Salinity (ppt)	29 – 31	30 – 32	30 – 31	25 – 35
pH	6.53 – 7.83	7.90 – 8.01	7.40 – 8.35	7 – 8.50
DO (mg/L)	6.42 – 6.89	6.51 – 6.80	6.60 – 7.08	> 5
Temperature (^{0}C)	27.70 – 30.41	28.93 – 32.52	29.54 – 32.80	28 – 32

* Ministry of Environment of the Republic of Indonesia (2004)

The water quality observations indicate that salinity across all stations remains stable within the standard range of 29–32 ppt. The pH value at Station 1 is slightly lower than the others but still within acceptable limits. Dissolved oxygen (DO) levels are sufficient in all locations, exceeding the minimum required for aquatic life. Meanwhile, the water temperature at Stations 2 and 3 slightly surpasses the upper standard limit, which may affect the aquatic ecosystem. Overall, the water conditions remain within quality standards, despite minor variations in pH and temperature at certain locations.

DISCUSSION

The morphometric observations in this study indicate that both male and female *Tegillarca granosa* specimens exhibited relatively uniform shell sizes across all sampling stations, suggesting consistent and stable environmental conditions within the study area. These findings are in agreement with those reported by **Seran *et al.* (2024)**, who also found similarity in shell length, height, and umbo height. However, the blood cockles observed in this study appeared to have thinner shells, possibly due to environmental factors specific to North Aceh's coastal ecosystem.

In comparison, significantly larger specimens have been documented in other regions of Indonesia, with individuals reaching 61.9 mm in Kuala Putri, North Sumatra **(Mulya & Jhon, 2021)**, 57.5 mm along the east coast of Aceh **(Azmi *et al.*, 2022)**, and even up to 78.5 mm in Letman Village, Kei Kecil District, Southeast Maluku **(Tuhumury *et al.*, 2024)**. Despite these size variations, the shell sizes recorded in this study remain within the commonly harvested commercial range of 30.00–35.00 mm **(Mulya & Jhon, 2021; Azmi *et al.*, 2022)**, indicating that the cockles from North Aceh are suitable for market purposes. According to **Pursetyo *et al.* (2015)**, differences in shell size can reflect the influence of local environmental conditions, which are crucial for sustaining healthy populations of blood cockles. Several studies, including those by **Silaban *et al.* (2022)** and **Alburhana *et al.* (2023)**, have identified key environmental factors affecting size variation, such as water quality, substrate composition, food availability, seasonal changes, and fishing pressure.

Beyond size, meat yield is another important indicator of the commercial value and nutritional quality of blood cockles. As emphasized by **Kaya *et al.* (2024)**, yield calculations are essential for determining the proportion of edible tissue per individual. The wet edible tissue typically constitutes 30–35% of the total body weight **(Rahmiati *et al.*, 2024)**, although other studies have reported lower values, ranging between 18% and 24.35%, with 19.4% observed after boiling. A decline in total weight and meat yield can reflect environmental stress, reduced food availability, or poor health conditions during the sampling period, as noted by **Al Ayubi and Gimin (2016)** and **Sotelo-Gonzalez *et al.* (2020)**.

One of the notable findings from this study is the male-dominated sex ratio, with males comprising between 65.33% and 76.00% of the total population, while females accounted for only 24.00% to 34.67%. This trend differs from earlier reports that observed a higher proportion of females, such as the 55% female ratio in Pasir Limau Kapas, Riau **(Efriyeldi & Effendi, 2022)** and similar findings in Moheshkhali Island, Bangladesh **(Uddin *et al.*, 2024)**. Interestingly, the male-biased sex ratio observed in this study aligns more closely with ratios seen in other bivalves such as *Aulacomya ater* (66:34%), *Perna perna* (64:36%), and *Choromytilus meridionalis* (60:40%) as reported by **van Erkom Schurink and Griffiths (1991)**.

According to **Al Ayubi and Gimin (2016)**, a predominantly male population may lead to reduced egg production and decreased genetic diversity, potentially impacting reproductive success. This skewed ratio is often linked to environmental stressors and long-term exploitation, which accelerate male maturation and the transition to females. Further support comes from **Yurimoto *et al.* (2024)**, who argue that environmental factors such as salinity and chlorophyll concentrations may influence maturation rates and reproductive cycles, contributing to the observed imbalance.

Reproductive observations revealed that most individuals were at Gonadal Maturity Level I (Immature), with only a small proportion reaching Level III (Mature), indicating early developmental stages during the study period. The classification of maturity stages used in this study follows the five-stage framework established by **Maung *et al.* (2021)**. The low levels of maturity observed are likely linked to the reproductive season, which varies by location. Peak spawning seasons for *T. granosa* have been recorded from October to January in the Strait of Malacca **(Khalil, 2013)**, January to March along the

Riau Coast **(Efriyeldi & Effendi, 2022)**, November to January in West Langsa **(Mawardi *et al.*, 2024)**, and January in Maluku **(Tuhumury *et al.*, 2024)**. These spawning periods typically coincide with the rainy season, which brings favorable water temperatures and salinity levels. As reported by **Yurimoto *et al.* (2014)** and **Srisunont and Srisunont (2022)**, seasonal rainfall, freshwater runoff, and stable temperature conditions support gonadal development and reproductive success.

The bioaccumulation of heavy metals is another critical concern for food safety and environmental health. According to **Jomova *et al.* (2024)** and **Yap and Al-Mutairi (2024)**, lead (Pb) exposure can result in neurological disorders, developmental delays in children, kidney damage, and hypertension. While zinc (Zn) is an essential trace element, excessive exposure can lead to nausea, weakened immune function, and copper deficiency, as noted by **Jyothi (2020)**. Blood cockles are known to accumulate heavy metals from sediments and water, making them valuable bioindicators for monitoring marine pollution. **Dinulislam *et al.* (2021)** noted that metal bioaccumulation is influenced by the age, size, and environmental conditions of the habitat.

In this study, the concentrations of Pb and Zn in the cockle tissues remained within the permissible limits established by **BPOM (2022)**, which are 2.0 mg/kg for Pb and 40 mg/kg for Zn. These results confirm that blood cockles from North Aceh remain safe for consumption. Similar findings were reported by **Sudsandee *et al.* (2017)**, who found that heavy metal levels in bivalves were below hazard thresholds, and **Soegianto *et al.* (2020)**, who recorded lower Pb levels but higher Zn levels in Eastern Indonesia. Nonetheless, the presence of Pb and Zn in coastal waters can often be traced back to industrial discharge, urban runoff, agricultural activity, mining, and improper waste disposal.

Several measures can help minimize heavy metal contamination in blood cockles, including depuration (holding cockles in clean water), raising them in controlled aquaculture systems with filtered water to reduce exposure by up to 31.5%, and conducting regular testing of both water and cockle tissues to detect contamination early **(Sudsandee *et al.*, 2017)**. A regression analysis conducted in this study revealed strong correlations between heavy metal concentration and body weight, with correlation coefficients of 89% for Pb and 97% for Zn. This suggests that heavier cockles may accumulate more metals, a finding consistent with the work of **Yunus *et al.* (2014)**, who noted that younger cockles tend to retain fewer metals due to shorter exposure times and higher metabolic activity. Conversely, **Amisah *et al.* (2009)** and **Mahmudi and Musa (2015)** reported that larger cockles exhibit higher levels of bioaccumulation, further confirming that both growth dynamics and environmental exposure influence metal uptake.

Finally, the water quality parameters recorded during this study—including salinity, temperature, dissolved oxygen, and pH—were found to be within the optimal ranges for the survival and growth of *Anadara granosa*, as established by **KLH (2004)** and **Prasetiyono *et al.* (2022)**. Although these parameters indicate a suitable habitat, the presence of heavy metals highlights that good water quality alone does not ensure the absence of contaminants. As explained by **Abouzied *et al.* (2022)** and **Zhang *et al.* (2023b)**, high-quality water may still contain harmful substances due to natural or anthropogenic processes.

Each water quality parameter plays a critical role in the health of blood cockles. Salinity affects osmoregulation and metabolism **(Srisunont & Srisunont, 2022)**, with optimal growth typically observed between 20 and 30 ppt **(Baker *et al.*, 2002)**. A pH range of 6.5–7.5 is favorable for physiological function, while deviations can disrupt shell formation and metabolic processes. Adequate dissolved oxygen levels—at least 3 mg/L—are essential for respiration and survival, with hypoxic conditions posing serious threats to cockle health **(Saif *et al.*, 2020; Srisunont & Srisunont, 2022)**. Temperatures above 30°C can increase metabolic demands, leading to stress and reduced growth rates **(Baker *et al.*, 2002; Ihwan *et al.*, 2025)**.

CONCLUSION

The study results indicate that the morphometric measurements of blood cockles showed no significant differences between males and females or across sampling locations. Allometric variation was observed, with males having higher values compared to females, while the condition factor remained stable at all stations. The meat yield of female blood cockles was slightly greater than that of males, though statistically, the difference was not significant. The sex ratio revealed that male cockles were dominant, with an average ratio of 2.46:1, and statistical analysis showed significant differences in sex percentages. Gonadal observations revealed that most cockles were in Gonadal Maturity Level I (immature), with further development observed but not yet fully matured in Level III. Heavy metal concentrations of Pb and Zn in cockle meat were within acceptable limits set by BPOM, with a strong correlation between heavy metal content and cockle body weight. Water quality parameters at all stations met environmental standards, with salinity, pH, dissolved oxygen (DO), and temperature supporting a healthy ecosystem for blood cockles. Overall, the findings suggest that blood cockles and their habitat in the study areas are in good condition, providing a safe and sustainable environment for their survival.

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