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Reproductive Biology and Condition Index of *Meretrix meretrix* in Marudu Bay, Malaysia: Implications for Conservation and Management

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ABSTRACT

The Asiatic hard clam, *Meretrix meretrix*, is a crucial bivalve species that supports artisanal fisheries in Marudu Bay, Sabah, Malaysia. However, the clam population has declined due to overexploitation. The objective of this study was to investigate the gonad development of the clam in response to environmental variations. Five hundred specimens were collected and analyzed for gonad and condition indexes over ten months. The population of clams was dioecious with a ♀ dominance (♂:♀ ratio of 1:1.058), and hermaphrodites were infrequent (0.4%). The clam exhibited year-round spawning with increased peaks in July-August and November-December. Monthly variation was observed in the condition index ($P<0.05$) but not in the gonad index ($P>0.05$). The condition index was correlated with environmental variables, while the gonad index was only linked with total rainfall. This study provides essential insights into the reproductive biology of *Meretrix meretrix*, which can aid in its sustainable management and conservation.

INTRODUCTION

Meretrix meretrix, also known as Asiatic hard clam, is a common bivalve species found in the coastal waters of Sabah, Malaysia, as reported by **Ridzwan and Kaswandi (1995)**, **Abdullah *et al.* (2007)** and **Mohd Hamdan *et al.* (2020)**. This bivalve species is vital for artisanal fishery (**Mohd Hamdan *et al.*, 2017**) and is dominant in the muddy sandy shore of Marudu Bay (**Tan *et al.*, 2017**). In contrast to the People's Republic of China (**Tang *et al.*, 2006**; **Huang *et al.*, 2016**), the supply of *M. meretrix* in the Malaysian market comes mainly from the wild and not from aquaculture (**Mohd Hamdan *et al.*, 2020**). However, **Tan *et al.* (2017)** and **Admodisastro *et al.* (2021)** have reported that the clam population in Marudu Bay is already being overexploited, and there is limited information on its breeding and recruitment in the bay. Although **Duisan**

***et al.* (2021)** briefly investigated the gonad development of *M. meretrix* according to shell size, additional research is necessary to preserve this clam resource in the bay. The current study aimed to examine the gametogenesis and condition of *M. meretrix* in Marudu Bay and its association with environmental factors.

MATERIALS AND METHODS

1. Sampling site

Sampling was carried out at five stations on the muddy shores in the inner part of Marudu Bay (6035’ to 70N; 116045’ to 1170E) for ten months from May 2019 to February 2020 (Fig. 1). Marudu Bay experiences heavy rainfall during the northeast monsoon (NEM) from November to March each year, and limited rainfall during the southwest monsoon (SWM) from May to September (**Malaysian Meteorological Department, 2021**). These meteorological patterns have been well documented in previous studies (e.g., **Tan & Ransangan, 2016**) and can significantly affect the environmental variables, which in turn can influence the growth and development of bivalve species such as the Asiatic hard clam, *Meretrix meretrix*. Therefore, understanding the relationship between the environmental variables and the reproductive biology of *M. meretrix* is essential for its sustainable management and conservation.

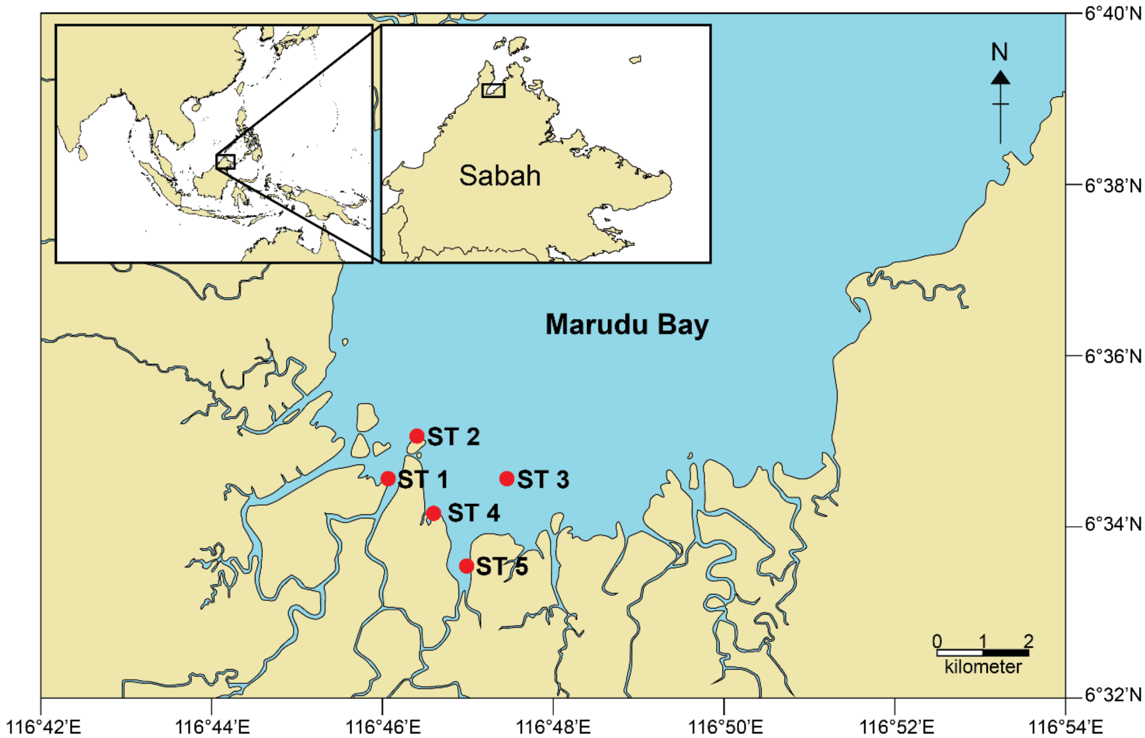

Fig. 1. Study sites in the inner part of Marudu Bay, Sabah, Malaysia

2. Clam collection

During the period of May 2019 to February 2020, 500 clams (n = 50 clams/month) were collected, ranging in size from 24.50 to 74.50mm. The clams were collected using a kerek fishing gear (**Tan *et al.*, 2017**). The shell length and total weight of each specimen were measured in the laboratory using a vernier caliper (Mitutoyo, Malaysia) and an electronic balance (Shimazu, Malaysia), respectively.

3. Environmental variables

Monthly measurements of *in situ* physical parameters, including temperature (°C), salinity (ppt), pH, and dissolved oxygen (mg/L) were taken at 0.5m above the sediment surface using a YSI multi-function environmental probe (YSI, Loveland, CO, USA). Water transparency was assessed using a Secchi disc, and seawater depth (m) was recorded using a depth sounder (Hondex, Japan). Monthly rainfall data from May 2019 to February 2020 were obtained from the Meteorology Department of Malaysia. Water samples (3L) were collected in triplicate at 0.5m above the seafloor using a Van Dorn water sampler for total seston (total particulate matter, TPM; particle organic matter, POM; particle inorganic matter, PIM, and organic content, OC), chlorophyll-*a*, dissolved nutrients, and phytoplankton analyses. The determination of total seston followed **Wong and Cheung (1999)**. Chlorophyll-*a* concentration and dissolved nutrients (total ammonia-nitrogen, total phosphate, nitrate, and nitrite) were analyzed according to **Parson *et al.* (1984)**. For phytoplankton, the Utermöhl sedimentation method was used for sample processing (**Utermöhl, 1958**), and cell counts were calculated according to **Aktan *et al.* (2005)**. Phytoplankton samples were identified to the genus level using the taxonomic keys of **Tomas (1996)** and **Hartley *et al.* (1996)** after observation under an inverted microscope. Phytoplankton species diversity and evenness were calculated and expressed using the Shannon-Wiener index (H') (**Shannon & Weaver, 1963**) and Pielou's evenness index (J') (**Pielou, 1966**), respectively, using the formula below:

Shannon-Wiener Index, H'

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Where, pi is the composition of each phytoplankton taxa.

Pielou's Evenness Index, J'

$$J = \frac{H'}{\ln(S)}$$

Where,

H' = Shannon-Wiener index
S = Total number of phytoplankton taxa

4. Condition index

Two hundred and fifty clams were dissected and dried at 105°C using a Memmert oven (Memmert, Germany) for 24 hours before being weighed. The condition index (CI) was determined using the formula described by **Freeman (1974)** and **Hamli *et al.* (2017)** as the percentage of the ratio of dry tissue/organic weight (DW) to the dry shell weight (DSW), as follows:

$$CI = \frac{DW\ (g)}{DSW\ (g)}\ x\ 100$$

5. Gonad histology

A total of 250 clam specimens (>21mm shell length) were analyzed in this study by removing their gonads and subjecting them to histological examination as described in **Duisan *et al.* (2021)**. Each specimen's sex was determined, and gametogenesis stages (resting, development, maturity, spawning, and spent) were classified based on **Wilson and Seed (1974)** grouping system.

6. Gonad index

The classification of gonad development stages of the clams was based on the methods proposed by **Cebballos-Vazquez *et al.* (2000)** and **Hamli *et al.* (2015)**. The gonad index was computed using the formula recommended by **King *et al.* (1989)**.

$$GI = \frac{\sum \mathrm{nR}}{\mathrm{N}}$$

Where, n denotes the number of each gonad development stage; R denotes the rank of the stage, and N denotes the total sample size.

The numerical ranking of the gonad development stage (1 = Resting and spent stages, 2 = Developing, 3 = Ripe and spawning).

7. Data and statistical analyses

The IBM SPSS Statistics software version 26 was used for statistical analysis in this study. All analyses were conducted with a 95% confidence level. Prior to analysis, normality tests were performed on the environmental variables, condition index, overall gonad index, and male and female gonad index data using the Shapiro-Wilk test. The chi-square test analysis was used to determine the significant difference in sex ratio among the clams. The one-way ANOVA was used to test the significant difference in condition index and gonad index between months, followed by the Tukey multiple comparisons (Tukey HSD). The Kruskal-Wallis test was used to analyze the significant difference in gonad index between males and females. Pearson correlation was employed to analyze the correlation between the gonad index and condition index with different environmental parameters, and the correlation between the condition index values with the gonad index. Statistical tests were considered significant when the *p*-value was less than 0.05 ($p<0.05$).

RESULTS

1. Sex ratio

In this study, 250 specimens of *M. meretrix* were analyzed, and 121 (48.4%) males and 128 (51.2%) females were successfully identified. The overall sex ratio was 1:1.058 (male:female), and a low occurrence of hermaphrodites (0.4%) was observed. Although the number of females was higher than males, it was not significantly deviated (χ^2:0.2, df:1 $P>0.05$) from the expected 1:1 ratio. In Marudu Bay, the population of *M. meretrix* showed seasonal variations in sex ratios. Males were dominant in August 2019, September 2019, October 2019, and February 2020, while females were dominant in June 2019, July 2019, November 2019, December 2019, and January 2020, forming 56%, 68%, 52%, 52%, and 76% of the population, respectively. In May 2020, an equal proportion of males and females were observed, but with the presence of 4% hermaphrodite specimens. The highest female dominancy (76%) was significantly ($P<0.05$) recorded in January 2020.

2. Gonad development

In this study, the gonad development of *M. meretrix* was observed, and five stages of development were identified, including resting, developing, ripe or mature, partially spawning, and spent. Figs. (2, 3) illustrate the gonad development stages for males and females, respectively, while Fig. (4) shows the gonad development stages in hermaphrodite clams.

3. Temporal variation in gonad development

The gonadal histology analysis of *M. meretrix* in Marudu Bay revealed the presence of all five stages of gonad development (resting, development, ripe, spawning, and spent) during most months. However, the resting and spent stages were absent in August 2019 and January 2020 and in June 2019 and September 2019, respectively. The spawning stage occurred every month, with the highest proportion of clams (36%) in the spawning stage observed in September 2019 and the lowest proportion (20%) in July 2019. Fig. (5a) presents the temporal variations in the gonad development of the clams. Analysis of male gonads revealed that all stages of gonad development were present in clams collected in May 2019, July 2019, October 2019, December 2019, and February 2019 (Fig. 5b). In contrast, females exhibited all stages of gonad development only in December 2019 (Fig. 5c). Notably, the resting stage was observed more frequently in males than in females.

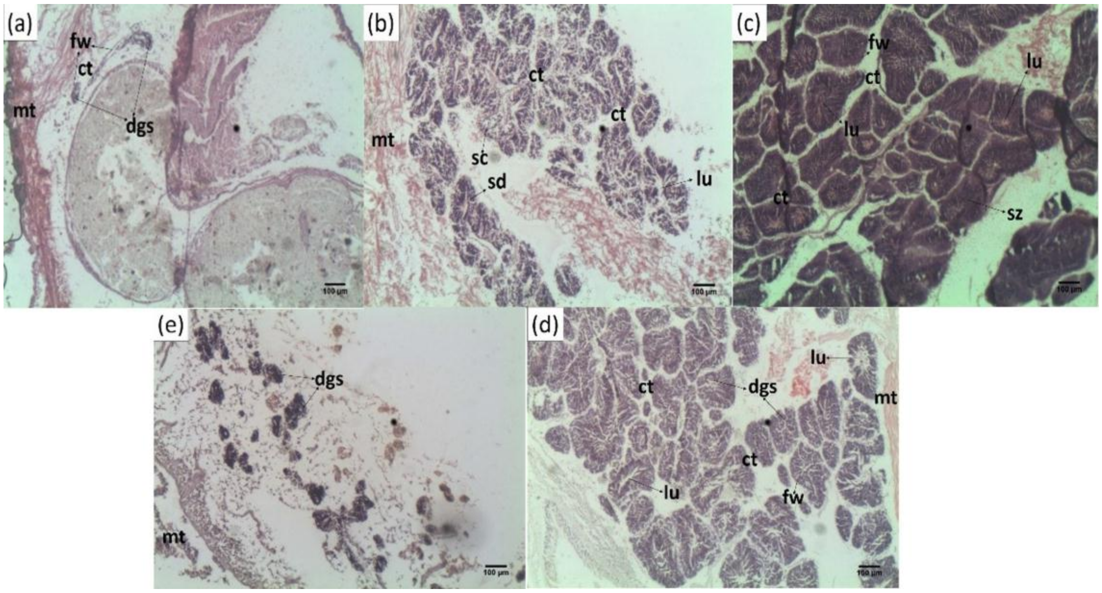

Fig. 2. Gonad development stages in male clams showing: (a) Resting stage; (b) Developing stage; (c) Ripe stage; (d) Spawning; (e) Spent

(Note: lu: lumen, ct: connective tissue, fw: follicle wall, mt: muscular tissue, sc: spermatocyte, sz: spermatozoa, sd:spermatid, dgs: degenerate spermatocyte/spermatid/spermatozoa).

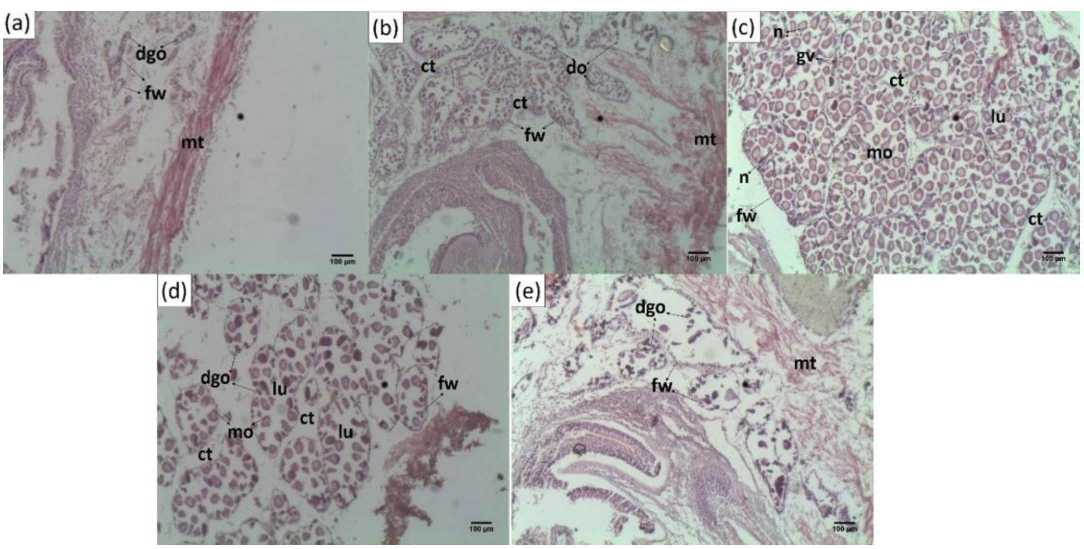

Fig. 3. Gonad development stages in female clams showing: (a) Resting; (b) Developing; (c) Ripe; (d) Spawning; (e) Spent

(Note: lu: lumen, ct: connective tissue, fw: follicle wall, mt: muscular tissue, do: developing oocyte, mo: matured oocyte, dgo: degenerate oocyte, n: nucleus, gv: germinal vesical).

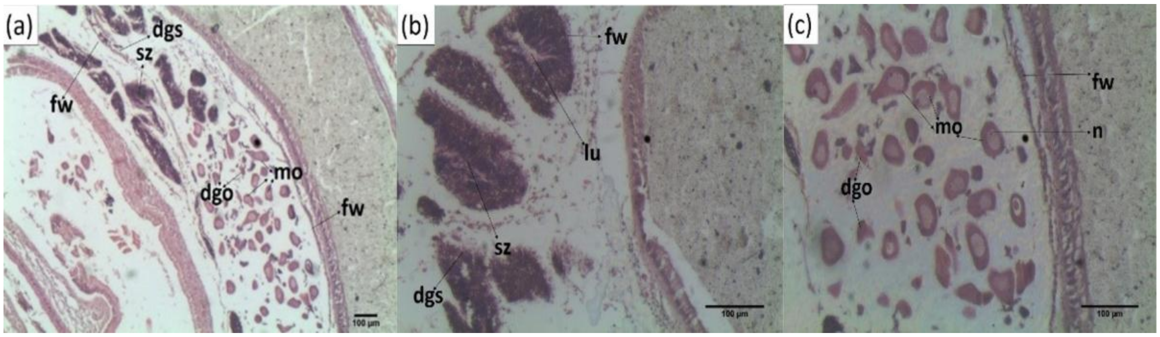

Fig. 4. Gonad development stages of hermaphrodite clams displaying: (a) Partially spawning; (b) Male gametes in hermaphrodite gonad; (c) Female gametes in the hermaphrodite gonad
(Note: lu: lumen, ct: connective tissue, fw: follicle wall, mt: muscular tissue, do: developing oocyte, mo: matured oocyte, dgo: degenerate oocyte, n: nucleus, sc: spermatocyte, sz: spermatozoa, sd: spermatid, dgs: degenerate spermatocyte/spermatid/spermatozoa).

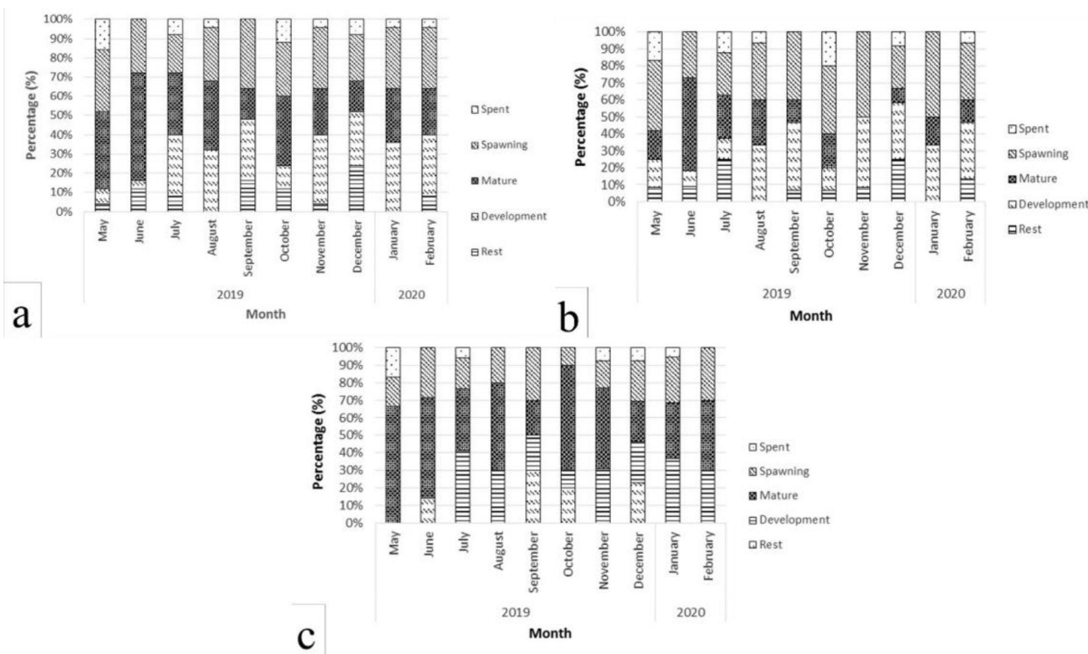

Fig. 5. Temporal variation of gonad development (%) of the clams showing: (a) Overall; (b) Male, and (c) Female.

4. Gonad index

The findings of this study showed variations in the gonad index of *M. meretrix* (Fig. 6a), with the highest index recorded in June 2019 (2.72) and the lowest in December 2019 (2.08). However, the observed differences were not statistically significant (P>0.05). Male and female clams were observed in the ripe and spawning stages almost throughout the year, which was consistent with the gonad indexes (Fig. 6b) recorded for males (2.00 to 2.73) and females (2.15 to 2.75). The results of the Kruskal-Wallis nonparametric test showed no significant difference (*P*>0.05) in the gonad indexes between sexes.

5. Condition index

In this study, the condition index of *M. meretrix* was investigated and ranged from 4.67 to 2.54, with a mean value of 3.39±0.59 (Fig. 6c). Notably, the condition index exhibited significant temporal variation (*P*<0.05), with the highest mean value recorded in June 2019 (4.67±1.43), and comparatively lower mean values in October 2019 (3.05±0.45), December 2019 (2.54±0.35), and February 2020 (3.00±0.20), respectively.

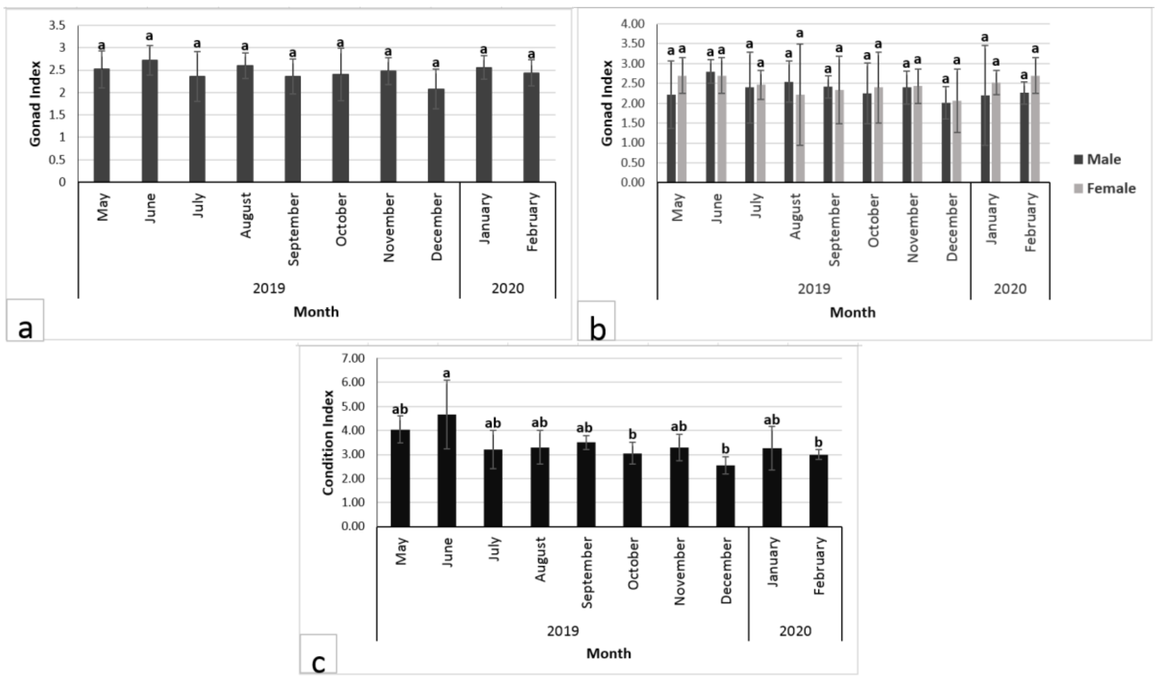

Fig. 6. Temporal variation in gonad and condition indexes exhibiting: (a) Overall temporal variation of gonad indexes; (b) Temporal variation of gonad indices in males and females clams; (c) Overall temporal variation in condition index.

6. Correlation between condition index and environmental variables

Analysis of the monthly condition index (Table 1) showed a positive correlation with environmental variables such as temperature, salinity, seston (total particulate matter and particulate organic matter), and chlorophyll-*a*. In contrast, a negative correlation was observed between the condition index and ammonia nitrogen concentration, total phosphorus concentration, Shannon Weaver diversity index, Pielou Evenness Index, dinoflagellates cell density, and total rainfall. No significant correlation was observed between the condition index and other environmental variables.

Table 1: Pearson's correlation of the condition index and environmental variables

Environmental variable	r	Significant (2-tailed)
Temperature	0.342*	0.015
Salinity	0.331*	0.019
Total Particulate Matter (TPM)	0.287*	0.043
Particulate Organic Matter (POM)	0.381**	0.006
Chlorophyll-*a*	0.360*	0.010
Dinoflagellates	-0.285*	0.045
Shannon Weaver Diversity Index	-0.391**	0.005
Pielou Evenness Index	-0.293*	0.039
Total Ammonia Nitrogen	-0.281*	0.048
Total Phosphorus	-0.348*	0.013
Total Rainfall	-0.361*	0.010

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

7. Correlation between gonad index and the environmental variables

The results of the Pearson correlation analysis showed a significant positive correlation (r = 0.286*, P = 0.044) between the gonad index value of *M. meretrix* and the condition index. Statistical analysis revealed a significant difference (P< 0.05) in the condition index between months, while no significant variation (P> 0.05) was observed in the gonad index throughout the sampling period. The highest and lowest values for the condition and gonad indices, respectively, were recorded in June 2019 and December 2019. Moreover, a significant negative correlation (P< 0.05) was observed between the gonad index and total rainfall (r = -0.286, P = 0.044). However, no significant correlation was found between the gonad index and other environmental variables.

DISCUSSION

1. Sex ratio

The gonads of *M. meretrix* clams are located between the lower part of the mid-intestinal glands and connective tissue of the foot and appear externally milky white to creamy. However, external features cannot reliably determine the sex of the clam. Hence, a histological analysis was conducted to determine the sex distribution of the population. The examination revealed that the clam population in the study area was mostly dioecious, with a slightly skewed distribution towards females, and a sex ratio (male:female) of 1:1.058, consistent with a previous study by **Duisan *et al.* (2021)**. Female-dominated populations were reported in Korampallam Creek and Maharashtra, while the Vellar Estuary in India was male-dominated **(Jayabal & Kalyani, 1986**; **Narasimham *et al.*, 1988**; **Sawant & Mohite, 2013)**. The female-biased sex ratio observed in the current study maximizes population reproductive success. Hermaphroditism was observed in 0.4% of the clam population, which contrasts with the report of **Duisan *et al.* (2021)**. This difference could be attributed to the larger sample size in the current study (n=250) compared to their previous work (n=86). A related study by **Chu and Kumar (2008)** on *M. lyrata* species reported that 6% of individuals in the population exhibited hermaphroditism. The low occurrence of functional hermaphroditism in dioecious bivalve species serves as a "fail-safe" mechanism for species survival in the absence of cross-fertilization, according to **Cohen (1966)**.

2. Temporal variation in gametogenesis, gonad index, and condition index

The results of this study indicate that gametogenesis, maturation, and spawning occur throughout the year in Marudu Bay, as evidenced by the presence of gonads in developing, mature, and spawning stages every month. The high mean gonad index values (2.08-2.72) suggest that most clams undergo gonad maturation each month. While peak spawning occurred in June to July 2019 and November to December 2019, respectively, high percentages of clams were observed to spawn throughout the year. This observation is in line with the continuous breeding pattern exhibited by many members of the Veneridae family, including *M. meretrix*, which typically exhibit one to three spawning peaks annually **(Jagadis & Rajagopal, 2007**). The continuous gametogenic development observed in the *M. meretrix* population in this study is consistent with earlier observations by **Rai (1932)** of year-round breeding in this species, which was linked to favorable conditions.

The results of this study suggest that the number of clams in the spent and resting stages was lower than in other stages, indicating a short duration of these stages. The low number of individuals with spent and resting gonads observed each month suggests that the clams likely moved to the next gametogenesis stage during subsequent sampling. Similar observations have been reported in other studies, such as those of *Paphia undulate* (**Campos & Campos, 2010)** and *Lutraria philippinarum* from Negros Occidental, Philippines (**Bantoto & Ilano, 2012**). **Campos and Campos (2010)** noted that tropical species tend to redevelop new gametes soon after spawning.

Based on the findings of this study, the clam stock in Marudu Bay can be classified as having moderate fatness, as measured by the condition index. This is consistent with similar studies conducted by **Admodisastro *et al.* (2021)** and **Duisan *et al.* (2021)** in the same area. The condition index values observed in this study are comparable to those reported for *Meretrix* species in Maharashtra, India (**Lagade *et al.*, 2015**). On the other hand, they are lower than those reported for *M. meretrix* populations in Korampallam, India (**Narasimhan *et al.*, 1988**). Additionally, the condition index values for the clams are similar to those reported for other *Meretrix* species, such as *M. casta* from Goa, India (**Krishna Kumari *et al.*, 1977**) and *M. lyrata* from Sarawak, Malaysia **(Hamli *et al.*, 2017**).

3. Correlation between condition index and environmental variables

Spawning is a known factor that can contribute to a significant loss in tissue weight as gamete release occurs (**Sahin *et al.*, 2006**), which can lead to a decrease in the condition index of bivalves during the spawning season. However, it is important to note that water parameters can also have an impact on the index (**Hamli *et al.*, 2017**). In particular, *M. meretrix* is sensitive to temperature changes, with a decrease to 25°C causing up to a 17% reduction in the condition index and a 36% reduction at 20°C **(Lagade & Mulley, 2014)**. Additionally, **Zhuang and Wang (2004)** found a significant increase in the absorbance efficiency of *M. meretrix* during feeding as the temperature rises. In December 2019, the lowest temperature (26.67°C) was recorded, which may explain the low condition index value for that month. There is a significant positive correlation between the condition index and temperature (r: 0.342*, P = 0.015).

In December 2019, the recorded salinity was at its lowest point (14.87ppt), likely due to heavy rainfall during the northeast monsoon season. The condition index of *M. meretrix* was found to have a negative correlation with total rainfall (r=-0.361*, p=0.010). Meretrix clams have the highest ingestion rate at a salinity range of 27 to 30 ppt, and levels outside this range can decrease ingestion rates. Salinity below 18 ppt is particularly stressful to the clams and impairs feeding, leading to a decline in flesh quality **(Zhuang, 2006)**. Additionally, Venerid clams cannot maintain normal metabolic activity below a salinity of 15 ppt **(Kim *et al.*, 2001)**. This may explain the correlation observed in this study between the condition index and salinity (r=0.331*, P=0.019).

The study found that the condition index was positively correlated with total particulate matter (TPM) (r=0.287*, P=0.043), particulate organic matter (POM) (r=0.381**, P=0.006), and chlorophyll-*a* (r=0.360*, P=0.010) concentrations. This suggests that food availability and quality are the primary determinants of flesh quality in *M. meretrix*. Furthermore, a higher condition index was associated with months having greater chlorophyll-*a* concentrations in the seawater. POM is a commonly used measure of food availability for bivalves **(Grant & Bacher, 1998; Hawkins *et al.*, 1998)**.

The study observed a negative correlation between the condition index of *M. meretrix* and ammonia nitrogen (r=-0.281*, P=0.048) and total phosphorus (r=-0.348*, P=0.013) concentrations. The study site is located near the river mouth and experiences heavy rainfall during the northeast monsoon, which brings nutrients from the runoff **(Adam *et al.*, 2011; Mohammad-Noor *et al.*, 2012)**. Bivalves release ammonia nitrogen into the environment during their metabolic process, leading to higher ammonia nitrogen concentrations in areas with high densities of bivalves **(Strain, 2002)**. High nutrient concentrations cause stress to bivalves, reducing their assimilation and feeding activity, and eventually leading to growth setbacks **(Gosling, 2003**; **Sobral & Fernandes, 2004)**. The study also found a negative correlation between the condition index and dinoflagellate cell density, suggesting that dinoflagellates did not satisfy the nutritional requirements of the clams compared to diatoms. Diatoms are a better food source due to their high percentage of unsaturated and polyunsaturated fatty acids and oil reserves **(Ahlgren *et al.*, 1992)**.

4. Correlation between gonad index and the environmental variables

The present study found a significant positive correlation between the gonad index and the condition index (r = 0.286, $P = 0.044$). The condition index is a widely used eco-physiological approach to estimate meat quality and yield in bivalves, and it is sensitive to changes in the reproductive cycle. Typically, the condition index correlates well with the gonad index (**Ojea *et al.,* 2004; Peharda *et al.,* 2006**), making it a quick method to assess the reproductive condition of bivalve broodstock (**Gribben *et al.,* 2004**). The gonad contributes significantly to the total weight of the individual bivalve, representing about 59% of the total soft tissue weight (**Duinker *et al.,* 2008**). Both indices showed the highest value in June 2019 and the lowest in December 2019, which could be attributed to more clams being in the mature and partially spawning phases in June 2019 and a larger proportion in the resting and spent stages in December 2019. **Hamli *et al.* (2017)** suggested that more somatic biomass accumulates when the gonad reaches the maturation stage, leading to an increase in the condition index. In contrast, the condition index decreases when the gonad is in the spent or resting stage.

The gonad index in this study exhibited a significant negative correlation with the total monthly rainfall (r = -0.286, $P= 0.044$). Though salinity is known to play an important role in the reproductive cycle of *Meretrix* clam (**Jayabal & Kalyani, 1987**), there was no significant correlation between salinity and the gonad index. However, the highest total rainfall during the northeast monsoon season coincided with the lowest gonad index and the lowest salinity. Rainfall is often considered a driving factor of reproductive cycles in clams inhabiting tidal flats due to its ability to reduce salinity **(Riascos, 2006; Nakamura *et al.,* 2010; Baek *et al.,* 2014)**. This finding suggests that environmental variables have more effect on the condition index than that recorded on the gonad index.

5. Suggested conservation and management strategies

Based on the findings of this study, three management strategies and conservation policies are proposed to safeguard the dwindling local resources of *M. meretrix*. The first strategy is the implementation of fishing regulations to control harvesting activities and prevent overexploitation of the species. The second strategy is the adoption of community-based fisheries co-management and marine reserves to involve local communities in the conservation and management of the resources. The third strategy is the establishment of regular stock assessment and monitoring activities to determine the status of the population and assess the effectiveness of the implemented management strategies.

5.1 Fishing regulation

Artisanal fisheries are crucial for the livelihoods and food security of millions of people worldwide, and if well-managed, they can contribute significantly to socio-economic development **(Cohen, 1966**; **Béné *et al.*, 2010)**. However, *M. meretrix* is not currently included in the IUCN Red List of Threatened Species, and therefore, there are no guidelines or regulations available for its harvesting. The Malaysian Department of Fisheries (DOF) introduced Fisheries (Cockle Conservation and Culture) in 2002, but this regulation is restricted to cockles. Hence, fishing regulations for *M. meretrix* should be enforced and supervised under the management of the local fisheries department.

Fishing regulations, such as establishing a quota system for clam harvesting to limit the number of clams taken from the bay each year, prohibitory fishing size, and seasonal closure of the fishery during peak spawning periods, should be implemented to allow for the reproduction and replenishment of the clam population **(Zhang *et al.*, 2021)**. However, it is important to note that fishermen may resist regulations that ignore the economic aspects of their community since they are more concerned with short-term economic benefits or meeting their daily needs **(Priyo *et al.*, 2015)**. Nevertheless, some form of intervention through fisheries regulation is necessary to reduce resource exploitation and preserve not only the sustainability of the species but also their habitat.

According to **Gosling (2003)**, the effectiveness of fisheries management regulations depends on their enforcement, and public education should be used instead of coercion. This can help raise public awareness about the importance of sustainable clam harvesting practices and the need for conservation efforts to protect the clam population. One potential strategy could be to create marine protected areas in the bay to ensure the preservation of the clam population and its habitat.

5.2 Community-based fisheries co-management system

Establishing a community-based management system is a recommended approach for managing and conserving clam populations by engaging local fishermen and stakeholders in decision-making processes. Co-management, which recognizes the importance of involving user groups in creating sustainable livelihoods and implementing management policies, is an accepted tool in coastal management **(SEAFDEC, 2001)**. The local fishers can sustain their livelihoods by collecting and selling clams while also practicing sea ranching or farming. This involves rearing the juvenile clams they catch and allowing them to breed in the wild before marketing them.

Clam farming is a sustainable alternative to wild harvesting, as it is eco-friendly and involves low-cost culture technology. It can also help reduce the pressure on wild populations and promote socio-economic development in coastal rural communities. The best management practices for sea ranching or farming will depend on site-specific circumstances, economic opportunities, and environmental considerations **(Leavitt, 2004)**. To ensure the sustainability of clam fisheries, it is also essential to establish marine reserves that protect resources from various forms of human exploitation **(SEAFDEC, 2001; Suanrattanachai, 2011)**. Moreover, promoting eco-tourism practices that encourage the conservation of the clam population and its habitat while providing economic benefits to the local community is encouraged. This management strategy has been implemented in various shellfish fisheries worldwide, including in Latin America **(Castilla and Defeo. 2001**), Southeast Asia **(Gorris, 2016)**, the Mediterranean **(Raicevich *et al.*, 2018**), China **(Huang & He, 2019)** and Europe **(Hansen *et al.*, 2023)**. Therefore, implementing sustainable management practices can aid in the conservation and long-term viability of *M. meretrix* populations in Marudu Bay and other similar areas.

5.3 Regular stock assessment and monitoring activity

The sustainable management of fishery resources is crucial for the long-term viability of the fishing industry. Regular stock assessments have gained worldwide attention as an effective management practice **(Nagvenkar, 2014)**. These assessments provide important information for impact assessment studies and aid in fisheries regulation and management. The data collected from these assessments are critical for evaluating management decisions **(Wijsman *et al.*, 2009)**. To ensure the conservation of *M. meretrix* in Marudu Bay, regular surveys and monitoring of the population and its environment are necessary. These measures will enable the tracking of population trends and the evaluation of the effectiveness of management strategies. A comprehensive management plan that prioritizes the sustainability and conservation of the *M. meretrix* population should be developed and implemented in collaboration with government agencies and other stakeholders.

CONCLUSION

In conclusion, the study found that the clam population in Marudu Bay was mostly dioecious, with a slightly skewed distribution towards females and a low occurrence of functional hermaphroditism. The continuous gametogenic development observed in the *M. meretrix* population suggests that gametogenesis, maturation, and spawning occur throughout the year in Marudu Bay. The study also found that environmental factors such as salinity, temperature, and food availability were significant determinants of the condition index of the clams. Based on the findings, the study proposes three management strategies and conservation policies to safeguard the dwindling local resources of *M. meretrix*, including implementing fishing regulations, adopting community-based fisheries co-management and marine reserves, and establishing regular stock assessment and monitoring activities. These strategies have been successfully implemented in various clam fisheries management programs worldwide, and their implementation can aid in the conservation and long-term viability of *M. meretrix* populations in Marudu Bay and other similar areas.

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