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Small Tropical Abalone (*Haliotis squamata* Reeve, 1846) in Indonesia: Current Research Status and Future Prospect

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ABSTRACT

Abalone farming is gaining popularity worldwide as demand grows. The importance of abalone farming throughout Indonesia is due in part to expanding demand for both local and foreign abalone, and to a growing awareness of the necessity for sustainable seafood production. This study relies on fourty-six scientific papers published between 2000 and 2023. The distribution and variety, bio-reproduction and breeding, growth, and commerce of small tropical abalones are carefully explored to highlight the current research state, as well as the opportunities and challenges in the existing abalone sector. Finally, all interactions yield findings that can be utilized to guide government policy. To realize its full potential, the Indonesian abalone industry must overcome difficulties such as competition and price fluctuations. Key goals include developing sustainability collection and trading methods, reliably supplying high-quality abalone goods, and expanding their reach through global trade. Addressing these challenges will enable the Indonesian abalone industry to thrive in the next years. The abalone business in Indonesia has a long history, is now growing and active, and presents significant potential. With ongoing R&D investments, the Indonesian abalone sector can meet national and global market demands while being sustainable. Understanding the current situation of abalone research in Indonesia is critical to maintaining the industry's long-term survival.

Keywords: Abalone; *Haliotis*; Shellfish; Tropical; Aquaculture

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INTRODUCTION

Aquaculture supplies two-thirds of Indonesia's animal protein requirements. It is an important contribution to the economy of Indonesia, employing within 2.5 million people, supplying nourishment, and creating significant foreign cash and domestic revenue. In the past, global abalone production was mostly dependent on fisheries; however, aquaculture now accounts for more than 95% of abalone production (Hernández-Casas *et al.*, 2023). Though abalone quantity produced is low in comparison to other seafood items, it is highly valued, accounting for about 2.6 billion dollars in 2017. Abalone is recognized as the second most important species of aquaculture in many countries currently, such as Indonesia, because of its high price (as much as of US$33/kg) and the reality that its cultivation has grown into a successful aqua-business venture.

Indonesia has a high potential for abalone farming due to its abundant coastal resources and vast interior water bodies. A growing population and falling fisheries production have resulted in an increasing disparity among supply and demand for seafood. Globally, farm production increased from low levels in the 1970s to 243,506 mt in 2020/21. Abalones are a highly profitable shellfish in China's aquaculture industry. In 2020, China's abalone aquaculture production reached 203,500 tons, which represents nearly 90% of global production (Gao, *et al.*, 2023).

Abalone cultivation seemed to be very promising because global demand remained high (Taridalla *et al.*, 2021). It has gained in relevance in Indonesia, with numerous scholars and practitioners researching various aspects of abalone technology (Wamucii, 2023). The importance of abalone farming in Indonesia stems in part from rising demand for domestic and international abalone, as well as a growing recognition of the necessity for sustainable seafood production (Tridge, 2003). Consequently, understanding the current state of abalone study in Indonesia is crucial for the industry's long-term viability.

MATERIALS AND METHODS

The paper utilizes material from fourty-six scholarly articles published between 2000 and 2023. The range and diversity, bioreproduction and breeding, growth, and trade of small abalone are all well explored. Based on these articles, the current state of research was given, as well as the potential and challenges of the abalone sector. Finally, all talks concluded that may be used to enact government policy.

RESULTS AND DISCUSSION

Distribution and diversity

Abalone is a gastropod from the Haliotidae family, genus *Haliotis*, that lives in tropical and temperate oceans (Gieger 2000). Abalone can be found in both intertidal and subtidal environments, however they are more common in rocky habitats and locations with high waves (Dharma 2005). There are 56 recognized species and 18 subspecies (Cook, 2023b). *Haliotis squamata* is a fascinating Indonesian abalone species to study. This species lives in the southern seas of Java, Bali, and Sumbawa (Dharma, 2005). Currents play an essential role in abalone dispersal because their larvae are planktonic and follow ocean currents resulting in fragmented and reproductively separated populations.

The *Haliotis* genus is difficult to distinguish. *H. squamata* species showed unique morphological features in a variety of settings, including color patterns, textures, and shapes (Bachry *et al.*, 2019a). As a result, the abalone measurement standard is crucial

for accurately identifying abalone shellfish based on shell structure. A comprehensive study can separate *H. squamata* populations from Java and Bali Island in Indonesia showed that Bali's population has the highest inter-population sharing component (100%) and the lowest inter-population sharing component (0%) (Bachry *et al.*, 2019b). The highest percentage of similarities was 99.91% for Binuangeun and Pangandaran in West Java, while the lowest was 99.31% for Banyuwangi in East and Bali.

The examination of mtDNA COI gene sequences from Taiwan, Japan, and Indonesia indicated high genetic variation. Furthermore, Indonesian populations differ significantly from other populations and may warrant categorization as a separate species (Hsu and Gwo, 2017). Permana *et al.* (2017a) identified seven haplotypes in *Haliotis squamata* from Indonesia using the 16S rRNA gene and divided them into two groups. The inclusion of *H. diversicolor* as an outgroup in the test revealed that *H. squamata* populations on Bali Island and in some sites on Java Island belonged to a distinct group than the outgroup. According to Bachry *et al.* (2019a), the molecular characteristics of *H. diversicolor* squamata species from the southern waters of Java and Bali, which are currently considered subspecies found in China, Taiwan, and Japan, should be classified as a new species, *H. squamata* Reeve 1846. The percentage difference in interpopulation genetic distance between Java and Bali is around 0.000%-0.011%, or 0.0%-0.11%, with an average of 0.60%. According to Cyt B, the genetic distance between *H. squamata* intraspecies on Java's southern coast and Bali is 0.96%-1.06%. This genetic gap is sufficient to separate the two populations and form phylogenetic groups (Bachry *et al.*, 2020)

Bioreproduction and breeding

Identifying the stage of gonad maturity in a specimen is critical for calculating the spawning time (Fig. 1). Lifting the leg and epipodium reveals the abalone gonad on the left side of the shell. Velez-Arellano *et al.* (2015) refer to the gonads that line the digestive glands as the canonical appendages or hepatogonadal complex. Female gonads are often greenish in hue, whereas males are cream-colored (Singhakaew *et al.*, 2003; Hadijah *et al.*, 2013; Roux *et al.*, 2013).

The cycle of gonadal maturation in abalone occurs all year. However, abalone have distinct gonadal maturation features that are impacted by geographical and life circumstances. Gonadal pictures can be used to differentiate between abalone gonadal development phases at the same level (Bachry *et al.*, 2019c). An increase in gonadal size will also be seen and occur in hepatopancreatic shrinkage caused by the delivery of nutrients to the gonads. The color of the gonads varies as the cells within them mature, reflecting the development of gonadal maturity based on macroscopic features. Cooked (2023c) describes in depth the differences in reproduction of several abalone species in their natural environment, as well as a discussion of reproduction in hatcheries and the numerous elements that influence reproductive regulation.

Abalone is a gastropod that reproduces through spawning and dispersal. The egg-laying female has gonads that occupy more than half of the hepatopancreas (Permana *et al.*, 2017; Iskandar *et al.*, 2022). A hatching in spawning containers produced a 60% fertilization rate and an 85% hatching rate (Iskandar *et al.*, 2022). Permana *et al.* (2014) found that cultivated abalone matures faster than wild abalone. Third-generation gonads develop at 16 months and are capable of laying eggs at 18 months. F-3 abalone eggs have a diameter of 185.5 ± 1.4 μm, which is lower than the F-2 of 186.5 ± 2.0 μm (n = 50). FR of F3 eggs is 92.07%. During this time, the most common problem in abalone seed

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production was considerable mortality (>90%) after larvae settled in rearing regions, with a survival rate of 0.1-1.0% (Iskandar *et al.*, 2020).

After 60 days of treatment in a diatom-rich medium, larvae can develop into abalone with a one-month juvenile stage of 1-2 cm. It takes 2-3 months to raise 3 cm abalone seeds fit for sale (Iskandar *et al.*, 2022). Khotimah *et al.* (2018) found that abalone larvae fed with Spirulina sp. flour had the highest survival rate ($P<0.05$) compared to those fed with diatomaceous flour, Chaetoceros sp., and Ulva sp. (81.49%, 79.25%, 76.57%, and 76.46%, respectively), but did not differ significantly from those feds with Gracilaria sp. (81.37%) ($P>0.05$). Abalone larvae fed Gracilaria sp. flour and Spirulina sp. showed the highest daily shell length development rate (203.81 ± 1.23 μm and 205.47 ± 1.71 μm, respectively). Abalone larvae fed with Ulva sp. flour showed the slowest daily rate of development in shell length (146.07 ± 1.73 μm/day). Cook (2023d) reviews larval rearing techniques and concludes that there is no single universally accepted method of cultivating abalone; rather, the preferred method is determined by factors such as local ocean conditions, availability of land or lease areas at sea, labor and energy costs, and local environmental regulations. Bullon *et al.* (2023) studied the role of aquafeeding in abalone nutrition and health.

Growing out

Abalone grows slowly, hence more research is needed to accelerate its growth. Several actions have been conducted in the zootechnic of abalone production. Abalone seed stocking was investigated utilizing a hanging basket system, which consisted of two plastic baskets with holes measuring 47.5 x 36.5 x 12.4 cm that were organized and suspended vertically in floating cages.

Each hanging basket unit is set at a depth of 2-3 meters from sea level. Abalone with an average shell length of 3.21±0.32 cm and weight of 5.74±1.09 g, are distributed in rearing baskets with a density of 150 individuals per hanger. During rearing, abalone were fed fresh seaweed (*Gracillaria* sp.). After five months of rearing, abalone shell length and body weight increased by 4.3-4.4 cm (35-38%) and 12.6-14.4 g (120-150%), respectively, with survival rates ranging from 77.93-83.5% (Susanto *et al.*, 2016). Other tests using *H. squamata* measuring 3.4 ± 0.251 cm long and weighing 6.17 ± 1.67 g with *Gracillaria verrucosa* feed as much as 30% of body weight in a 30 x 20 x 18 cm^3 caramba in tidal areas for two months showed that different stocking densities (25, 50, 75 abalone/karamba) had no effect on absolute growth survival Length, weight, daily growth rate, and FCR (Humaidi *et al.*, 2014). The round shelter shape of PVC piping was shown to be the most effective for *H. squamata* growth and survival in the tidal environment ($P<0.05$), compared to square and without shelter. While survival had no influence ($P>0.05$) (Ardi *et al.*, 2020). Aalto *et al.* (2020) suggest that future environmental stressor experiments encompass many life stages to capture effects on population structure and dynamics, particularly for species with size-dependent fecundity.

Rearing using the floating basket method with a recirculation system or a running water system in the concrete tanks resulted in the highest growth in daily shell length (121.12±7.78 μm/day), daily weight growth rate (11.97±0.89 μg/day), and survival (86.7±11.0%) compared to the recirculation system (Rusdi *et al.*, 2015). After 4 months of rearing, juvenile abalone F1 with an initial shell length of 12.5 ± 1.27 mm in a plastic container measuring 35 x 25 x 13 cm^3 with a density of 25 individuals/container showed the highest growth rate (A) with a combination of *Gracilaria spp* seaweed feed treatment and pellets, followed by seaweed (B) and pellets (C) of 21.4 ± 3.72 mm and 14.8 ± 1.61

mm, respectively. Susanto *et al.* (2010) found that treatment A differs from treatments B and C, while treatment B differs from treatment C ($P<0.05$).

The feeding preferences and growth performance of adult *H. squamata* were evaluated using seven plant species, with *Ulva lactuca* and *Enteromorpha sp.* responding the most. They were four times more responsive than the least, *Halymenia sp*. and *Sargassum sp*, *Gracillaria sp.*, *Eucheuma spinosum*, *U. lactuca*, *Halymenia sp.*, *Enteromorpha sp*., and *Sarga* had the highest and lowest intakes of pleasant feed (FI), respectively (Yusuf *et al.*, 2020). The first four palatable macroalgae produced different growth responses. Except for *Halymenia sp*., the feed intake (FI) rate had a negative linear connection with growth response and FCR. *Ulva lactuca* (0.104) had the fastest daily growth rate (g/day), followed by Enteropmorpha sp. (0.085), *Gracillaria sp*. (0.084), and *Halymenia sp.* (0.016) (Yusup *et al.* 2020). Bullon *et al.* (2021) examined the nutritional and health benefits, as well as the drawbacks, of the two basic abalone feeds (seaweed and formulation feed), with the goal of developing sustainable abalone feed. According to Stone *et al.* (2023), despite substantial research into abalone dietary development, there are still knowledge gaps about nutrient requirements and their role in growth, health, and product quality. There are various challenges to developing a commercially available diet for optimal growth and health. To improve abalone output even further, investigations should be done to determine more comprehensive nutrient requirements for abalone on a species-by-species basis. To maximize abalone production, research should be conducted on age, water temperature, and the utilization of conventional and innovative ingredients in designed meals.

Other approaches to improving growth performance in abalone enlargement include selection (Permana *et al.*, 2015), hybridization (Permana *et al.*, 2013), and the application of growth genes (Khotimah *et al.*, 2016). According to observations, increased heterozygosity in the selection program can lead to an increase in body weight. The global abalone culture will continue to grow, necessitating a greater use of selective breeding operations. These will capitalize on the natural genetic variety seen in abalone, as well as the potential provided by the ease of interspecies hybridization and the incorporation of genomic information to aid selection decisions (Elliott, 2023). In China, the hybrid *Haliotis discus hannai*♀ × *H. fulgens*♂ has potential for large-scale cultivation in southern China due to its fast growth rate and tolerance to higher temperatures (Wang *et al.* 2020). In this study, the studies show that the top three dominating taxa remain stable across different temperatures, diets, and genotypes.

Moore (2023) states that over the last 40 years, there has been a tremendous gain in understanding regarding infectious illnesses in abalone, owing primarily to investigations into mass mortality events in both wild and farmed populations. Viruses, bacteria, protozoa, metazoan diseases, and pests all have a big influence on abalone health. The most common viral pathogens include herpesviruses, a novel "shriveling syndrome" virus, and an ill-defined amyotrophia virus. *Candidatus Xenohaliotis californiensis* (the cause of withering syndrome) and a number of Vibrio species have been the most dangerous bacteria. Perkinsus olseni and two haplosporidians are among the most important protozoa. Herpesviruses, a unique "shriveling syndrome" virus, and a poorly defined amyotrophia virus are the most common viral pathogens. *Candidatus Xenohaliotis californiensis* (the agent of withering syndrome) and several Vibrio species have been the most harmful bacteria. Herpesviruses, a unique "shriveling syndrome" virus, and a poorly defined amyotrophia virus are the most common viral pathogens. *Candidatus Xenohaliotis californiensis* (the agent of withering syndrome) and several Vibrio species have been the most harmful bacteria. Significant protozoa include

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Perkinsus olseni and two haplosporidians. Metazoan pests that damage abalone include the boring sponge Cliona, polydorid polychaetes, sabellid polychaetes, and fungi that invade the shell or soft tissues.

Figure 1. Breeding at the hatchery demonstrates broodstock size, mature gonads, spawning activity, and larval and juvenile rearing.

Trading and sustainability

Hernández-Casas *et al.* (2023) confirm the existence of strong relationships among the numerous processes that influence abalone demand, supply, and price. It was discovered that the supply behavior (catch-price) of Mexican and Australian abalone was adjusted to the bioeconomic model of the backward-bending supply curve for fisheries, because of overexploitation or the implementation of catch limits. Rising demand for abalone in domestic and international markets, as well as research and development investments, have propelled Indonesia's abalone sector growth. In 2019, Indonesia exported 302 tons of abalone (Wamucii, 2023). Between 2017 and 2019, abalone exports climbed by 4214.29 percent. As a result, the market value reached about USD 700,000 in 2019. This market value is a 993.75% increase over the total abalone export in 2018. The abalone industry in Indonesia is significantly influenced by competition and global trade trends (Tridge, 2023). The interaction of supply and demand has a significant impact on pricing and profitability in the sector. A study discovered that global demand for abalone has been gradually increasing (Cook, 2023a). The increase in demand can be attributed to abalone's high nutritional value and growing popularity as a premium meal. Because of the increased demand, the market price of abalone has risen, creating profitable opportunities for industry operators.

It should be noted, however, that Indonesia is currently not among the top ten abalone exporting countries, as shown in Table 1 (Cook, 2023a). While abalone prices in Indonesia typically range between USD 22 and USD 26 per kilogram, manufacturing supply is 40% below demand (Taridala, 2021). Indonesia's domestic market predominantly utilizes locally produced abalone (Selly 2014). Nonetheless, there is growing demand for Indonesian abalone in worldwide markets, particularly in the United States, Japan, and Germany (Tridge, 2023). Abalone prices in Indonesia are impacted by several factors, including supply and demand, product quality, and food safety. Abalone is traditionally gathered from wild populations along the Indonesian coast, providing a

vital source of food and cash for coastal communities. However, overexploitation and depletion of wild abalone supplies have caused the industry to decline in recent decades (Setyono *et al.*, 2023; Taridala *et al.*, 2021). To address this issue, the Indonesian government has implemented strict regulations and procedures to monitor and restrict fish harvesting and trafficking, including abalone (Barnhart and Ferse, 2023). These laws have played an important role in ensuring that only responsibly sourced abalone reaches the market, therefore boosting the reputation of the market. This improves the reputation of the Indonesian abalone sector and increases its global competitiveness. Amerika Serikat is the largest buyer of Indonesian beef, accounting for 88.5% of the country's total production (Tridge, 2023). This indicates a significant potential for growth and expansion in the international market for Indonesia. To preserve its worldwide market position, Indonesia must focus on manufacturing high-quality abalone on a constant basis. This goal requires simplifying production processes as well as the establishment of effective marketing and distribution channels. Indonesia has an abalone fishery, focused on H. asinina and *H. diversicolor*. Indonesia's abalone fishery has been reduced due to strong demand and high export prices, as witnessed in other producing countries. Middlemen and exporters frequently control the price of abalone fishermen's harvests, resulting in disproportionately large profits.

Improving abalone fry production and culture methods is essential for ongoing development. A reliable fry supply is critical for investors looking to generate large amounts. The government can help poor fishermen by adopting marine ranching or stock development programs to increase their harvest. The supply of seaweed (Gracilaria sp), a popular natural food for abalone, in Indonesia can also have a substantial impact on the industry's growth. Middlemen and exporters frequently control the price of abalone fishermen's harvests, resulting in disproportionately large profits.

Table 1. Farm production of different countries (mt) from 2015 to 2021 (modified from Cook, 2023a).

	Year of prodution			
Country	2015	2016/2017	2018/2019	2020/2021
China	127,967	139,697	163,139	217,431
Korea	9,400	12,343	12,400	20,053
South Africa	1,400	1,685	1,522	2,664
Chile	950	1,153	2,035	1,120
Australia	815	971	1,149	1,429
Taiwan	171	300	287	177
Japan (seed only)	200	200	200	200
USA	362	175	175	154
New Zealand	60	60	70	70
Mexico	20	22	30	50
Europe	9	9	10	10
Oman	-	-	-	5
Thailand	8	8	5	5
Philipines	4	5	5	5
Total	141,366	156,875	180,393	243,506

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Challenges and prospect

Despite its growth and profitability, Indonesia's abalone industry has several challenges, including overfishing and depletion of wild abalone species, legislative constraints, and environmental issues. The growing demand for abalone has put a pressure on natural populations, prompting concerns about overfishing and depletion of abalone stocks resulting in stricter restrictions on wild gathering, hence increasing the importance of farmed abalone in the Indonesian market. On the other hand, the sector has several opportunities for growth and development, such as developing new and innovative abalone culture methods, forming partnerships with research institutes, and expanding local and global markets.

Advances in abalone cultivation and production technology have created new potential for cost-effective and sustainable abalone production, including new culture methods, abalone health management studies, and feed and nutrition. The abalone industry in Indonesia appears to have potential. With continued investment in R&D, the Indonesian abalone sector is well-positioned to overcome present challenges and ensure long-term viability. The expanding demand for abalone in both domestic and international markets serve as a strong impetus for the industry's continual growth and expansion.

The development of novel and innovative abalone cultivation systems has significant potential for Indonesia's abalone industry. These culture options, which include recirculating aquaculture systems (RAS) and land-based systems, have significant advantages over traditional abalone culture methods. For example, RAS and land-based systems provide you greater control over water quality and temperature, which can improve abalone health and growth rates. They also provide the potential for increased efficiency and cheaper costs, making them more economically viable for farmers (Akbar *et al.,* 2022; Nur, 2020; Supriyono *et al.,* 2020). You's (2023) success story of abalone culture in China serves as an excellent model for Indonesia to follow.

CONCLUSIONS

The abalone market and trade in Indonesia exhibit considerable potential for future growth. To realize its full potential, the Indonesian abalone industry must overcome challenges like as competition and price fluctuations. Key goals include implementing sustainable collection and trading methods, consistently producing high-quality abalone goods, and expanding market reach through international commerce. Addressing these challenges would enable the Indonesian abalone industry to prosper in the coming years.

Indonesia's abalone industry has a long history and is growing and thriving, with bright prospects for the future. With continued investment in R&D, the Indonesian abalone sector is well-positioned to meet local and international market demands while maintaining long-term viability.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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