Uncover giant clam (Tridacnidae) density status and substrate in coral reef ecosystems of Kri Island, Raja Ampat, Indonesia

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Abstract. Coral reefs are among the richest and most productive ecosystems that provide habitat to a diverse range of various marine fauna, one of which being the giant clam (Tridacnidae). The giant clam is an important marine invertebrate that plays an essential role in providing food and substrate for the marine ecosystem. Over time, the population of giant clams continued to decline due to habitat degradation and unsustainable fishing practices. Limited information also makes conservation of this species more challenging. The study was conducted in January 2024 to gain more information about the species, substrates, and densities of giant clams in the Kri island area. The results showed that 643 individuals of six different species of giant clam, including *Tridacna crocea*, *Tridacna maxima*, *Tridacna squamosa*, *Tridacna gigas*, *Hippopus hippopus*, and *Hippopus porcellanus* inhabited this area. Each species had preferred substrates that can provide essential nutrients in supporting the giant clam growth, where most of the giant clam species preferred dead coral with algal substrates. In addition, the density of giant clams in the area was 0.018867 ind m^{-2} which categorized as low density, indicating the threatened condition of giant clam population in the area.

Key Words: density, Raja Ampat, substrate, Tridacnidae.

Introduction. Coral reefs are known as the coastal ecosystems with highest level of productivity and diversity in the world, where various species of marine megafauna, invertebrates, and endemic animals can be found (Allen et al 2016; Tapilatu et al 2022c). Coral reef ecosystem plays essential roles by providing various ecosystem services to support ecological and socio-economic aspects of the surrounding of the coastal communities. Through the lens of ecology and biology, coral reef ecosystems can provide protection and nourishment for many marine and coastal species (Ramah 2017; Espinoza-Rodríguez et al 2021). Moreover, the presence of coral reef ecosystems in an area can also support the socio-economic needs of coastal communities through a range of services and goods, such as the provision of seafood stocks, ecotourism attraction, and protection for coastal areas from the threat of abrasion due to large waves (Martins et al 2019; Rabiyanti et al 2020; Siburian et al 2022).

As an area known to be the heart of the world's coral triangle, Raja Ampat has an exceptionally higher level of coral reef biodiversity compared to other regions or countries (Ender et al 2014; Larsen et al 2018). The strategic geographic location, namely on the western border of the equatorial Pacific Ocean and at the 'entry point' to the northeast of Indonesia's Transboundary Current from the Pacific to the Indian Ocean, has offered the region a rich diversity of species (Nugraha et al 2022). Additionally, the high level of Sea Surface Temperature (SST) in the area has played important role in supporting the biodiversity level of this area (Mangubhai et al 2012; Nugraha et al 2018). Raja Ampat area covers over four million hectares of land and sea, where Kri island is known to be one of the best diving spots, with the highest reef fish diversity in the Raja Ampat area (Andradi-Brown 2021).

In addition to the biodiversity, the coral reef ecosystem of Kri island also provide a suitable habitat to support the growth of many other species of invertebrates, including giant clams. Giant clams are the largest living bivalves from the Tridacnidae subfamily consisting of two genera and 12 species (Tan et al 2023). They are most commonly found in shallow and clear waters of coral reef ecosystems (Mies 2016; Iriansyah et al 2021). In this regard, giant clams have a very important ecological role as a food source, substrate, and microhabitat that can support the growth of other animals associated with the coral reefs (Vicentuan et al 2014; Neo et al 2015; van der Schoot et al 2016; de Gier & Becker 2020). The calcium carbonate of giant clam shells provides a secure habitat for small epibionts such as barnacles, polychaetes, and sponges (Vicentuan-Cabaitan et al 2014), as well as nurseries for coral fish (Cabaitan et al 2008). In addition, their symbiotic relationship with zooxanthellae enables giant clam to filter dissolved nutrients, that contributes to the productivity of coral reefs and enhances the water quality (Ikeda et al 2017).

Despite their important role in the ecosystem, giant clams are vulnerable to many anthropogenic and environment threats. Over the past few decades, giant clams have been considered as one of the important fishery commodities in providing source of protein, as well as household ornaments (Lai 2015; Gomez 2015; Mies et al 2017a; Mies et al 2017b). However, the biological characteristics of giant clams are a late sexual maturity and limited distributions, which have made the species very vulnerable to extinction (Watson & Neo 2021). High market demand of giant clams has led to various unsustainable anthropogenic practices such as illegal and overexploited harvesting, which have caused its population to decline over the time (Neo et al 2015; Tapilatu et al 2021; Tapilatu et al 2023). Given their important role in coral reef ecosystems, various conservation efforts need to be implemented to preserve giant clams' populations in the environment.

To date, several studies have been conducted to understand the condition of coral reefs and fish in the Kri Island area, Raja Ampat (Anzani et al 2019; Bohne et al 2011; Hukom et al 2018; Kurniasih et al 2020). However, information about the species and densities of giant clams that supports the life of coral reef ecosystems in the Kri island area is still very limited. Giant clams can be found in a wide range of areas, from Japan to Australia, and from East Africa to the East Pacific. However, studies conducted to understand their distribution and their current status in specific regions are scarce. Therefore, this research was conducted to provide important information on giant clam's density, habitat quality and substrate type in Kri Island, Raja Ampat. The results of this study aimed to provide an informational reference to support giant clam conservation efforts as well as promoting further research on giant clams in Raja Ampat.

Material and Method

Description of the study sites. This study was conducted between the 5th and 26th of January 2024 in the coastal area of Kri Island, Raja Ampat, Indonesia (Figure 1). Kri Island is located in Dampier Strait Marine Protected Area (MPA), a prominent tourism area in Raja Ampat. The Dampier Strait encompasses three parts, including: the coast of Gam and Mansuar island, the coast of Batanta Island, and the coast of the island of Salawati. The area's dynamic environment, characterized by strong currents and nutrient-rich waters has supported diversified marine ecosystems. This area located in a non–take zone since 2019. The research site is located at 0˚33'22"S and 130˚41'14"E, at approximately 45 minutes from the capital city of Raja Ampat, Waisai.

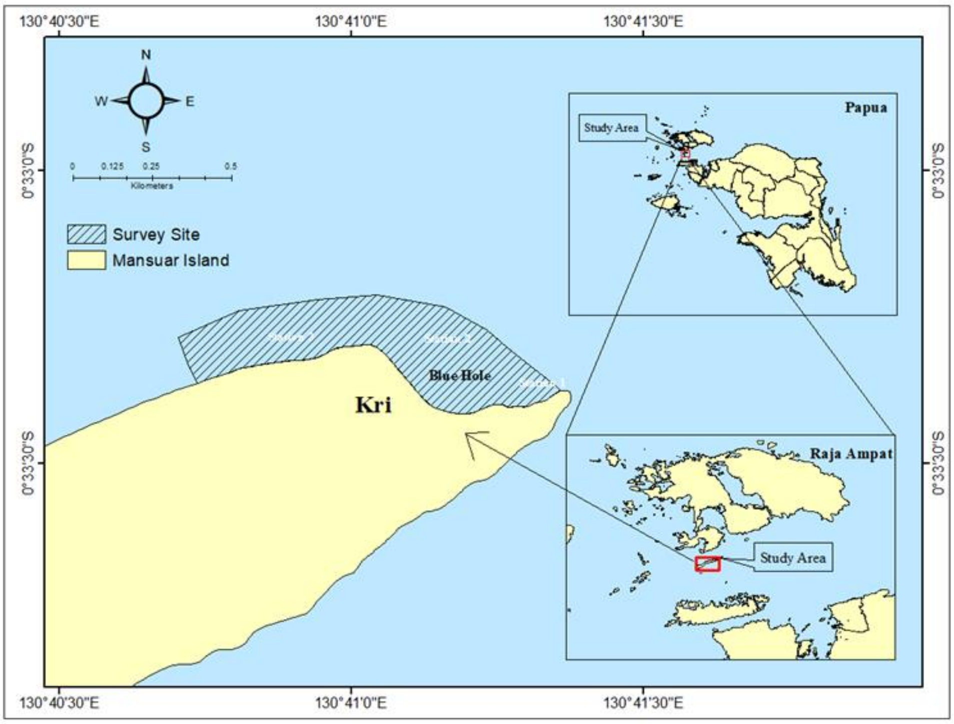

Figure 1. Research site of giant clam community structure in Kri Island.

Data collection. The research data collection was done by gathering information of giant clam species, substrate types and the condition of water quality parameters (temperature, pH, and salinity levels). The giant clams' data were collected by applying the cruise method specified by Rugayah & Pratiwi (2004) at three sample points using a quadrat of 100 x 100 m at 0.6–0.8 m depth of low tide. All giant clam samples found within the quadrat area were first documented, then visually identified for the species and substrate type based on the research of Copland & Lucas (1988), and Knop (1996). In this regard the classification of giant clam's substrate type in this research was based on English et al (1994), with the following details: (i) Coral Cover (CC) a substrate characteristic of clams that inhabit dense coral cover areas; (ii) Dead Coral Algae (DCA), a clam habitat formed of dead coral substrates overgrown with algae; (iii) Faviidae (FAV) a substrate characteristic of clams that inhabit massive coral reef areas with a monocentric shape; (iv) Porites (POR) a substrate characteristic of clams that are immersed in small coral reefs; (v) Rubble (RB) a substrate characteristic of clams that live on coral fragments.

Aside from the primary data collection, the research also collected supporting data at each quadrat location, by determining chemical and physical parameters of the water in the area. The supporting data collection was done through the utilization of several tools including: Traceable Long-Stem Thermometer, Oakton pH meter and RZ portable refractometer.

Data analysis. The density of giant clam was analyzed using the formula of Snedecor & Cochran (1980) as follows:

$$K = D / (\Sigma ni*A)$$

Where:
K - density (ind m^{-2});
ni - number of individuals in sampling sites;
D – total number of individuals of species populations in all sampling sites;
A - the sampled i^{th} site area (m^2).

In addition, the research also conducted a review analysis on giant clam substrate types based on the five substrate categories, according to English et al (1994). After categorizing giant clam species and substrate types, the results were presented using facet and dot plots. This analysis method has been known as one of a convenient method in comparing the percentage of giant clam species on different substrate types (Streit & Gehlenborg 2014).

Results. The coastal area of Kri island, Raja Ampat have twice daily tidal dynamics which is influenced by the Pacific Ocean (Tapilatu et al 2022a,2022b). The water quality of this research focuses on three main parameters, i.e. temperature, salinity, and pH (acid-base) level. The result of water quality data is shown in Table 1. At Site 1, the temperature was 29.2±1.1°C, at Site 2 it was 29.5±0.9°C, and at Site 3 it was 29.3±0.05 ◦C in. The salinity was 34±0.5‰ at Site 1, 35±0.2‰ at Site 2, and 34±0.3‰ at Site 3. The pH was 8.16±0.02 at Site 1, 8.14±0.03 at Site 2, and was 8.12±0.04 at Site 3. Overall, there are no significant differences in the three parameters ($p<0.05$).

Table 1

Water quality parameters of Kri island

Site	*Temperature*	*Salinity*	*pH*
1	29.2±1.1	34±0.5	8.16±0.02
2	29.5±0.9	35±0.2	8.14±0.03
3	29.3±0.05	34±0.3	8.12±0.04

In this regard the water quality in the area holds an important role in sustaining the life of aquatic organisms that inhabit the area. Any drastic change that affects the condition of water in the area, will have a potential to significantly impact the well-being of the organisms in the area, particularly organisms with limited movement, including giant clams (Gaol et al 2017).

Giant clam of Kri Island. To date, 12 distinct species of Tridacnidae from genus Tridacna and Hippopus has been identified (Tan et al 2021). Based on the results of the study, six species of Tridacnidae can be found on Kri Island, which includes: *T. maxima, T. squamosa, T. gigas, T. crocea*, *H. hippopus*, and *H. porcellanus.* The following is the lists of giant clam species found in the three sites in Kri, Raja Ampat (Table 2).

Table 2

Species of giant clam species and their abundance at each site

Species	*Density*			*Total*
	Site 1	*Site 2*	*Site 3*	
Tridacna crocea	358	163	45	566
Tridacna maxima	39	8	5	52
Tridacna squamosa	7	8	2	17
Tridacna gigas	1	0	0	1
Hippopus hippopus	3	0	3	6
Hippopus porcellanus	1	0	0	1
Total	409	179	55	643

In addition, this study also assessed the abundance and density of giant clam species in the Kri island region. The study found that the overall density (a combination of all species and all sites) of giant clam in the area is 0.018867 ind m^{-2}. According to Planes et al (1993), this value considered as a low density. Giant clam density in coral reef ecosystems has an important role in supporting ecosystem biodiversity, where the higher value of density will support higher biodiversity in the area (Tatsumi & Loreau 2023). The detailed information about the density of giant clams in the Kri Island area presented in Table 3.

Table 3

Density (individuals m^{-2}) and giant clam percentage in each site

Species	*Location*			*Total*
	Site 1	*Site 2*	*Site 3*	
Tridacna crocea	0.0358 (87.53%)	0.0163 (91.06%)	0.0045 (81.81%)	0.018867
Tridacna maxima	0.0039 (9.53%)	0.0008 (4.46%)	0.0005 (9.09%)	0.001733
Tridacna squamosa	0.0007 (1.71%)	0.0008 (4.46%)	0.0002 (3.63%)	0.000567
Tridacna gigas	0.0001 (0.24%)	0	0	0.000033
Hippopus hippopus	0.0003 (0.73%)	0	0.0003 (5.45%)	0.000200
Hippopus porcellanus	0.0001 (0.24%)	0	0	0.000033
Total	0.0409	0.0179	0.0055	0.018867

Substrate preference of Tridacnidae in Kri Island. According to Siburian et al (2023), the invertebrate population in the Kri Island area has diverse habitat preferences. The result shown five types of giant clam substrates that can be found in the Kri Island area (Figure 2), with the following distribution of giant clam per substrate type: 2% on coral cover (CC), 75% on dead coral algae (DCA), 18% on Faviidae (FAV), 3% on Porites (POR), and 2% on rubble (RB).

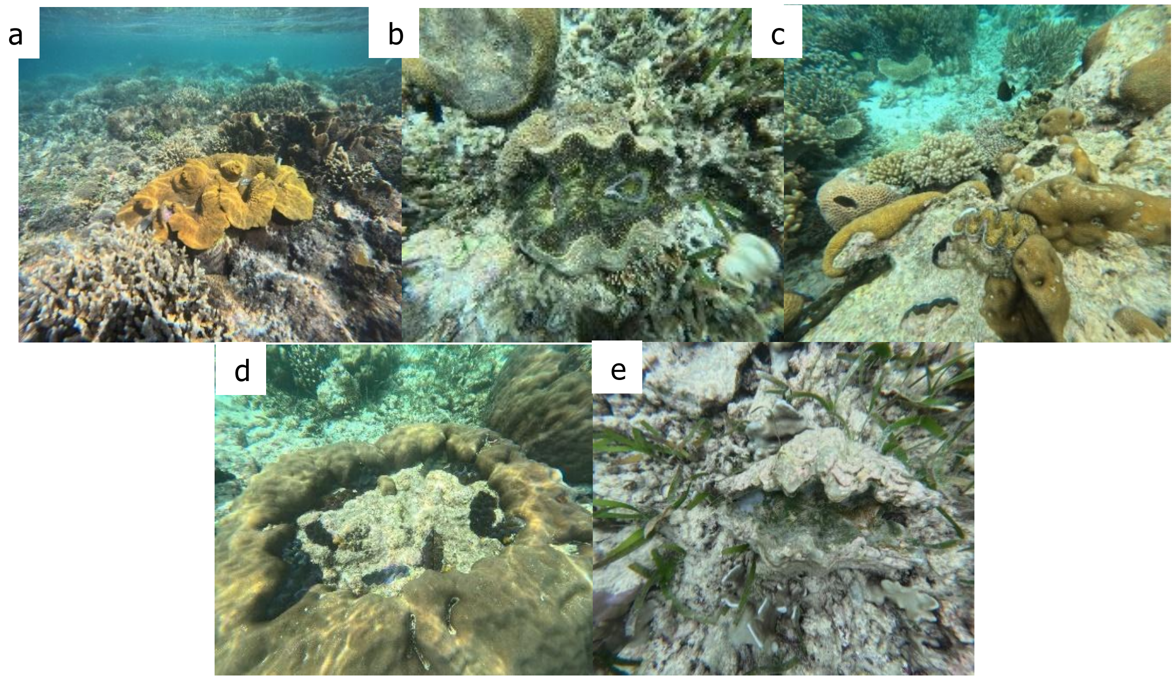

Figure 2. Giant clam substrates in Kri island a. Coral cover (CC), b. Dead coral algae (DCA), c. Faviidae (FAV), d. Porites (POR), and e. Rubble (RB).

Among the five types of giant clam substrates identified, dead coral with algae (DCA) was one type of substrate with the highest number of giant clam preference, consisting of 482 giant clam individuals. In this case, the different species of giant clams that prefer a DCA substrate include: *T. crocea*, *T. maxima*, *T. squamosa*, and *H. hippopus*. In contrast, the least preferred substrate type was rubble with 11 individuals. There are several types of giant clams that prefer a rubble habitat, including *T. crocea, T. maxima, T. squamosa, H. hippopus,* and *H. porcellanus*. The details regarding the number and type of giant clam substrate preferences in the Kri island area shown in Figure 3.

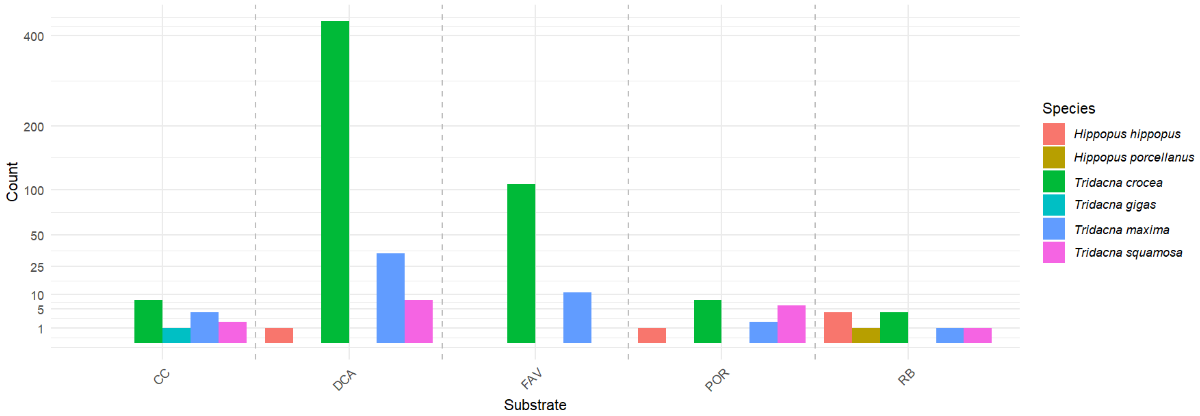

Figure 3. Giant clam species and its substrate preferences.

Discussion. The water physical and chemical parameters are essential components that can support and affect the level of growth, reproductive traits, and annual recruitment level of aquatic organisms (Vayghan & Lee 2022). The study was conducted by measuring several water parameters that support the life of giant clams in the area. In this regard temperature is one of the most important physical aspects that can support the growth, reproductive period, and survival rate of giant clams (Gadomski et al 2015; Enricuso et al 2019). The study shows that water temperature in Kri Island ranges between 29.2 and 29.5°C (Table 1). According to Ellis (1999), the optimal water temperatures for the giant clam range around 27 to 31°C. Therefore, in this regard, the waters in the area are consideredappropriate for supporting the life of giant clams and their symbionts. In addition, the symbiotic relationship of giant clams and zooxanthellae has made giant clams more sensitive to the water temperature. According to Caroselli et al (2015), photosynthetic efficiency of zooxanthellae in giant clams increased in high temperatures (32 and 34°C); this condition could induce excessive oxidative stress and significantly affect the antioxidant enzyme activities of giant clams (Ma et al 2021). High temperatures also increase the potential in reducing the larval survival rate of some giant clam species such as *T. gigas* (Enricuso et al 2019).

Furthermore, pH level is also another essential chemical parameter of waters, that can affect the life of aquatic species in the environment. Based on the findings, the pH level at Site 1 was 8.16±0.02, at Site 2 it was 8.14±0.03, and at Site 3 it was 8.12±0.04. In this regard, most aquatic species living in certain areas are characterized by a limited pH tolerance (Omer et al 2019). According to Pinheiro et al (2021), a slight change of pH of the environment can have negative impacts on many species in the area, where in the case of giant clam the changes of pH level can affect the availability of nitrogen that is needed for giant clams' symbionts (Fitt et al 1995). The changes in pH may change inorganic carbon concentration that affect photosynthesis of the symbiotic zooxanthellae with the giant clam (Ma et al 2021).

In addition, the level of salinity has also been recorded to describe the water quality of the study area. Based on the comparison results, the salinity levels from the study sites were not significantly different; the salinity values were 34±0.5‰ at Site 1, 35±0.2‰ at Site 2, and 34±0.3‰ at Site 3. According to Tan et al (2023) and Lee et al (2024), salinity is an essential parameter that can affect the survival rate (SR) and the physiological functions of marine bivalves. Maboloc et al (2017) found that, at low levels of salinity, giant clams can exhibit highly granulated nuclei with ruptured nuclear membranes. Furthermore, Sayco et al (2019) found that salinity had an effect on giant clams' fertilization success. In summary of water quality parameters, the conditions of the water parameters in the Kri island area are still classified in the optimum category and can support the life of giant clams in this area.

The total of 643 giant clamspecimenscaptured at the Kri island study sites, in Raja Ampat, belong to six species (Table 2). As shown in Table 2, the number of species found in this study was lower than previous study by Wakum et al (2017), which found eight species of giant clam in Amdui waters of South Batanta Districts in Raja Ampat. Compared to the previous study conducted in Amdui, South Batanta, the study result did not find the species of *Tridacna tevoroa* and *Tridacna derasa*. Futhermore, based on the findings of DeBoer et al (2012), *T. crocea*, *T. maxima*, and *T. squamosa* are also found in other areas of Raja Ampat such in Dampier Strait and Misool. These species were also found in the Kei Kecil Islands by Hernawan (2010), as well as in Kei Islands by Triandiza et al (2019). Among all of the species discovered in the study, the *T. crocea* has the highest number of individuals compared to other species, with a total of 566 individuals. *T. crocea* is the smallest giant clams species, with an average size of 15 cm, which is generally abundant in its known habitats (Neo et al 2015; Meadows 2016). This result is in line with the recent study of Triandiza et al (2019), which showed the dominance of *T. crocea* species at the sampling sites of Sulawesi waters and Kei Island. The abundance of *T. crocea* at several research locations is thought to be due to its life behavior: the giant clam bores itself into strong coral structures, which makes it difficult to be collected by the fishing community (Conales et al 2015). In addition to *T. crocea*, another giant clam species that partially burrows itself between coral substrates is *T. maxima* (Cappenberg 2017). This is thought to provide extra protection for this species. Therefore, based on the observation, the study shows that *T. maxima* was in the second highest number of giant clam individuals with a total of 52.

In contrast, the giant clam species with the lowest abundance were *H. porcellanus* and *T. gigas*, with only one individual eachat site 1. *H. porcellanus* and *T. gigas* are large-sized giant clam species. According to Triandiza et al (2019), the average shell size of *H. porcellanus* reaches 191 mm and the shell size of *T. gigas* can reach 740 mm. Although the condition of Kri island water quality is very suitable in supporting the life of giant clams in the area, the abundance of giant clam species might also be affected by other factors, such as the exploitation by the local community (Wakum et al 2017 and Ode 2017). Due to their massive sizes, these giant clams are typically targeted by fishermen, as they can be used for various purposes such as jewelry and medicine (Larson 2016). According to Dolorosa et al (2014), *H. porcellanus* and *T. gigas* are currently in extreme low numbers across various Indo-Pacific regions, due to over-exploitation practices, and have a limited distribution range.

Giant clam density is the total number of giant clam individuals found in the studied area of the marine environment (Van Wynsberge et al 2016). From the results, there are approximately 188 giant clams can be found on a hectare; this number was lower compare to some other regions. Arbi (2017) found that there were 0.53 ind m^{-2}giant clam in North Sulawesi; Savage et al (2013) found 0.13-0.72 ind m^{-2} of giant clam in Kong Rong Archipelago, Cambodia, and Triandiza et al (2019) found 0.0428 in Kei Islands, Maluku, Indonesia. In fact, the density of each species was lower compared to the results found by Wakum et al (2017) in Amdui area, South Batanta District, Raja Ampat. One of the factors that can affect the different giant clam density levels between regions is the presence of anthropogenic activities, such as exploitation practices, or the protection of marine areas (Triandiza et al 2019). In this regard, the most protected areas usually have higher giant clam densities compared to unprotected areas.

In addition, the distribution and density of giant clams is also highly dependent on the type of substrate in the area (Van Wynsberge et al 2016). Areas that have a higher diversity of substrate cover tend to have higher giant clam densities compared to areas that have lower substrate diversity (Ruensik et al 2014). Site one has the highest density of giant clam with the value of 0.0409 ind m^{-2}. The high density of giant clams in this area is attributed to the various substrate variations in this area, thus providing space for various types and sizes of giant clams to grow in this area (Van Wynsberge et al 2016). On the other hand, site three is the research site area that has the lowest giant clam density of 0.0055 ind m^{-2}. The low population density at Site 2 and Site 3 were assumed to be affected due to anthropogenic factors in the area. Nevertheless, the density of giant clams in the Kri island area has a higher value compared to several other areas in Papua, such as Manokwari area, with a density value of 0.0056 ind m^{-2} (Iriansyah et al 2021), and Kali Lemon waters in Teluk Cendrawasih National Park, which have a density of 0.0073 ind m^{-2} (Tapilatu et al 2021).

Moreover the substrate preference of an organism plays an important ecological role for its population's survival, as well as its efforts to support the balance of the ecosystem it lives in (Douglas 2020). Since the larval stage, giant clams have the ability to select their substrate preferences through exploration and benthic locomotion, using the posterior adductor muscles (Soo & Todd 2014). The substrate preference of giant clam was aimed to find the type of substrate that can support the availability of nutrients and essential substances that can support their growth (Neo et al 2015; Bahari et al 2021). Each species of clam usually has its own substrate preference, which is adapted to the size and behavior of the clam in sustaining its survival (Meadows 2016).

Five type of preferred substrates were identified in the study site, including: Coral Cover (CC), Dead Coral Algae (DCA), Faviidae (FAV), Porites (POR), and Rubble (RB). The CC substrate is characterized by the growth of various species of living coral reefs with many branches and crevices (Zhou et al 2021). On the other hand, DCA is a type of substrate dominated by dead coral colonies and overgrown algae. According to Swierts & Vermeij (2016), this substrate mostly formed due to eutrophication factors that support the fertility of algae growth on degraded coral reef areas. The result discover that among the five types of susbstrate, DCA has the highest giant clam abundance. These findings are similar to a previous study of Triandiza et al (2019) in the Kei Island area, Maluku, which showed the giant clam preference for DCA substrates, with a percentage of 75% of its total abundance. Among all species that inhabit DCA substrates, *T. crocea* was dominant. Its abundance on this substrate is likely due to the burrowing behavior of the species, that anchors itself into the hard coral substrate (Hill et al 2018).

Another type of substrate is Faviidae. The characteristics of this substrate can be determined from its hermatypic shape in the coral reef ecosystem (Rust 2022). Faviidae substrate in the Kri Island area was overgrown by various types of bryozoa, sponges, and giant clams. Porites is another type of substrate that can be found in the area of Kri Island. The boulder shape of the Porites substrate in this area provides aspace that can support the growth of small giant clams species such as *T. crocea* and *T. maxima*. Lastly, rubble is the type of giant clam substrate found in the study that consists of a mixture of dead coral fragments, sand, and seagrass. According to Siburian et al (2023), the rubble substrate conditions in this area can provide a suitable habitat for various types of invertebrates such as Echinodermata and various types of giant clams. The result found that among all of the substrates, rubble has the least preference, with a total of 11 individuals. The low level of giant clam preference for this substrate is due to the loose fragments and unstable mixture of sand that could not provide a solid and strong protection for clam shells from various threads (de Guzman et al 2023). Nevertheless, according to Soo & Todd (2014), giant clams with large size and heavy body weight such as *H. hippopus* usually prefer this type of substrate.

Furthermore, this research shows that the clam population in the area is threatened with extinction, as indicated by the low clam population density. In addition, the majority of giant clams in the area inhabit dead corals with algae substrates, indicating a coral reef degradation due to the human activities in the area. Therefore, based on the results of this study, we suggest that local governments and communities should work collaboratively to improve the management of clam conservation. To date, number of countries adopted specific regulations to protect clams in several areas and regions (Neo et al 2017). Therefore, the results of this research hope to provide the information needed to support more conservation actions in protecting giant clam from overexploitation.

Conclusions. The results showed that the water parameters at the three research sites in the waters of Kri Island are optimal for supporting the growth and development of giant clams in this area. 643 individuals of six species were sampled in the area, including: *T. crocea*, *T. maxima*, *T. squamosa*, *T. gigas*, *H. hippopus*, and *H. porcellanus*. In addition, the density of giant clams in this area was 0.018867 ind m^{-2}, which falls into the low-density category. Furthermore the abundance of giant clams in the area is strongly influenced by several factors, one of which being the type of substrate. The substrate types that can be found in the waters of Kri Island, include: coral cover, dead coral with algae, Faviidae, Porites, and rubble. Dead coral with algae is the most preferred substrate type, where as many as 482 individual giant clams of the species *T. crocea*, *T. maxima*, *T. squamosa*, and *H. hippopus* were found. In contrast, the least preferred substrate, as habitat for giant clams, was the rubble type, with 11 individuals found.

Conflict of interest. The authors declare no conflict of interest.

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Received: 14 August 2024. Accepted: 16 October 2024. Published online: 30 October 2024.
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How to cite this article:
Siburian R. H. S., Tapilatu J. R., Tapilatu M. E., 2024 Uncover giant clam (Tridacnidae) density status and substrate in coral reef ecosystems of Kri Island, Raja Ampat, Indonesia. AACL Bioflux 17(5):2386-2398.