Distribution of target strength and fish density in Kapota Atoll, Wakatobi Waters

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Abstract. Target strength (TS) is an acoustic backscatter measurement that reflects fish size, whereas fish density is an important indicator of aquatic ecosystem conditions. This study aimed to describe the distribution patterns of TS and fish density in Kapota Atoll, Wakatobi Waters, using hydroacoustic technology with a single-beam chosounder, Simrad EK-15. The results showed that TS values ranged from -51.8 dB to -37.6 dB, with an average of -42.5 dB, and tended to increase with depth, indicating the presence of larger fish. The spatial distribution of fish density varied significantly both horizontally and vertically. The highest density was detected at depths of 21–25 m, with a maximum of 45,602 individuals/1000m³ and minimum of 2 individuals/1000m³. An average density of 514 individuals/1000m³ reflects a good environmental carrying capacity. The lagoon area tended to be the center of fish aggregation because of its more complex habitat, whereas depths beyond 33 m showed a significant decrease in density. The negative relationship between TS and fish density indicates that larger fish are more commonly found in deeper layers but in lower numbers. These findings provide a scientific basis for sustainable fisheries management in the Kapota Atoll.

Keywords: Echosounder, fish density, Kapota Atoll, target strength, Wakatobi

1 Indroduction

Wakatobi, located in Southeast Sulawesi, Indonesia, is widely recognized as a global marine biodiversity hotspot and has been designated as a national marine park. The archipelago consists of four major islands: Wangi-Wangi, Kaledupa, Tomia, and Binongko, together with several smaller islands and atolls, including Kapota Atoll. These waters sustain diverse ecosystems such as coral reefs, mangroves, and seagrass beds, supporting more than 900 reef fish species. Such ecological complexity provides essential habitats for reef-associated fish, which underpin trophic dynamics, fishery productivity, and ecosystem resilience.

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Local communities in Wakatobi rely heavily on capture fisheries, with reef-associated species contributing nearly 40% of the total catch [1]. However, increasing fishing pressure and habitat degradation pose serious challenges to the sustainability of these fish stocks. Effective resource management requires accurate and spatially explicit information on the distribution and abundance of fish populations [2]. However, traditional stock assessment methods, which depend on landing data, often fail to represent in situ conditions and thus provide limited ecological insight [2].

Hydroacoustic techniques offer a robust and noninvasive alternative for assessing fish populations by enabling high-resolution mapping of vertical and horizontal distribution patterns [3]. Target strength (TS), defined as the acoustic backscatter from an individual fish, is closely related to body size and is widely applied in fisheries research [4]. It is expressed as the number of individuals per unit of water volume and provides additional information on population structure and habitat utilization [5]. Despite the ecological and socioeconomic value of sites, such as the Kapota Atoll, spatial information on these parameters remains scarce. A significant scientific gap exists because most hydroacoustic studies in Indonesia have focused on regional or large-scale assessments, leaving site-specific investigations at the atoll-scale limited.

Kapota Atoll, located west of Wakatobi's administrative center, is an ecologically significant and socioeconomically valuable site [6]. Despite its importance, spatial information on fish density and target strength in this area remains scarce [7]. Most hydroacoustic studies in Indonesia have focused on regional or large-scale assessments [8]. In contrast, site-specific investigations are still limited despite the necessity of formulating effective local management strategies [9]. Previous research has emphasized the importance of integrating ecological data into fisheries policy, yet empirical evidence at the atoll scale is insufficient [10].

The present study addresses this gap by investigating the distribution of TS and fish density in the Kapota Atoll using a single-beam echosounder (Simrad EK-15) [4]. This equipment is appropriate for the study area because it effectively maps distributions in shallow lagoons and reef-flat zones with minimal ecosystem disturbance. By integrating hydroacoustic measurements with spatial mapping, this study aimed to describe the vertical and horizontal patterns of fish distribution [5]. However, it is important to acknowledge the limitations of single-beam acoustics, particularly its reduced capability to resolve individual targets in high-density areas compared with split-beam systems.

Furthermore, this research moves beyond generic management claims by demonstrating how acoustic data inform policies. Specifically, TS data serve as a proxy for fish size and age structure, while density mapping identifies critical aggregation "hotspots" within the lagoon. These analytical links provide empirical evidence necessary for formulating effective local management strategies, such as identifying zones for targeted protection or monitoring the resilience of reef-fish communities in Wakatobi.

2 Method

2.1 Study area

The research was conducted in May 2023 at Kapota Atoll, Wakatobi National Park, Southeast Sulawesi, Indonesia. The atoll lies between 05°17′–05°22′ S and 123°30′–123°36′ E. Kapota Atoll consists of lagoon, reef flat, and outer reef slope zones, each supporting distinct ecological characteristics and fish assemblages. The research location map is shown in **Fig. 1**.

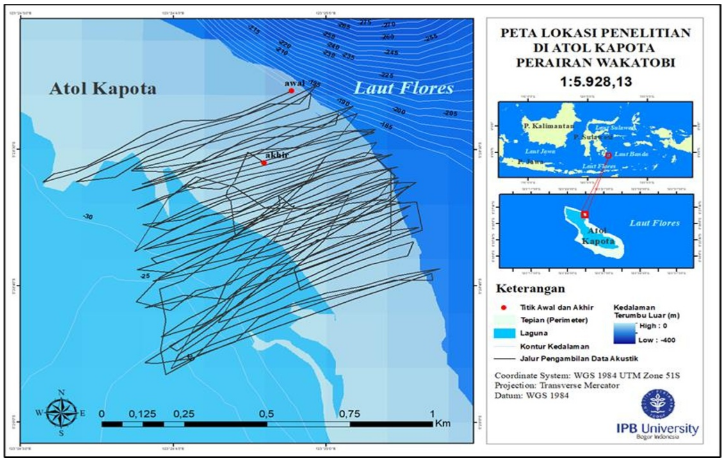

Fig. 1. Research location map.

2.2 Acoustic survey and data acquisition

Hydroacoustic data collection was performed using a single-beam chosounder (Simrad EK-15, 200 kHz) mounted on a research vessel. The transducer was positioned approximately 0.5 m below the sea surface to reduce surface noise interference. Acoustic signals were transmitted vertically through the water column, and the backscattered echoes were continuously recorded along a 43.84 km transect line that covered the lagoon, reef flat, and reef slope zones.

The survey was conducted during the daytime under calm sea conditions to minimize the effects of turbulence and wave-induced noise. A ping rate of 1 Hz was applied to ensure a high density of the acoustic measurements. Simultaneously, the survey track was georeferenced using GPS integration, which allowed the spatial mapping of fish distribution.

Raw acoustic signals were stored in. raw format for subsequent post-processing. Echoes were classified into plankton, fish, coral structures, and seabed categories depending on the strength and depth of the returned signal. **Fig. 2** illustrates the principle of acoustic data acquisition, in which the echosounder transmits sound pulses downward, and the reflected signals represent different targets in the water column.

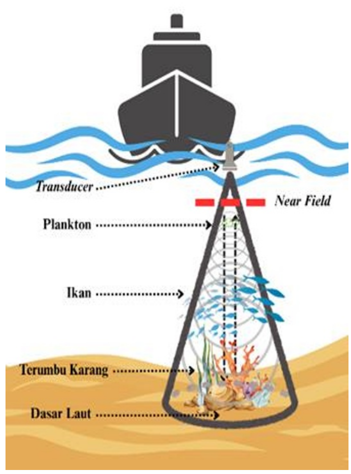

Fig. 2. Illustration of acoustic data acquisition process.

2.3 Data processing

2.3.1 Estimation of target strength and fish density

The acoustic data were processed using Sonar5-Pro v.6.0 (Lindem Data Acquisition, Norway), following standard hydroacoustic analysis procedures. The main parameters calculated were the Target Strength (TS), backscattering cross-section (σbs), volume backscattering strength (SV), and fish density.

When the transducer transmits sound waves into the water, part of the signal is reflected back to the receiver. The intensity ratio between the outgoing and incoming signals is expressed as the target strength [7].

$$TS = 10\log\left(\frac{i_{out}}{i_{in}}\right) = 10\log\left(\frac{\sigma_{sp}}{4\pi r_0^2}\right) dB \qquad (1)$$

$$\sigma_{sp} = 4\pi r_0^2 . 10^{\frac{TS}{10}} \qquad (2)$$

$$ts = \sigma_{bs} = 10^{\frac{TS}{10}} \qquad (3)$$

where TS is the target strength (dB), σ_{sp} is the spherical scattering cross-section, σ_{bs} is the backscattering cross-section, and r_0 is the reference radius (commonly 1 m).
The linear volume backscattering strength (sv) and area backscattering strength (sa) are derived as follows:

$$sv = \sum \frac{\sigma_{bs}}{V_0} \qquad (4)$$

$$sa = \int_{R1}^{R2} sv dR \qquad (5)$$

where V_0 is the ensonified water volume and R1 and R2 are the integration limits of the depth range. The relationship between fish density (ρ_v) and acoustic backscatter is given by:

$$sv = \rho_v . \sigma_{bs} \qquad (6)$$

$$\sigma_{bsk} = \frac{1}{N} \sum_{k=i}^{N} n_k \, \sigma_{bsk} \qquad (7)$$

$$\rho_v = \frac{sv}{\overline{\sigma_{bs}}} \quad \left(\frac{f}{m^3}\right) \qquad (8)$$

$$\rho_a = \frac{sa}{\overline{\sigma_{bs}}} \quad \left(\frac{f}{m^2}\right) \qquad (9)$$

where ρ_v is the volumetric fish density (individuals/1000 m^3), ρ_a is the areal fish density, N is the number of detected targets, and n_k is the number of fish in class k. To validate acoustic data, fish samples were collected to measure standard length (SL), which was then converted to TS using the empirical relationship:

$$\alpha_{bs} = 10^{\frac{TS_c}{10}} \qquad (10)$$

$$\overline{TS} = 10\log_{10}(\overline{\alpha_{bs}}) \qquad (11)$$

where TSc is the compensated TS value, and $\overline{TS}$ is the mean target strength at a given depth.

2.3.2 Mapping fish density distribution

The spatial distribution of fish density was mapped using ArcGIS 10.8 (ESRI, USA). The interpolation was performed using the Inverse Distance Weighting (IDW) method, whereas the classification of density into four categories (low, medium, high, and very high) applied the Natural Breaks (Jenks) method [6]. This approach highlights spatial variability both horizontally (across atoll zones) and vertically (across depth layers).

2.3.3 Linear regression analysis

To examine the relationship between fish size and abundance, a simple linear regression was applied, with TS (dB) as the independent variable and fish density (ind/1000 m³) as the dependent variable. The regression model is expressed as

$$Y = \alpha + bX \quad (12)$$

where Y is fish density, X is the target strength, α is the intercept, and *b* is the regression coefficient. The statistical significance of the model was evaluated to determine whether fish density decreased with increasing TS, indicating a trade-off between fish size and abundance [7].

3 Result and discussion

3.1 Target strength estimation

The analysis of acoustic data revealed that the target strength (TS) in Kapota Atoll ranged from –51.8 dB to –37.6 dB, with an average of –42.5 dB. The lowest TS values were recorded in the shallow layer (1–5 m), whereas the highest values were found in the deeper waters. The maximum mean TS was observed at a depth of 37–41 m (–39.2 dB), indicating the occurrence of larger fish in the deeper layers. The target strength values based on the depth layer are listed in **Table 1**.

Table 1. Target strength (TS) values by depth layer in Kapota Atoll.

E	Mean TS (dB)	Depth (m)	Mean TS (dB)
1	-51.8	26	-43.4
2	-47.0	27	-41.6
3	-43.3	28	-43.1
4	-43.1	29	-41.7
5	-42.2	30	-41.9
6	-42.4	31	-39.8
7	-41.5	32	-39.3
8	-43.2	33	-41.1
9	-43.9	34	-39.1
10	-48.1	35	-40.9
11	-47.0	36	-38.5
12	-46.1	37	-39.9
13	-46.4	39	-39.7
14	-46.5	40	-39.9
15	-47.5	42	-37.8
16	-47.3	43	-39.9

E	Mean TS (dB)	Depth (m)	Mean TS (dB)
17	-47.2	44	-38.3
18	-45.5	45	-37.8
19	-45.2	46	-38.2
20	-45.0	47	-38.5
21	-45.6	48	-37.9
22	-45.4	49	-38.6
23	-48.5	50	-38.0
24	-44.5	51	-37.6
25	-42.0	52	-37.6

The table indicates a general trend of increasing TS with depth, suggesting that larger individuals tend to inhabit deeper zones. This pattern is consistent with previous studies, which showed that reef-associated fish are often stratified by body size along depth gradients [4]. An example of an echogram is shown in **Fig. 3**.

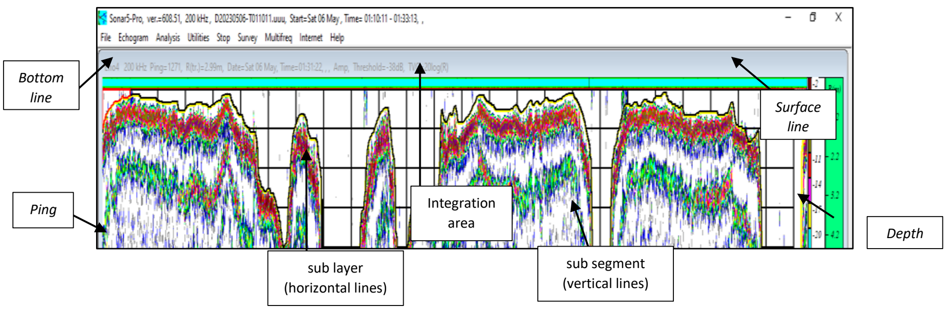

Fig. 3. Example of echogram display.

The example echogram shows the raw vertical acoustic returns used for all downstream processing: distinct backscatter layers (surface/noise, scattering layers, and fish aggregations), and a clear seabed signature. Individual schools and diffuse scattering layers were visible at different depths, which guided the choice of integration bounds (R_1–R_2) and sub-layer segmentation for the SV/SA calculation. Therefore, the echogram provides primary visual validation that the recorded backscatter contains both discrete targets (single echoes) and diffuse aggregations for echo-integration processing.

The regression analysis between TS and depth produced the equation $\overline{\mathrm{TS}} = 0{,}2D - 47{,}5$ with a coefficient of determination $R^2 = 0{,}6$ and a correlation coefficient of $R = 0{,}8$ (**Fig. 4**). This indicates that depth accounts for approximately 60% of the variability in $\overline{\mathrm{TS}}$ values, suggesting that depth is a strong predictor of fish target strength in Kapota Atoll. The positive correlation further shows that TS increases with depth, implying that larger fish tend to inhabit deeper layers.

These findings are supported by previous studies showing that fish body size and morphology strongly influence TS values [3]. Body size and swim bladder structure are the primary determinants of acoustic reflectivity, which explains the higher TS observed in deeper strata. Furthermore, ecological observations indicate that as fish size increases with depth, overall abundance tends to decline, which is consistent with life-history strategies and predator–prey dynamics in reef systems [5].

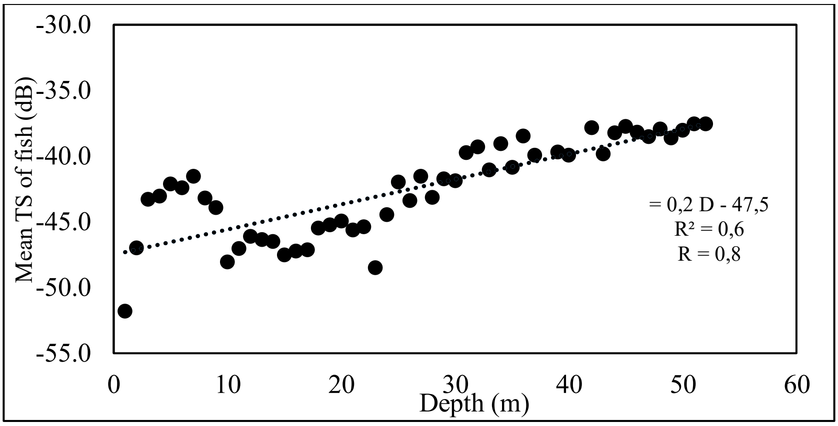

Fig. 4. Relationship between mean TS and depth in Kapota Atoll.

Oceanographic parameters, such as light penetration and nutrient availability up to 53 m depth in the Kapota Atoll, also support the presence of larger predatory fish in deeper habitats, where prey species are available within suitable energy ranges [11]. Other environmental factors, including hydrostatic pressure, oxygen availability, and swimming behavior, may also contribute to the observed variation in TS values across depth layers [1].

3.2 Fish density distribution

Fish density in the Kapota Atoll varied significantly, ranging from a maximum of 45.602 ind/1000 m³ to a minimum of 2 ind/1000 m³, with an average of 514 ind/1000 m³. These values indicate strong spatial heterogeneity, with certain lagoon areas serving as important aggregation zones such as coral reef structures and potential spawning grounds. Conversely, the minimum values were associated with less favorable environmental conditions.

Density estimates were expressed as the number of individuals per 1000 m³, a common metric used in fisheries acoustics to represent biomass per unit volume [2]. This approach allows spatial representation of fish density in the water column based on the volume backscattering strength (Sv) processed using Sonar5-Pro.

Fish density values were classified into four categories according to the FAO [17]: absent, low, medium, and high (**Table 2**). To improve the representation of fish distribution in the Kapota Atoll, these ranges were further refined using the Natural Breaks (Jenks) method, which optimizes class intervals by minimizing variance within groups and maximizing variance between groups.

Table 2. Criteria for fish density classification in Kapota Atoll.

Fish density class	Criteria (ind/1000 m³)
Very low	≤ 1,985
Low	1,986 – 7,197
Medium	7,198 – 23,986
High	23,987 – 45,602

The distribution of fish density is divided based on layers, this is to be able to describe the conditions of fish distribution in detail.

The spatial distribution of fish density in the Kapota Atoll revealed strong vertical and horizontal variability, with clear patterns linked to depth and habitat type (**Fig. 5**). The highest concentrations were consistently observed in the lagoon and reef-flat zones, where shallow habitats provide structural refuges, such as coral heads, seagrass beds, and rubble substrates, that enhance food availability and protection from predators [9]. In the shallowest layer (1–5 m), the maximum density reached 45,602 ind/1000 m^3, which is significantly higher than that in other strata. This finding underscores the critical ecological function of shallow lagoon habitats as primary aggregation areas for reef-fish communities.

In the mid-depth layers, particularly between 21 and 25 m, fish densities remained elevated, with a mean of 2,606 ind/1000 m^3, reflecting the persistence of suitable environmental conditions, such as optimal light penetration and moderate structural complexity [6]. These results suggest that the mid-lagoon depth range is equally important for sustaining reef fish populations, as it supports both the juvenile and adult life stages. However, densities declined sharply beyond 33 m, with values generally below 1,000 ind/1000 m^3. This pattern indicates a depth-related threshold beyond which habitat suitability decreases, owing to factors such as reduced light, lower benthic complexity, and possible limitations in prey availability [12].

In the deepest layers (>45 m), acoustic backscatter indicated only scattered low-density signals, confirming that fish communities in the Kapota Atoll are concentrated above the 33 m isobath [13]. The horizontal distribution maps also demonstrated that fish aggregations were unevenly spread within the lagoon, with density “hotspots” forming in localized areas that likely coincided with microhabitats rich in food resources and shelter [14]. In contrast, the outer reef slope exhibited lower densities, but the individuals detected at these depths were characterized by larger target strength (TS) values, consistent with the presence of bigger-bodied fish in deeper strata [20].

This vertical segregation suggests a size-based distribution pattern, in which smaller fish dominate shallow and mid-depth habitats in large numbers, whereas larger but less abundant species occupy deeper reef slopes. Such a trade-off between fish size and abundance has been widely documented in reef ecosystems, where life history strategies and predator–prey interactions drive habitat partitioning across depth gradients [15]. The implications of this pattern are ecologically significant; lagoon areas function not only as biodiversity hotspots but also as nurseries and feeding grounds, whereas deeper habitats may play a role as refuges for larger, more mobile species [16].

Overall, the fish density distribution in the Kapota Atoll reflects the strong influence of habitat complexity and depth on fish assemblages. The combination of the high fish abundance in the lagoon and the presence of larger individuals in deeper waters highlights the importance of managing both habitat types to maintain ecosystem productivity. These findings align with previous acoustic studies on Wakatobi and other Indonesian reef systems, which similarly reported high variability in fish distribution linked to environmental gradients [18].

Based on the linear regression analysis, the resulting equation was $\rho = -11.56D + 845.56$, where y is the depth and x is the fish density. The coefficient of determination (R^2) was 0.13, indicating that only 13% of fish density variation could be explained by depth; thus, depth has a relatively minor role in predicting the distribution of fish in the Kapota Atoll. This finding is consistent with studies emphasizing the role of other factors such as habitat complexity [13], nutrient availability, ocean currents [14], and species interactions [17], which may have a greater influence on fish distribution. Furthermore, Farhan et al. [15] reported that a combination of multiple environmental factors, including temperature, salinity, and light availability, is often more important than depth in structuring reef fish communities.

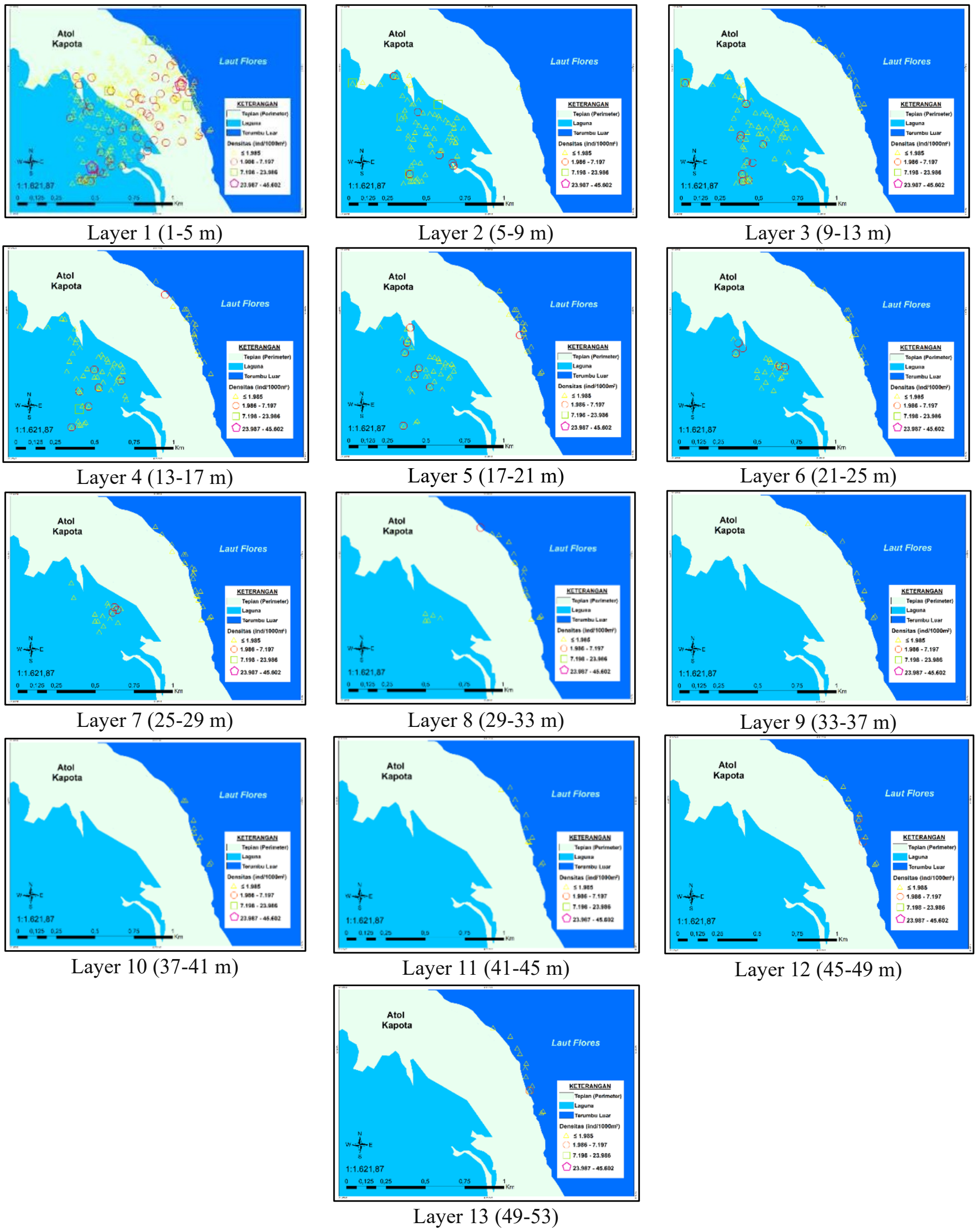

Fig. 5. Fish density distribution in layers 1-13 (1-53 meters).

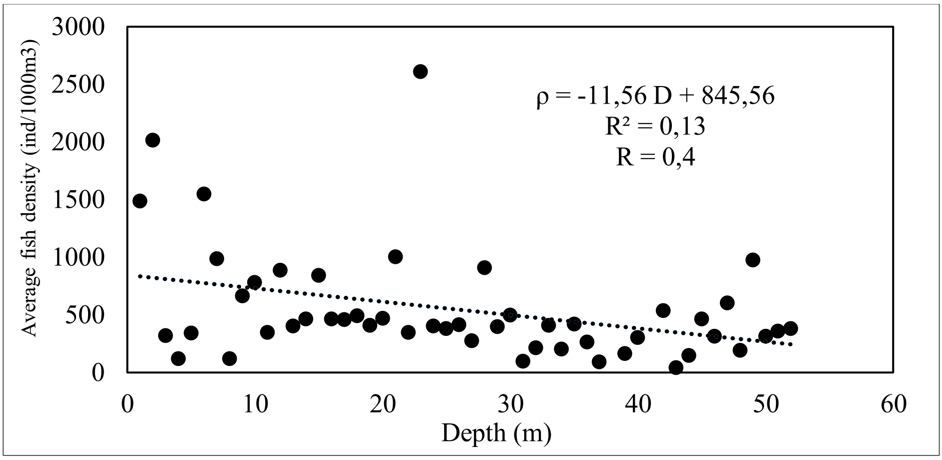

Fig. 6. The relationship between the average value of fish density and the depth detected in Kapota Atoll.

3.3 Relationship between target strength (TS) and fish density

The relationship between mean TS and mean fish density across depths of 1–53 m in the Kapota Atoll showed a distinct vertical pattern (**Fig. 7**). The highest mean fish density was recorded at 21–25 m, with 947 ind/1000 m³, followed by 855 ind/1000 m³ at 1–5 m and 730 ind/1000 m³ at 5–9 m. The TS values in these layers ranged from –45 to –43 dB, indicating the dominance of smaller individuals.

Conversely, the highest TS value (–24 dB) was observed at 37–41 m, suggesting the presence of relatively larger fish. However, the mean density at this depth was only 111 ind/1000 m³, reflecting the tendency of larger fish to occur in deeper layers but in lower numbers. In contrast, smaller fish dominated the surface to mid-depth layers, where densities were much higher.

Overall, these results illustrate a size-abundance trade-off in Kapota Atoll: small fish occur in greater numbers in shallow and mid-depth zones, whereas large fish are distributed in deeper waters with lower density. This vertical structuring is consistent with the ecological theory of reef fish communities, where habitat complexity and resource availability favor small schooling fish near the surface, whereas larger individuals occupy deeper habitats with reduced competition but lower productivity.

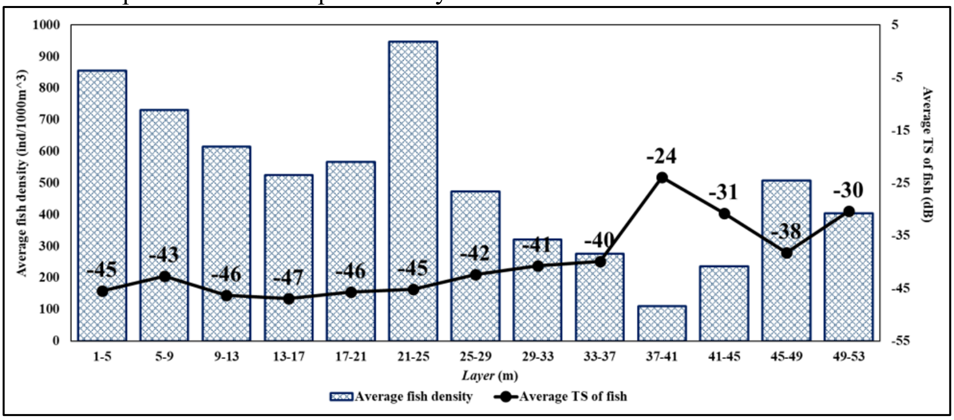

Fig 7. Relationship between mean TS and mean fish density in Kapota Atoll.

The relationship between mean TS and fish density in Kapota Atoll showed a negative trend (**Fig. 8**). This indicates that 30% of the variation in fish density can be explained by TS values, whereas the remaining 70% is likely influenced by other unmeasured factors, such as species composition, oceanographic conditions, time of sampling, and behavioral patterns within habitats. The negative correlation implies that, as TS increases (reflecting larger fish), the density tends to decrease.

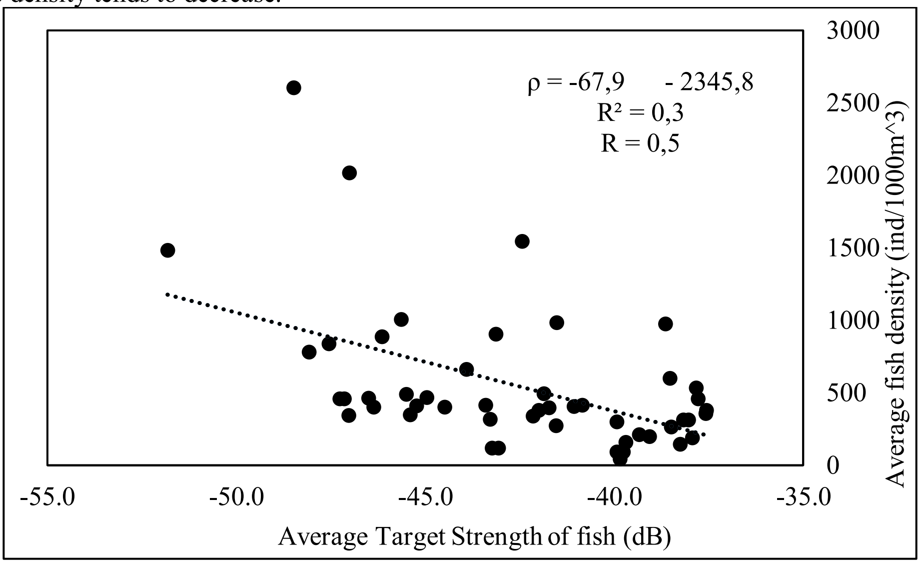

Fig. 8. Relationship between mean TS and mean fish density in Kapota Atoll.

This pattern is ecologically consistent with the size-abundance relationship, where smaller fish are typically more numerous and occur in schools, whereas larger fish are less abundant and often solitary or occur in smaller groups [18]. Consequently, the vertical distribution in the Kapota Atoll demonstrates that small-bodied species dominate the surface and mid-depth layers with higher densities, whereas larger fish are more frequently found in deeper layers with lower densities.

4 Conclusion

The results showed that the TS and fish density varied spatially, both horizontally and vertically. The TS values ranged from − 47 dB to − 24 dB, with the highest mean recorded at 37–41 m depth. The fish density distribution indicated aggregation in several depth layers, particularly at 1–5, 9–13, and 21–25 m, with a maximum of 45,602 ind/1000 m^3 and a minimum of 2 ind/1000 m^3. Fish density decreased significantly below 33 m, whereas the highest aggregation was concentrated in the lagoon areas of the Kapota Atoll, which are assumed to provide more complex and productive habitats. Overall, the distribution pattern suggests that small fish tend to aggregate in shallow to mid-depth waters (1–33 m), classified as shallow reef environments, whereas variations in TS values reflect the presence of diverse fish sizes and species.

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