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Sustainability analysis of tuna (*Thunnus* sp.) management in 11 Fisheries Management Areas 573 Malang District, East Java, Indonesia

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Abstract. *Hermawan D. 2025. Sustainability analysis of tuna (*Thunnus *sp.) management in 11 Fisheries Management Areas 573 Malang District, East Java, Indonesia. Biodiversitas 26: 2662-2673.* The sustainability of tuna management in Indonesia, especially in Fisheries Management Areas (FMA) 573, Malang District, East Java, Indonesia, is essential to guarantee that tuna resources are used sustainably over the long term without harming the marine ecosystem. One of the key challenges in tuna management is striking a balance between the economic exploitation and conservation of fishery resources. This study seeks to assess the sustainability of tuna resource utilization and the factors that will affect the long-term sustainability of its management. The research examines three primary dimensions of sustainable development: the ecological, economic, and social dimensions. The study was conducted from October to December 2024 at Sendang Biru, Malang, East Java, Indonesia. A quantitative research approach was used, incorporating primary data and the MDS-Rapfish data analysis method. The findings of the study indicate that the current management of tuna (*Thunnus* sp.) in FMA 573, Malang, is classified as fairly good, with sustainability indices ranging from 56.30 to 59.50, categorized as quite sustainable. The highest level of sustainability is calculated in the economic aspect, with a score of 59.50 (quite sustainable), followed by the ecological aspect at 58.13 (quite sustainable) and the social aspect at 56.30 (quite sustainable). Three key factors that significantly affect the sustainability of tuna management in FMA 573, Malang, include: (i) the decline in the size of fish caught, (ii) cost of trip, (iii) compliance with laws and regulations.

Keywords: Fisheries, index, MDS-Rapfish, monte-carlo

INTRODUCTION

Indonesia is the second largest archipelago in the world, with more than 17,000 islands and a coastline of 108,000 km (KKP 2020). The potential of capture fisheries and aquaculture makes the marine sector one of the mainstays of the national economy (KKP 2023), is advancing its marine and fisheries economic development, focusing on achieving three interconnected pillars: sovereignty, sustainability, and prosperity (Asche et al. 2018). Indonesia's marine waters are divided into 11 Fisheries Management Areas (FMA) (KKP 2021). Indonesia's Fisheries Management Areas (FMA) are delineated and numbered (e.g., 571, 713) based on FAO's global fishing statistical areas-specifically Areas 57 (Eastern Indian Ocean) and 71 (Western Central Pacific) (FAO 2020). The subdivisions are further aligned with marine ecoregions, a concept developed in collaboration with international environmental NGOs to support ecosystem-based fisheries management (Spalding et al. 2007). According to Wang (2024), the partition of marine areas in fisheries management is very important in ensuring the sustainability of fishery resources in the region. The establishment of these areas (FMA) also helps estimate biomass and stock conditions, ensures conservation, and facilitates the management and monitoring of fishery resources (Di Lorenzo et al. 2020; Hampton et al. 2023).

The position of FMA 573, located between Indonesia and Australia, imparts unique geographical characteristics due to factors including the influence of three distinct water masses (e.g., the Indonesian Throughflow, the South Equatorial Current, and the Leeuwin Current) that shape its marine ecosystem (Sandaruwan et al. 2023), the seasonal differences between the Asian and Australian continents, and the occurrence of upwelling phenomena during the east monsoon winds (Zhang 2019; Fadhilah et al. 2022; Sambah et al. 2023). These factors contribute to the region's rich and abundant marine biodiversity and fisheries resources (Triyono et al. 2019). These three oceanographic factors are Indonesian Throughflow, the South Equatorial Current, and the Leeuwin Current make the Indian Ocean. The Indian Ocean, including FMA 573, a potential habitat for economically important fish species (Orúe et al. 2020) such as skipjack (*Katsuwonus pelamis*), bigeye tuna (*Thunnus obesus*), albacore (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*), mackerel tuna (*Euthynnus affinis*), and bluefin tuna (*Thunnus maccoyii*) (Orúe et al. 2020; Heidrich et al. 2023a).

Tuna fishing activities in FMA 573 are part of the Indian Ocean Tuna Commission (IOTC) area, which is responsible for managing tuna and tuna-like species in the Indian Ocean (Sinan and Bailey 2020), it's tasked with collecting and reporting catch data on behalf of its member countries, ensuring the sustainable management of tuna and related species in the region (Heidrich et al. 2023b). On the other hand, the growing demand for tuna in both domestic and global markets has made tuna one of the target fish species, consequently placing significant pressure on its utilization (Mccluney et al. 2019).

Sustaining tuna resource stocks will provide ecological, economic, and social benefits. According to Castrejón and Defeo (2023), Ecologically, ensuring tuna sustainability helps preserve the balance of the marine ecosystem, where tuna plays a critical role as a top predator in regulating the populations of smaller fish species, which in turn impacts the health of coral reefs and other marine environments. Furthermore, the loss of tuna could result in a decline in overall marine biodiversity. The loss of tuna could result in a decline in overall marine biodiversity. Meanwhile, economically according to Moreno et al. (2019), tuna resources provide livelihoods, as tuna serves as a primary income source for many fishermen who rely on it as a target fish. The depletion of tuna could significantly impact local economies and communities that rely on tuna fishing for their income and food security (Hsu et al. 2021). Moreover, tuna can contribute to national revenue (foreign exchange) through fish exports (Costello 2024). Socially, according to Vaihola and Kininmonth (2023), tuna is the main livelihood of fishermen who provide a profitable catch.

Various studies related to tuna have been carried out, such as research on the biological parameters of tuna (Harlyan et al. 2023), reproductive biology of tuna (Hayashida et al. 2023; Nur et al. 2024), the relationship between length, weight, and water condition factors (Li et al. 2023; Nur et al. 2023), tuna habitat characteristics (Brough et al. 2023; Istnaeni et al. 2023), and the economic suitability of tuna (Erauskin-Extramiana et al. 2019; Bintoro et al. 2023). Habitat characterization and suitability analysis are crucial for sustainable fisheries resource management, as demonstrated by Budiyati et al. (2024) and Syahrir et al. (2024). All of these studies aim to ensure the sustainability of tuna fish management and optimize its utilization to encourage regional and national economic growth in the fisheries sector, as stated by Yusuf et al. (2024), fisheries and marine resources are key sectors of the blue economy that drive the regional economy and can be optimized to increase fishermen's income, encourage regional and national economic growth, and create jobs. This study plays a crucial role in optimizing the potential of fishery resources, particularly in enhancing the fisheries sector's contribution to the Gross Domestic Product (GDP) while preserving the sustainability of the resource stock. The outcomes of this research namely, the sustainability level of fisheries management and its influencing attributes can serve as a scientific basis for policy formulation and further academic inquiry.

MATERIALS AND METHODS

Study site

The study was conducted from October to December 2024 at Sendang Biru, Malang District, East Java Province, Indonesia (Figure 1). Sendang Biru Pondokdadap Coastal Fisheries Port (PPP) is one of the largest fish landing ports for tuna, skipjack, and mackerel (TTC) in Malang (Mawarida et al. 2022) and serves as a major landing site and base for tuna fishermen in FMA 573. Pane et al. (2019) noted that Sendang Biru is the leading fishing village in Malang District, with a Coastal Fisheries Port (CFP) and Fish Auction Place (FAP).

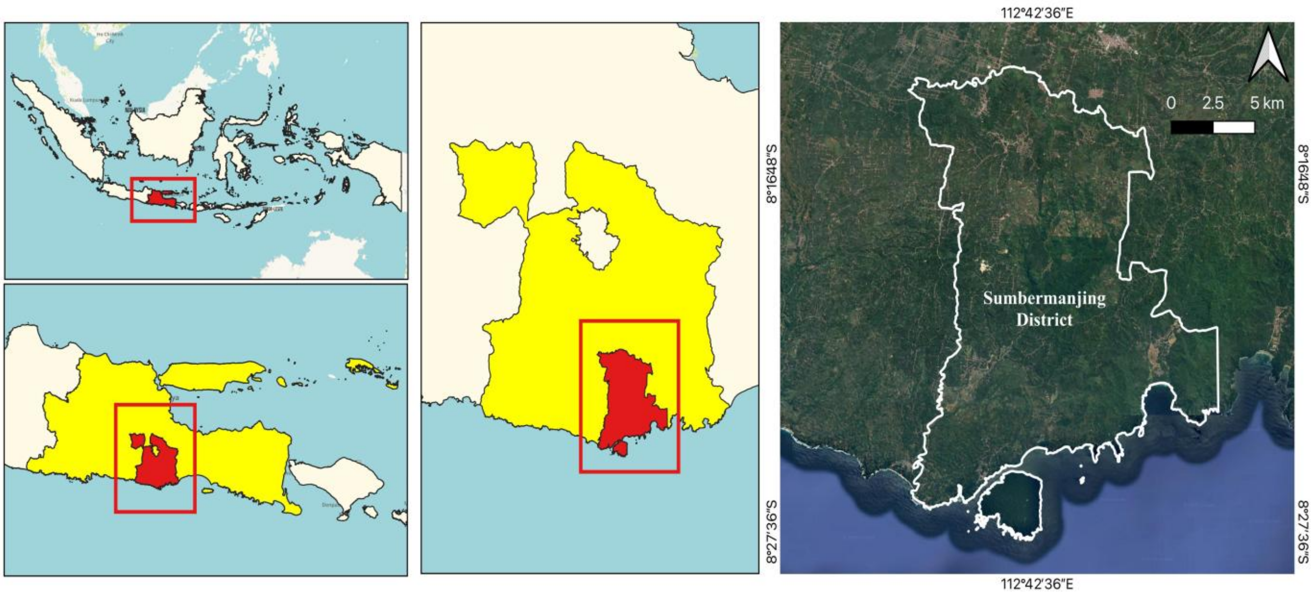

Figure 1. Map of research location

Types and methods of collecting data

The types of data used in this study are primary and secondary data. Primary data refers to information collected directly by the researcher in alignment with the research objectives (Cheung et al. 2024). Secondary data, on the other hand, consists of existing information that was collected for a different purpose but is necessary and will be used by the researcher to answer the research objectives (Martin-Melon et al. 2023). The primary data in this study consists of responses to a series of questions posed through a questionnaire. The questionnaire was developed based on questions derived from specific attributes that required responses from participants. It was distributed to respondents both through face-to-face interactions and sent to email. These responses were gathered from a variety of respondents, including: fishermen (5 people), the Fisheries Office of Malang (5 people), the Fisheries Office of East Java Province (5 people), tuna fishing entrepreneurs (5 people), the Indonesian Tuna Association (5 people), and NGOs focused on fisheries and marine conservation (5 people). Respondents were selected using purposive sampling based on specific criteria, namely: experts or scholars in the field of capture fisheries (academics), decision makers (from the fisheries department), and fisherman (capture fishers). As noted by Yusuf et al. (2021), primary data can come from respondents who represent institutions or communities/groups. Secondary data in this study includes data sourced from fisheries statistics, Malang District, and the Ministry of Marine Affairs and Fisheries. This secondary data is intended to provide answers to questions, such as regional revenue (PAD), investment in fisheries and marine, and institutional support for fishermen. The secondary data in this study were sourced from the Department of Marine and Fisheries of Malang District, including: tuna catch production data, data on the species of tuna caught, data on the types of fishing gear used, data on local revenue (PAD) from the fisheries sector (specifically from tuna capture fisheries), data on investments in tuna capture fisheries, data on the number of tuna fishers, average tuna prices, tuna market data, tuna fishing ground locations, tuna fishing base locations, data on fisher institutions, data on the types and amounts of assistance provided for tuna capture fisheries, and data on the quantity and types of bycatch in tuna fishing activities in Malang District. In addition, secondary data were also obtained from statistical reports of the Ministry of Marine Affairs and Fisheries, which include: Maximum Sustainable Yield (MSY) data FMA 573, tuna production data in FMA 573, data on the number of tuna capture fishers, data on the types of tuna fishing gear used in FMA 573, data on the scale of tuna capture fisheries businesses in FMA 573, data on capture fisheries assistance programs, data on the species and quantities of tuna caught, data on fisher institutions in FMA 573, and data on the types and quantities of bycatch in tuna fishing activities within FMA 573.

Data analysis method

This study used the Rapid Appraisal for Fisheries (Rapfish) Multidimensional Scaling (MDS) method. Rapfish is a multidisciplinary analytical tool used to assess the sustainability of fisheries (Pitcher and Preikshot 2001). It is based on ordination methodology (arranging items according to the measured attributes) and multidimensional scaling. Pitcher and Preikshot (2001) state that Rapfish is a Non-Parametric Multidimensional Scaling approach with ordination techniques based on the principles of Multi-Criteria Analysis (MCA), utilizing an algorithm known as ASCAL. The MDS-Rapfish method was chosen for this study because it was considered the most appropriate for addressing the research objectives. According to Yusuf et al. (2021), MDS-Rapfish is an effective tool for determining the sustainability index of fisheries management. From this index, the management status can be derived.

Using the MDS-Rapfish method, the observed objects or points are mapped within a two- or three-dimensional space, ensuring that the objects or points are positioned as close as possible to the origin. Points that are different from each other are represented by being positioned far apart. The ordination distance in MDS is determined based on Euclidean Distance in a dimensional space (Mandanas and Kotropoulos 2017), as represented below:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

Where,
d : Dimensional
x : Ecological dimension
y : Economic dimension
z : Social dimension

The configuration or ordination of a single point or object in MDS is then approximated by regressing the Euclidean distance from point i to point j with respect to the origin, as shown in the following equation:

$$d_{ij} = \sqrt{\sum_{k=1}^{p} (x_{ik} - x_{jk})^2}$$

Where:
d_{ij} : Euclidean distance between object i and object j
x_{ik} : Attribute value of object k to object i
x_{jk} : Attribute value of object k to object j
p : The number of dimensions or original variables before being mapped to low-dimensional spaces

The regression technique used is the ALSCAL algorithm, which optimizes the squared distance (dijk) against the squared data (origin point: Oijk). The three-dimensional form is represented in the stress formula as follows:

$$Stress = \sqrt{\frac{\sum_{i<j} dij - d\hat{}ij^2}{\sum_{i<j} dij^2}}$$

Where,
Stress : Badness-of-fit between the original distance and the distance in the representation of MDS results
∑i<j : The sum for all object pairs I and J, is calculated only once because the distance is symmetrical
dij : The original distance between objects i and j in the input data (based on the dissimilarity matrix)

d^ij : The projection distance between objects i and j in low-dimensional space (2D or 3D)

It is crucial to determine how well (goodness of fit) the distance between the predicted point and the origin point aligns in each measurement (metric). In MDS, goodness of fit is assessed by how accurately the configuration of a point reflects the original data. This value is commonly represented by the stress value, which is calculated from the S-stress value. If the stress value is low or close to 0 (zero), it indicates a good fit, whereas a high stress value signifies a poor fit. A stress value less than 0.25 is generally considered to be good. The validation of simulation models is a critical process to evaluate their accuracy and reliability in representing real-world systems. The validation process involves comparing model outputs with real-world data to determine if the model is sufficiently accurate for its intended purpose (Sargent 2020). Various approaches and techniques are employed in model validation, including conceptual model validity, operational validity, and data validity (Thum et al. 2024).

Furthermore, the sustainability status is determined based on the ordination index, with a value range from 0 (poor) to 100 (excellent). To evaluate the influence of parameters within each attribute used in the sustainability index, a sensitivity analysis in the form of leverage attribute analysis is performed. The results of the leverage attribute analysis highlight the key attributes that are most sensitive (either supporting or hindering) in the ordination of the sustainability index. The determination of each score range is based on direct observations or primary data, as well as secondary data collected from previous studies.

The dimensions used in this study are based on the principles of sustainable development, which include ecological sustainability, economic sustainability, and social sustainability. These three dimensions serve as the core pillars of sustainable development. The attributes for each dimension are determined based on the FAO Code of Conduct Ecological Approach to Fisheries Management (EAFM) guidebook (FAO 2014), and relevant previous studies (give the references). According to Yusuf et al. (2021), the number of attributes for each dimension typically ranges from 6 to 12; any number exceeding this would be considered excessive. Therefore, irrelevant, and less significant attributes should be eliminated at the outset. The attributes used in this study and their respective score ranges are given in Table 1.

Table 1. Attributes and scoring of tuna management sustainability analysis in FMA 573

No	Dimensions/attributes	Criteria	Measurement method
A	Ecological dimension		
1	Exploitation rate (MSY)	[0] above MSY (bad) [1] to MSY (moderate) [2] under MSY (good)	Data of fisheries production (KKP)
2	Selectivity of fishing gear	[0] not selective(bad) [1] quite selective(moderate) [2] very selective (good)	Field observations and fisheries statistics data
3	Fishing ground (location)	[0] less extensive (bad) [1] moderately large (moderate) [2] very many very extensive (good)	Interview
4	Habitat conditions/aquatic ecosystems	[0] damaged/contaminated (bad) [1] Partially damaged/lightly contaminated (moderate) [2] healthy/unpolluted (good)	Field observations and Research results
5	Bycatches	[0] high/many or >50% of target species (bad) [1] medium or 30-50% of target species (moderate) [2] low/less or <30% of target species (good)	Interview
6	Size of fish caught	[0] small (bad) [1] quite large (moderate) [2] large/above average (good)	Field observations and interview
7	Fishing method (impact/effect on the environment)	[0] destructive (bad) [1] quite destructive (moderate) [2] non-destructive (good)	Field observations and interview
8	Harvest rate	[0] low (bad) [1] medium (moderate) [2] high/many (good)	Field observations and interview
B	Economic dimension		
1	Fishermen's income (UMP)	[0] under UMP (bad) [1] to UMP (moderate) [2] above UMP (good)	Interview
2	Regional revenue (PAD)	[0] less than the previous year (bad) [1] equal to the previous year (moderate) [2] increases every year (good)	Data by Government of Malang District
3	Investment value in the fisheries sector	[0] less than the previous year (bad) [1] equal to the previous year (moderate) [2] increases every year (good)	Data by Government of Malang District

4	Business feasibility (economic and financial)	[0] unsuitable (bad) [1] suitable (moderate) [2] very suitable (good)	Interview and research results
5	Cost per trip	[0] high/very high (bad) [1] medium (moderate) [2] low (good)	Interview
6	Business scale	[0] small (bad) [1] medium (moderate) [2] big (good)	Field observations
7	Market potential	[0] low (bad) [1] medium (moderate) [2] high potential (good)	Interview
8	Price of fish	[0] cheap (bad) [1] medium (moderate) [2] expensive (good)	Interview
C	Social dimensions		
1	Employment opportunities	[0] low (bad) [1] some (moderate) [2] many (good)	Interview
2	Business opportunities	[0] low (bad) [1] some (moderate) [2] many (good)	Interview
3	Kinds of conflict	[0] high (bad) [1] some (moderate) [2] none (good)	Interview
4	Business assistance programs	[0] <10% of fishermen receive assistance programs (bad) [1] 10-30% of fishermen receive assistance programs (moderate) [2] >30% of fishermen receive assistance programs (good)	Government statistical data (KKP)
5	Government support	[0] low (bad) [1] medium (moderate) [2] high (good)	Interview
6	Fisherman's institution	[0] low (bad) [1] medium (moderate) [2] high (good)	Interview
7	Compliance with laws and regulations	[0] low (bad) [1] medium (moderate) [2] many (good)	Interview
8	Knowledge of natural resource	[0] low (bad) [1] not bad (moderate) [2] excellent (good)	Interview

Source: Modified FAO-Code of Conduct, EAFM (Ecological Approach of Fisheries Management) (FAO 2014). Note: MSY (Maximum Sustainable Yield), UMP (Upah Minimum Provinsi/provincial minimum wage). All parameters were assigned a score ranging from 0-2

RESULTS AND DISCUSSION

Model validation

Model validation is essential to ensure that the results are valid and reliable and can form a solid basis for decision-making. The validity measures used in the MDS-Rapfish approach include stress value, R-square value, and Monte Carlo value. The values of the three validity indicators were compared against the ordination value for each dimension examined in this study (Table 2).

Stress value is a crucial indicator of validity in MDS techniques, which are used to visualize the level of similarity between individual objects in a dataset (Vakili and Jahangiri 2018). The stress value represents the goodness of fit between the original data and the reduced-dimensional representation. Goodness of Fit indicates how well the research model aligns with the ideal model (the real model). In other words, GOFIT is a measure of model suitability. According to Yusuf et al. (2021), the smaller the stress value, the better the model, indicating that the monotonous relationship between inequality and disparity is improving, and the configuration map criteria formed are becoming more accurate. Conversely, the higher the stress value, the greater the mismatch between the data and the measurement, implying more errors or incompatibility.

The results of the model fit evaluation show that the stress value ranges from 0.1394 to 0.1406 (13-14%), which is below 20%. This is consistent with George et al. (2021), who stated that a tolerable stress value is <20%, and Di Leo and Sardanelli (2020), who suggested that a very good stress value is <0.25. Therefore, the resulting model is sufficiently good and valid for use as a predictor.

R-square, also known as the coefficient of determination, is a statistical measure used to assess the goodness of fit in regression models. It represents the proportion of variance in the dependent variable that can be predicted from the independent variable (Chicco et al. 2021). R-square (R^2) is the square of the correlation coefficient, which indicates the proportion of variance explained by the optimization of data scaling resulting from multidimensional scaling procedures and is also a measure of goodness of fit. The coefficient of determination (R^2) essentially measures how well a model can explain variations in the dependent variable. The higher the R-square value, the better the model; conversely, the lower the R-square value, the worse the resulting model. The R^2 value ranges from 0 (zero) to 1 (one), which, when expressed as a percentage, is between 0% and 100%.

The results of the model fit evaluation showed R^2 values ranging from 0.9444 to 0.9467, which is close to 1.0, categorizing the model as very good. R^2 values above 0.75 are considered strong, between 0.50 to 0.75 moderate, and below 0.25 weak. Therefore, based on the R^2 value, the model is considered valid and acceptable as a predictor.

Monte Carlo simulation is a powerful tool for validating complex systems and models across various fields. It enables realistic analysis by relaxing limiting assumptions about system behavior (Velikova et al. 2024). This method has been widely applied in areas such as system reliability, risk analysis, financial modeling, and public health. Monte Carlo values are used to evaluate the effect of random error on a process and to estimate the 'true' value of the statistic of interest (Kavanagh and Pitcher 2004). They further explain that random errors from computer-generated random numbers are added to the phenomenon being tested, generating scatter plots and other statistics. According to Kavanagh and Pitcher (2004), Monte Carlo analysis can be used as a simulation method to assess the impact of random errors in the statistical analysis performed.

Yusuf et al. (2021) also stated that Monte Carlo analysis can indicate errors caused by scoring each attribute, variations in multidimensional scoring due to different opinions, repetitive data analysis processes, and errors in data input or missing data. The evaluation results show Monte Carlo values ranging from 69.88 to 89.15, which align with the resulting ordination values, which also range from 71.47 to 92.02. When combined, a relatively small value is obtained, falling within the range of 1.69 to 2.87, which is less than <5.0. Therefore, the model can be accepted and used as a predictor. This aligns with Yusuf et al. (2021), who stated that the maximum allowable difference is 5%, with 5% being the significance level (alpha, α), typically based on a 95% confidence level or a 5% error rate.

Ecological sustainability

Ecological sustainability is a concept that involves efforts to maintain a balance between the utilization of natural resources and environmental protection for future generations. It includes managing natural resources sustainably, minimizing negative environmental impacts, and preserving biodiversity (Rai 2021; Anikwe and Ife 2023). This approach takes into account the interconnectedness between humans, animals, and the environment, as demonstrated by the One Health approach in the tropical rainforests of Hainan (Zhang et al. 2024). The ecological sustainability level of tuna management in FMA 573, Malang District, is visualized in Figure 2.

Based on the results of the MDS-Rapfish analysis, the ordination value for ecological sustainability is 58.13, which is categorized as quite sustainable. This value indicates that the ecological conditions are relatively good and sustainable. However, this condition must be maintained, given the various pressures and challenges in managing tuna (*Thunnus* sp.) in FMA 573, Malang District. According to Meinhold et al. (2024), there are several challenges and contradictions in achieving ecological sustainability. For instance, the increased use of digital technology for sustainability may create new issues related to the use of scarce natural resources. Additionally, the balance between environmental conservation and economic development is often difficult to achieve, as seen in the case of forest management in karst areas (Zhou et al. 2023).

To achieve ecological sustainability, a multidisciplinary approach involving various stakeholders is necessary. These approaches include the use of Artificial Intelligence (AI) to improve sustainability practices (Adanma and Ogunbiyi 2024), the application of circular economy principles in the bioeconomy (Anikwe and Ife 2023), and increased community awareness and participation in conservation efforts (Aktymbayeva et al. 2023; Gasciauskaite et al. 2023). These strategies aim to create a balance between human needs and long-term environmental conservation. The depiction of the contribution, influence, and sensitivity of each ecological dimension attribute on sustainable tuna management in FMA 573, Malang District, is visualized in Figure 3.

Table 2. Model validation indicator value

Dimension	Stress value	R squared	Monte-Carlo value	Ordination value	Difference	Validation
Ecology	0.1404	0.9457	57.06	58.13	1.07	Valid
Economy	0.1394	0.9467	58.23	59.50	1.27	Valid
Social	0.1406	0.9444	55.13	56.30	1.17	Valid

Sources: Data analysis of MDS Rapfish Modification (2025)

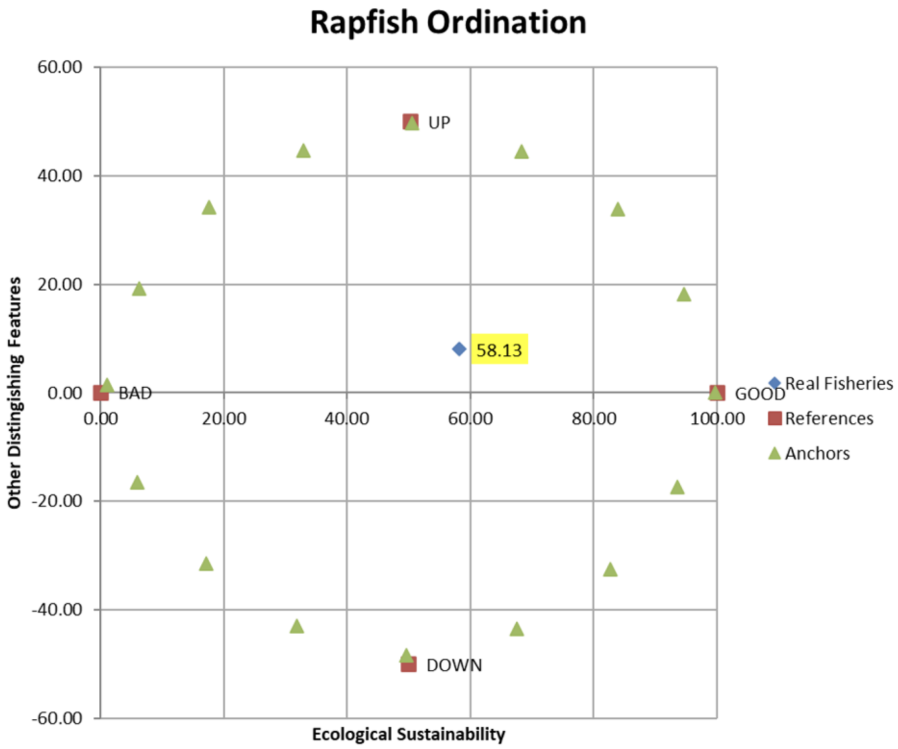

Figure 2. Rapfish ordination of ecology sustainability

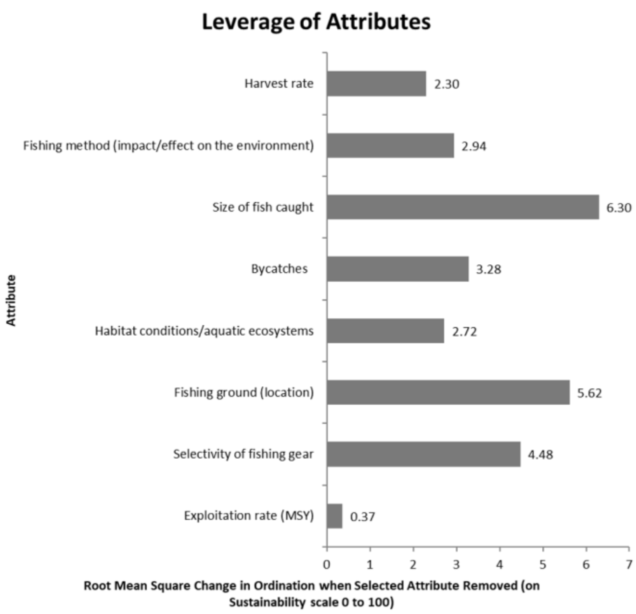

Figure 3. Leverage analysis of ecology sustainability attributes

Based on the results of the attribute leverage analysis, it was found that the size of the tuna caught was the most sensitive attribute in the ecological sustainability of tuna (*Thunnus* sp.) management in FMA 573, with an RMS value of 6.30. The size of the fish caught is a crucial indicator of ecological sustainability, as it provides information about the status of fish stocks and the overall health of the ecosystem. Catching smaller-sized fish and an increasing proportion of juveniles may indicate that fishing activities are not selective, which could reduce the number of individuals reaching reproductive size. This reduction in reproductive individuals could lower the recruitment rate and disrupt the balance of the ecosystem.

Tuna catches in FMA 573 have shown a decrease in size. The average size of bigeye tuna decreased from about 18.65 kg in 2020 to 15.25 kg in 2022 (Raup et al. 2023). Research results of Damayanti et al. (2023) in FMA 573 reported that most of the tuna caught were less than 100 cm in length, with an average length at first capture of approximately 65.7 cm. This indicates a predominance of small-sized fish in the catch, which may reflect excessive fishing pressure on tuna populations in the region. Similarly, Zahra et al. (2023) found similar results regarding the status of bigeye tuna (*T. obesus*) fisheries landed at the Cilacap Ocean Fishing Port (PPS). Therefore, the declining catch size in FMA 573 requires attention, as it signals potential ecological concerns.

Economic sustainability

Economic sustainability refers to the capacity of an economic system to continue developing and meeting societal needs in the long term, while maintaining a balance with social and environmental factors. It involves consistent economic growth, innovation, and diversification to reduce reliance on specific resources (Wahyono et al. 2023). In the context of tuna management, economic sustainability refers to efforts to strike a balance between the profitable exploitation of fish resources and the preservation of fish stocks for future generations. This approach integrates economic growth, natural resource management, and social welfare to ensure the long-term viability of the industry. The depiction of the economic sustainability level of tuna management in FMA 573, Malang District, is visualized in Figure 4.

Based on the results of the MDS-Rapfish analysis, the ordination value for economic sustainability is 59.50, which is categorized as sustainable. This value indicates that the economic conditions of tuna fishery management in FMA 573, Malang District, are classified as very good and sustainable. However, challenges such as overfishing, environmentally harmful fishing practices, the impact of global climate change (e.g., sea level rise and shifts in water masses), and the effect of marine debris remain significant in ensuring the sustainable management of tuna, including in FMA 573 in the Indian Ocean. These factors have a negative impact on long-term economic viability.

Therefore, tuna fisheries management requires a regional approach due to the migratory nature of tuna. Indonesia needs to collaborate with other countries through Regional Fisheries Management Organizations (RFMOs) for effective management (Schiller and Bailey 2021). Several strategies have been developed, including: (i) the implementation of harvest strategies agreed upon at the RFMO level (Schiller and Bailey 2021), (ii) enhanced monitoring and management using technologies such as drones and computer vision (Pham and Han 2024), (iii) seasonal closures of fishing areas to protect juveniles, as proposed in South Lombok (Wiryawan et al. 2020), (iv) ecolabel certification to promote sustainable fishing practices (Schiller and Bailey 2021). By comprehensively implementing these strategies, Indonesia can sustain the economic viability of the tuna industry in the long term. The depiction of the contribution, influence, and sensitivity of each economics dimension attribute on sustainable tuna management in FMA 573, Malang District, is visualized in Figure 5.

Based on the results of the leverage attribute analysis, it was found that the cost per trip is the most sensitive attribute in the economic sustainability of tuna (*Thunnus* sp.) management in FMA 573, with an RMS value of 7.10. This attribute stands out compared to other attributes in the economic dimension. One of the main economic challenges in tuna fishing in FMA 573 is the relatively high cost of fishing. The location of the fishing ground, which is the high seas (Indian Ocean), necessitates the use of large vessels with high engine capacities, leading to significant fuel requirements.

Research by Suharyanto et al. (2021) indicates that tuna fishing activities using fishing rods are considered less feasible, with a B/C ratio of 1.12, which is close to 1.0, indicating that the profit obtained is very small, almost breaking even. On the other hand, the Payback Period (PBP) is calculated to be 5.8 years, or nearly 6 years, meaning that the investment takes a relatively long time to recover. Furthermore, it is noted that one of the largest variables in the cost of tuna fishing includes expenses such as the cost of purchasing diesel fuel, bait, food ingredients, disposable equipment for deck and engine needs, and the salaries of the skipper and crew. The average cost per trip amounts to IDR 278,019,300.

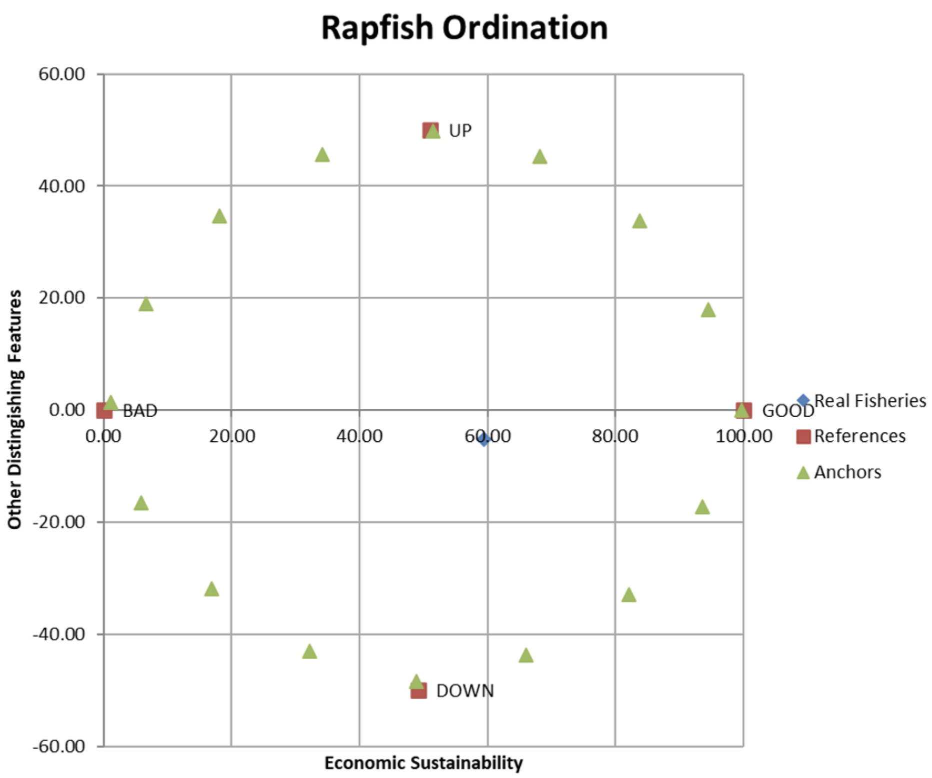

Figure 4. Rapfish ordination of economy sustainability

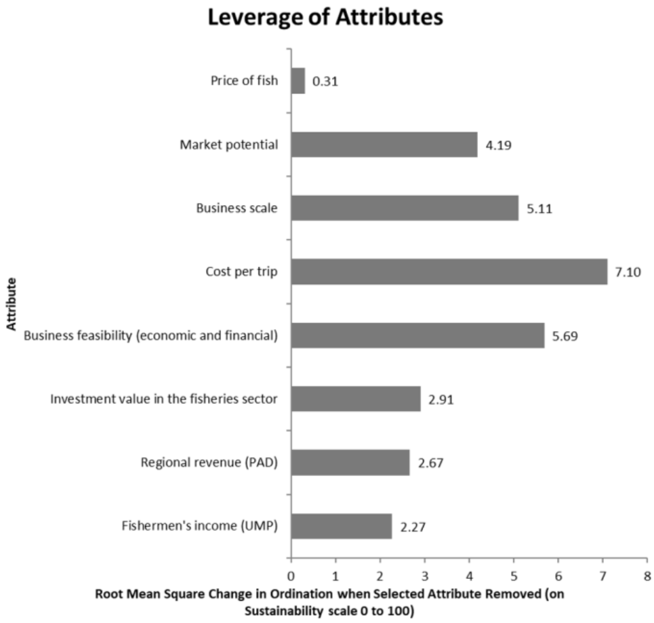

Figure 5. Leverage of attribute of economy sustainability

Social sustainability

Social sustainability is a crucial component of sustainable development, focusing on community well-being and social justice. It involves efforts to improve the quality of life for individuals, promote equality, and ensure the active participation of citizens in development processes. Social sustainability encompasses human resource development, community empowerment, and the creation of equitable opportunities for all (Tabatabaei et al. 2024). This concept also highlights the importance of balancing human needs with nature and fostering harmony among people (Hidalgo-Capitán et al. 2019). The depiction of the social sustainability level of tuna management in FMA 573, Malang District, is visualized in Figure 6.

Based on the results of the MDS-Rapfish analysis, the ordination value for social sustainability is 56.30, which is categorized as sustainable. This value indicates that social conditions in tuna fish management in FMA 573, Malang District, are considered very good and sustainable. Social sustainability is a multidimensional concept that encompasses aspects of justice, security, community participation, and inclusive development. Its implementation requires a holistic approach that addresses the needs of all stakeholders and focuses on creating a more just, secure, and sustainable society (Eizenberg and Jabareen 2017; Nogueira et al. 2024).

One of the challenges to social sustainability in tuna management in FMA 573, and Indonesia in general, is the high dependency of artisanal fishers on tuna fishing. In particular, tuna fishing using longlines often results in the capture of sharks, rays, and various other non-target fish species. These bycatch issues present challenges for artisanal fishers. On one hand, the relatively high market price of shark products may shift the fishing orientation of fishers, while on the other hand, sharks are protected species listed on The IUCN Red List of Threatened Species (Strijk and Fowler 2024). The depiction of the contribution, influence, and sensitivity of each socio dimension attribute on sustainable tuna management in FMA 573, Malang District, is visualized in Figure 7.

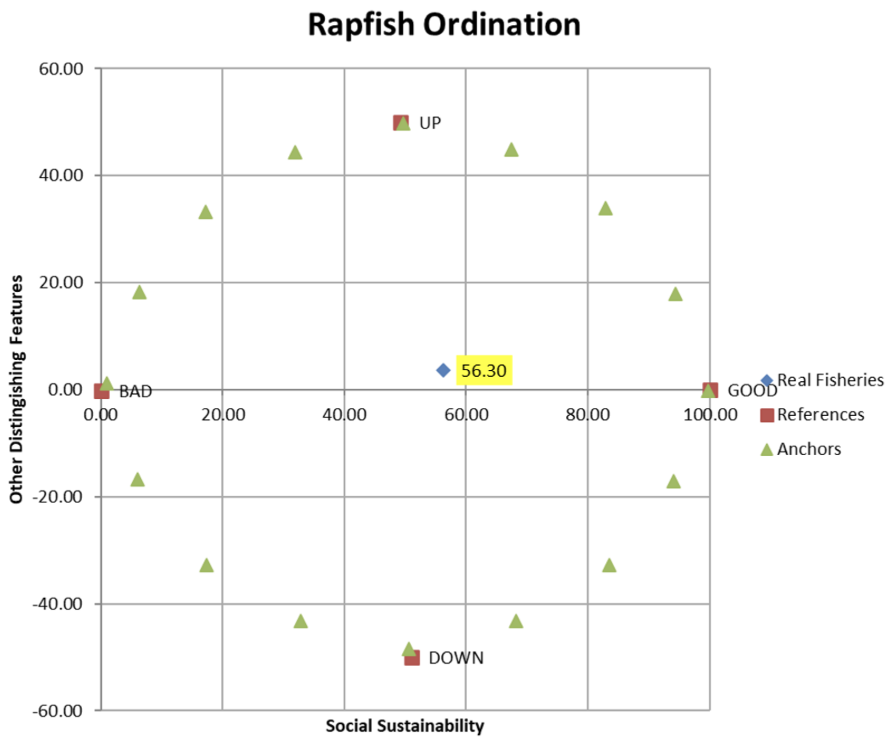

Figure 6. Rapfish ordination of social sustainability

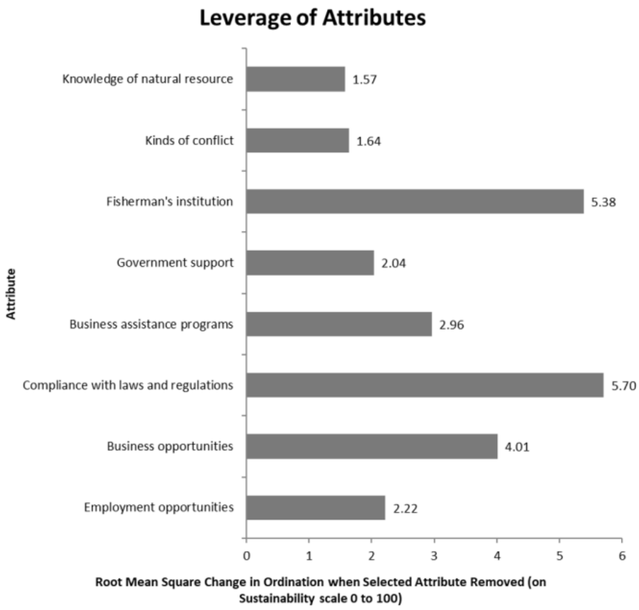

Figure 7. Leverage analysis of social sustainability attributes

Based on the results of the leverage attribute analysis, it was found that compliance with laws and regulations is the most sensitive attribute in the social sustainability of tuna (*Thunnus* sp.) management in FMA 573, with an RMS value of 5.70. This attribute stands out significantly compared to the sensitivity of other attributes. Compliance with laws and regulations is critical, especially in maintaining the sustainability of tuna (*Thunnus* sp.). Several national laws and regulations are essential, including: (i) KP Regulation No. 56/PERMEN-KP/2014 concerning the establishment of fishing quotas in Indonesian waters, including for tuna species, (ii) KP Regulation No. 2 of 2015 concerning selective fishing gear.

In addition, international conventions must be adhered to, such as: (i) The International Commission for the Conservation of Atlantic Tunas Resources (ICCAT). The International Commission for the Conservation of Atlantic Tunas (ICCAT) is a Regional Fisheries Management Organization (RFMO) responsible for the conservation of tunas and tuna-like species in the Atlantic Ocean and adjacent seas. Over time, ICCAT has evolved both institutionally and operationally to meet growing conservation challenges, particularly in managing fish stocks like Atlantic bluefin tuna, bigeye tuna, and associated bycatch species such as sharks. ICCAT has developed increasingly sophisticated tools for fisheries management, including Total Allowable Catch (TAC) systems, observer programs, and compliance mechanisms, its performance has been uneven. (ii) The Indian Ocean Tuna Commission (IOTC), which enforces international recommendations related to tuna fishing, including quotas, types and sizes, and the allowable types of fishing gear. The Indian Ocean Tuna Commission (IOTC) is an intergovernmental organization established to manage tuna and tuna-like species in the Indian Ocean and adjacent seas. It operates under the Food and Agriculture Organization (FAO) of the United Nations. Key Functions IOTC are, a) Data collection and analysis: Member states are required to collect and share data on tuna catches, fishing effort, and biological data; b) Stock assessment, that scientific committee conducts assessments on the status of tuna stocks (e.g., yellowfin, skipjack, bigeye); c) Management measures, the IOTC adopts binding resolutions on (Catch limits, gear restrictions, minimum size limits, monitoring, control, and surveillance); d) Combatting IUU Fishing, implements measures to prevent Illegal, Unreported, and Unregulated (IUU) fishing through vessel registries and port state controls. (iii) The Marine Stewardship Council (MSC), which mandates that tuna products traded are caught in an environmentally sustainable and responsible manner. The Marine Stewardship Council (MSC) is an international non-profit organization established to address the problem of unsustainable fishing and to safeguard seafood supplies for the future Key Aspects of the MSC are; a) MSC certification program, the MSC runs a certification and eco-labelling program for sustainable fishing which is based on three main principles (sustainable fish stocks, minimizing environmental impact, and effective management); b) MSC chain of custody certification to ensure that seafood bearing the MSC blue label comes from certified sustainable sources, the MSC also provides a chain of custody standard; c) MSC eco-label, seafood products that meet MSC standards can display the blue MSC label, which helps consumers make informed choices and supports sustainable fisheries by creating market incentives; d) Global reach, MSC-certified fisheries operate in more than 35 countries, and thousands of products bear the MSC label in over 100 countries. The MSC works with scientists, NGOs, and stakeholders in the fishing industry to continuously improve its standards. 4) Exported tuna products must comply with the health and hygiene standards of the destination country, such as FDA regulations in the United States and EU food safety standards.

In conclusion, the current tuna management in FMA 573, Malang District, in particular, is quite good, with a management sustainability index ranging from 56.30 to 59.50, categorized as quite sustainable. The highest level of sustainability is calculated in the economic aspect, with a score of 59.50 (quite sustainable), followed by the ecological aspect at 58.13 (quite sustainable) and the social aspect at 56.30 (quite sustainable). There are three key factors that are highly sensitive to the sustainability of tuna management in FMA 573, Malang District: (i) the decline in the size of fish caught, (ii) cost of trip, (iii) compliance with laws and regulations. There is a need for improved management, given that the sustainability levels of the three assessed aspects of tuna resource management in FMA 573, Malang District, remain relatively low. While the overall condition is still considered sustainable, the sustainability score is below 60. To address this, several management initiatives should be prioritized, focusing on: (i) conserving species and ecosystems to maintain tuna stock sustainability, (ii) increasing the efficiency and effectiveness of fishing activities to help reduce operational costs, (iii) strengthening outreach and education on laws and regulations to enhance compliance with existing policies.

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