Indian Fisheries Association

Journal of Indian Fisheries Association

Explicit traces of longliners to sustainably harness marine fisheries: Evidence from fuzzy VIKOR approach

J. Amali Infantina[1], [2]*, R. Jayaraman[1], Kalidoss Radhakrishnan [3]#, I. Sivaraman[4]

[1] *Fisheries College and Research Institute, Thoothukudi 628008, India*
[2] *National Centre for Sustainable Coastal Management, Chennai 600025, India*
[3] *ICAR-Central Institute of Fisheries Education, Mumbai 400061, India*
[4] *ICAR-Central Marine Fisheries Research Institute, Vizhinjam 695001, India*
[5] *ICAR-Central Institute of Freshwater Aquaculture, Bhubaneswar 751002, India*

Abstract

Sustainable and judicious exploitation of marine resources has been a highly debated topic in recent times, in particular relation to the growing environmental impacts such as diminishing fish stock, changes in climate leading to uncertain economic profitability in marine capture fisheries. Developing countries like India suffer the most due to the multi-species nature of the fisheries and its biodiversity. Indeed, there is a dire need for an ideal fishing gear to sustainably reap the marine fish without damaging the ecosystem. The aim of this study is to identify the most sustainable fishing system for the harvest of marine fisheries in Palk Bay, India, by analyzing the economic aspects of major fishing methods using Fussy VIKOR method and their compatibility with sustainable practices. Results demonstrate that the economic net profit US$ 40452 year^{-1} was higher for trawler than those of longliner (US$ 39738 year^{-1}) and gillnetter (US$ 19645 year^{-1}) with no significant difference observed between trawler and longliner (P>0.05). But the profit margin (20%) was low for trawler compared to longliner (25%); because; of the total gross revenue, the fuel cost was 10% higher for trawler compared to longliner. Profit of the fishing fleet relies heavily on the input of fossil fuel which also significantly affects the environment. The energy efficiency in terms of fuel use intensity (FUI) was estimated to be 3.5 and 2.7-fold greater for longliner and gillnetter, respectively compared to trawler. The lowest of 0.520 tons of CO_2 was emitted per ton of fish caught in a longliner whilst the same, amounted to 0.684 tons of CO_2 for gillnetter and 1.823 tons CO_2 for trawler. The fuzzy VIKOR index computed using different performance indicators of fishing fleets pointed long liner to be ideal. Result of the scenario analysis advocates that 40% existing trawler replacement aids to save fuel combustion of 121.33 million litre year–1 that could prevent emission of 9.5 million tons of CO_2 per annum during fishing which in turn would largely serve to reduce the climate change effect. Ground truthing for the same has been done for the conversion of trawler to longliner. The average catch amounted to 10 to 12 tons per trip (15 days per trip) generating a net profit of US$ 8065 to 11290 for the same.

Keywords:
Economic performance; Energy efficiency; Environmental efficiency; Multi-criteria analysis; Sustainability

***Corresponding author:**
amaliinfantina@gmail.com
J. Amali Infantina*
theradhakrishanank@gmail.com
Kalidoss Radhakrishnan#

Received : 17 March 2023
Accepted : 19 July 2023

Introduction

The food production sector – agriculture, livestock, and fisheries – is responsible for a quarter of greenhouse gas emission globally (Parker *et al.,* 2018). Of which CO_2 account for a major share being mainly sourced from fossil fuel burning (Allsopp *et al.,* 2009). The marine fish reap has emanated a sum of 207 mt of CO_2 in 2016 by engine combustion of fuel, contributing about 77% in industrial fishing fleets. Four-fold CO_2 emission among industrial fishing fleet was recorded since 1950 (39 million tons) (Greer *et al.,* 2019). An ample rise of CO_2 emission significantly affects the recruitment of the fish species, species distribution and ultimately disturbs food pyramid and ecosystem balance (Stiasny *et al.,* 2016). On the flipside, marine capture fisheries has been stagnant for a decade and this could be related to overfishing and decline of stock status (Ye and Gutierrez, 2017). The globalization

and trade in fish has motived the fishers to earn more and to overexploit the living organism (Myers and Worm, 2003). The entry of new fishing fleet, in particular, trawler with high engine power and its soaring numbers has a serious toll on the fragile habitat of ecosystem containing unique biodiversity and stock (Clark *et al.,* 2016). As a consequence, the exploited stocks may be more sensitive to climate change. Fishing under these circumstances has been questioned because of its environmental impact and uncertain economic profitability within exclusive economic zone (Norse *et al.,* 2012; Sala *et al.,* 2018). Therefore, these stocks can be recovered/optimized by adapting biological strategies such as establishment of marine reserve (Krueck *et al.,* 2017; Roberts *et al.,* 2005), stringent regulation of mesh size (Jones, 1983) and minimum legal size. For a multi-species fishery resource, these regulations are quite tough to enforce, but are sure to reap ample benefits in the long run. Needless to mention, the current fishing practices may further exacerbate remaining resources if no timely measures are enforced. On another side, the standard operating protocol for seed and grow–out production in marine aquaculture do not exist for all marine fish landings. Hence there is no scope for similar quantum production of the same, as like wild, except for few species like cobia, seabass and salmon at prohibitive cost and emitting colossal amount of CO_2 (FAO, 2018).

Evidences suggest that the right fishing gear should not only ensure the profitability, but also curtail CO_2 emission to diminish the current fishing pressure, minimize the damage to the marine ecosystem and environmental pollution thereby striving to accomplish sustainable harvest and better livelihood of the coastal fishers. It is well known that fishing is a complex dynamic system and it not only suffers from exploitation of fish stock but also poor economic profitability (Abernethy *et al.,* 2010; FAO, 2005). Fishing is a fuel-intensive activity (Greer *et al.,* 2019) which accounts for more than 50% of the total operating cost in a mechanized fleet (Cheilari *et al.,* 2013; Tyedmers, 2004; Ziegler and Hornborg, 2014). Fuel consumption can be saved in fishing operation through improved technique, technology, and operational practices (Tietze *et al.,* 2005; Wilson, 1999). Fuel consumption is swayed by several explanatory variables such as characteristics and abundance of target species, fleet size, type of gear operated, fishing hour, fleet operating speed and engine power (Cheilari *et al.,* 2013; Parente *et al.,* 2008; Thrane, 2004). The higher fuel consumption reduces the economic return and upsurges the environmental smog. In this relevance, few studies are available round the globe on regional specific fuel use, FUI, CO_2 emissions (Greer *et al.,* 2019; Parker *et al.,* 2018, 2015a; Tyedmers and Parker, 2011). The gear or species-specific FUI is an elite approach, rather than the regional specific FUI (Ziegler *et al.,* 2019). In a multi-species marine fish landing country like India, species specific study is hardly possible; therefore, an attempt has been made to estimate the FUI and CO_2 emission on gear specific basis. To the best of our knowledge, most of the studies have not performed the sensitivity analysis on CO_2 emission from fuel combustion, though it is important (Amala Shajeeva *et al.,* 2017; Parker *et al.,* 2018, 2015a; Vivekanandan *et al.,* 2013; Ziegler *et al.,* 2019). Analyzing the scenario would be an alternative, but it's not possible when the model is coarse (Ziegler *et al.,* 2019). To our best review, literature showed that there are no ground truth studies about the identification of economically and environmentally sustainable gear. Therefore, to find the sustainable elite gear, we have applied the fuzzy VIKOR index method using the economic and financial performance, technical specification of the fleet, operational specification of the fleet and energy efficiency or environmental indicators.

Indian marine capture fisheries

Major share of Indian marine fish capture has been attributed by mechanized fleet (37.3% of the total fleet of 194,490), accounting to 81.3% of the total fish production, 3.49 mmt (CMFRI, 2010). Of the mechanized fleet, half of them are trawlers (35,228), a third of them are gillnetter (20,257) and a meagre of 1.6% are liner (1,158) (CMFRI, 2010). Tamil Nadu state has secured top position in marine fish landing (7.75 lakh tons), accounting for 21.8% of the total landing in 2019. Of which, Ramanathapuram district contributed 27% of the total marine fish landing in Tamil Nadu. The catch was mainly landed by three fishing gears namely trawl net, gillnet and longline (FRAD CMFRI, 2020).

Trawl net is an active gear, conical in shape and varies largely. Typically, the trawl net mouth is square or circular to aid in opening during tow, by the doors that spread the wings of the nets together with the buoyancy of floats attached to the headline and the sinkers/weighted footrope attached to the bottom of the net mouth (Sreekrishna and Shenoy, 2001). A transducer is positioned on the headline to monitor during the tow. The sensor on the trawl supplies data about the potential catch and state of the gear (Stephenson and Smedbol, 2001). The gillnet is made of nylon filament. Gillnet, being a passive gear, catches fish by serving as a screen through which fish larger than mesh size cannot pass but become entangled at their gills and are removed when the net is retrieved (Sreekrishna and Shenoy, 2001; Stephenson and Smedbol, 2001). The headline of the net is attached with floats while the bottom line weighed down with leadline. It is used at desirable depth to catch a diverse range of target species and the size is also highly selectable (He, 2006). The longline is made of nylon monofilament and consists of a mainline where more branch lines are attached. The line is suspended in the water by float lines attached to floats, with or without flagpoles (Sreekrishna and Shenoy, 2001).

Methodology

Study area and data collection

A techno-economic survey was carried out through a structured face to face interview schedule (consulting with experts and review of literature), involving vessel owners and members of the crew. The data collection tool had a two-level structure: the first part focused on the technical and operational specification of the fleets and the latter dealt with financial aspects of the fleet to quantify the economic indicators. The analysis was performed for an ordinary year to evade considering prejudiced data from market or climate contingencies. Seven major fish landing centers; Pazhayar, Poombukar, Tharangampadi, Nagapattinam, Akkarapettai, Arcottudurai and Kodiakarai were chosen from Palk Bay, India (Fig 1) based fish catch landing.. A total of 315 fishers operating mechanized fishing fleets namely trawler, gillnetter and longliner were randomly chosen and interviewed for data collection during February 2014 to November 2014.

Budgetary analysis

The partial budgeting technique was applied to illustrate the structure of key costs and the revenue and profit of the fishing practices. It is specified by the following equation

$$\pi = TR - TC$$

Whereas π is the net profit; TR is the total revenue, and TC is the total cost. Total cost is the sum of total fixed cost (TFC) and total variable cost (TVC). The TFC includes depreciation (D), the opportunity cost of capital investment (OCC), and extraordinary maintenance of the vessel. The depreciation value was assessed, by following straight-line method, based on the anticipated life of the fishing vessel (Y), fishing vessel and engine (α) and the fishing gear and accessories (β). A fixed percentage of the capital cost – vessels and engine (20%) and fishing gear (for trawl and gillnet 33%; long line life has no depreciation due to its limited annual life span) were considered for each fishing vessel.

$$D = \Sigma \frac{(\alpha, \beta)}{Y}$$

The opportunity cost of capital investment was calculated by multiplying the purchasing value of the fishing vessel and engine (α) and the fishing gear and accessories (β) by an interest rate (r) of 18% which was fixed based on the sampled respondents.

$$OCC = \Sigma(\alpha, \beta) * r$$

The TVC includes the cost of diesel (DC), ice (IC), water (WC), food (FC) and labour cost (LC). The labour cost corresponding to the wages of the crew. The diesel cost was arrived after deducting the

Fig. 1. Map showing the study area in Palk Bay, South-east coast of India

subsidized amount of US $ 0.16 L^{-1} from the original diesel rate of US $ 0.85 L^{-1} for each fishing trip (subsidized diesel 15000 L $year^{-1}$). In general, the boat owner retains 60% of the earnings of catch (after covering the operating cost) and pays the remaining 40% for crew members share. The labour cost varied with the locality, on the type of fishery, and even between the periods of the fishing season. Further, if the owner was involved in the fishing activities, he also additionally receives a crew share. Finally, the revenue is generally determined by multiplying the amount of fish harvested by its sales price. Owing to fishers' reluctance to manifest the information on the type of fish, and individual quantity, the revenue was calculated indirectly by multiplying the average economic value of catch proclaimed by the respondent by the number of fishing days per annum.

Financial and economic performance

The cost and revenue obtained from the economic analysis were used to develop key indicators to check the level of profitability and management efficiency of the fishing gear adapted. Six indicators namely, gross profit, net profit, return on fixed tangible asset (RoFTA), efficiency level, operating ratio, and daily running cost have been considered in this study.

Gross profit (GP) refers to the total amount of revenue generated from the sale of fish caught minus the sum of all expenses incurred. The positive value indicates that revenue exceeds the investment made by owners. The net profit (NP) provides a measure of richness and efficiency of the producer in society view, which is equal to the sum of total revenue minus all expenses. The gross profit and net profit are recognized as the equivalent of financial profit and economic profit, respectively.

$$GP = R - \Sigma(DC + IC + WC + FoC + LC)$$

$$NP = R - \Sigma(DC + IC + WC + FoC + LC + FC)$$

The net profit margin is the ratio between the net profit and gross revenue. Profit margin of more than 10% indicates greater economic performance.

$$NPM\ (\%) = \frac{R - \Sigma(DC + IC + WC + FoC + LC + FC)}{TR}$$

RoFTA is considered as a proxy for ROI, and it measures the profit to the capital invested by suggesting how the fishing activity can be profitable with respect to its total assets. The capital investment is estimated by considering the initial value of the fishing vessel, engine and fishing gear.

$$ROI = \frac{NP}{CC}$$

The efficiency level (EL) is calculated as the ratio of net profit to total costs, and it reflects the percentage of income generated as profit after meeting all the expenses.

$$EL = \frac{NP}{TC}$$

The operating ratio (OR) is referred as the ratio between the total variable cost and revenue generated through the sale of fish caught.

$$OR = \frac{TVC}{R} \times 100$$

Daily running cost (DRC) refers to the ratio of the operating cost required to perform fishing activities to the number of fishing days. The running costs (RC) include expenses for fuel, lubricant, bait, ice, meals and ordinary repairs.

$$DRC = \frac{RC}{FD}$$

Technical Efficiency

Technical efficiency is the ratio of output to input, and it shows how a fishing vessel can maximize output with the given set of inputs. It is estimated by the parametric – stochastic production frontier (Aigner *et al.,* 1977) and the non-parametric – data envelopment analysis (DEA) (Charnes *et al.,* 1978) – method, of which DEA is used widely to assess the technical efficiency who could use different units of variables. DEA produce number ranged from 0 to 1 using input and output (Coelli *et al.,* 1998), where the efficiency score 1 implies the high efficiency. The DEA was first developed by (Charnes *et al.,* 1978) under the assumption of constant returns to scale (CRS). Later, (Banker *et al.,* 1984) redeveloped the DEA model considering variable returns to scale (VRS). Essentially, one should select an orientation according to which factors (inputs or outputs) have the most control over. It has been widely in the field of agriculture (Coelli *et al.,* 2002; Yao and Liu, 1998), and fisheries (Amali Infantina and Jayaraman, 2020; Esmaeili, 2006a, 2006b; Jamnia *et al.,* 2015; Maravelias and Tsitsika, 2008). The DEA method has been employed for different boats of Palk Bay to measure their fishing efficiency and capacity by adapting input-oriented VRS DEA model by following Fare et al (1994) and (Coelli *et al.,* 2002, 1998). It is defined as

$$\text{Min}_{\theta,\,\lambda}\ \theta$$

Subject to

$$-y_i + Y\lambda \geq 0,$$

$$\theta x_i^{*} - X\lambda \geq 0,$$

$$N_1\lambda = 1$$

$$\lambda \geq 0$$

where the subscript i represents the i^{th} vessel; θ is the technical efficiency score having a value ranging from 0 to 1; λ is Nx1 vector of constants. The x is input data for N^{th} vessel, and N is the number of vessels. $Y\lambda$ and $X\lambda$ are the efficient estimates on the frontier. It was measured by using the DEAP (version 2.1), which was developed by (Coelli, 1996).

The TE of fishing fleets were measured on the value as well as volume front, and results suggested that catch based was appropriate rather than value (Herrero and Pascoe, 2003).The fishing inputs, which decide the fish catch (kg), were considered as the independent variable (Reid and Squires, 2007; Sesabo and Tol, 2007). Fish catch details are usually recorded in logbooks by the boat owners and the state fisheries department also records the catch details of selected fishing vessels. The catch details were thus collected from both the fishers and the fisheries department. Though the anglers record their catch details, it's only done in a primitive way, viz. mentioning the total catch of the trip and not species-wise. Hence the scope of studying the influence of different species on efficiency was nullified. The technical efficiency of gill netter, trawler, longliner and the motorized vessel was estimated separately with respective input variables. The input variables were measured such as diesel (L), ice bars (individuals), water (L), oil (L), food (USD $), crew wages (USD $), boat OAL (M), gear mesh size (mm), engine power (HP), distance to the fishing ground (NM), age (years), experience (years) and education (years) (Duy *et al.,* 2012; Pascoe and Tingley, 2006; Reid and Squires, 2007; Sesabo and Tol, 2007).

Energy efficiency

Energy intensity shows the energy required to produce per kg of fish and is expressed as the total joules of energy essential to reap one ton of fish or shellfish (Tyedmers, 2004). One litre of fuel is calculated to contain 36.81 mJ. The fuel use intensity is the total litres of fuel combusted directly by the fishing vessels for every tonne of fish landed (Tyedmers, 2004; Ziegler and Hansson, 2003). The CO_2 emission has been estimated by using standard conversion factor i.e. one litre diesel produces 2.675 kg CO_2 (http://www.eia.doe/gov) (Vivekanandan *et al.,* 2013).

Fuzzy multi-criteria decision analysis

The multi-criteria decision analysis (MCA), a part of operational research, is used to analyze the complex dynamic system involving multiple criteria and is considered as an appropriate method for assessing the sustainable fishery system (Ashtiani and Abdollahi Azgomi, 2016; Mendoza and Prabhu, 2003). MCA can deal with technical specification, operational details of the fleet and cost and profit structure. It is conveniently structured to enable collaborative planning and decision making. It is simple, intuitive and transparent while it has solid technical and theoretical support to the procedure (Jeya Girubha and Vinodh, 2012; Vinodh *et al.,* 2013).

The fuzzy VIKOR method, relies on aggregative function (Opricovic, 2011) and was developed to solve the problems in an environment where the criteria and weights are fuzzy sets. It is a mathematical combination that allows to simultaneously aggregate conflicting indicators and/ or with different measurement units of one or more dimensions (Romeo and Marcianò, 2019). And it also introduces the ranking index, relies on the measure of closeness to the perfect solution and employs linear normalization method to eliminate the unit of criterion function and selection from a set of an alternative in the presence of conflicting criteria (Opricovic and Tzeng, 2004). Over the last few decades, many studies have applied MCA, however very few have dealt with economic performance including the quantitative and qualitative data. Indeed, economic performance measures must be holistic in including a wide range of values comprising socio-demographic aspects, technical specification of the fleets and gears, operational aspects of the fleets and gears and the economic key indicators.

Fuzzy VIKOR model

The fuzzy VIKOR method is suitable for solving and selecting the best alternative under a fuzzy environment which relies on the fuzzy linguistic and VIKOR MCDM technique. The step-by-step procedure of the proposed fuzzy VIKOR method is as follows

$$D = \begin{array}{c|cccc|l} & C_1 & C_2 & & C_m & \\ A1 & X_{11} & X_{12} & \dots & X_{1m} & \\ A2 & X_{21} & X_{22} & \dots & X_{2m} & \\ . & . & . & \dots & . & j=1,2\dots n:\ I=1,2\dots,m \\ . & . & . & \dots & . & \\ . & . & . & \dots & . & \\ A_n & X_{n1} & X_{n2} & \dots & X_{nm} & \end{array}$$

Where X_{ij} is the rate of alternative A_1 (A_j= A_1, A_2...A_n) examined with respect to (C_i= C_1, C_2, ...C_m), (X_{ij}= l_{ij}, m_{ij}, u_{ij}) is linguistic variable denoted by triangular fuzzy number m_{ij}, u_{ij} mean the lower and upper bound of triangular fuzzy number X_{ij}, m_{ij} is the model value for X_{ij}

Step 2: Using the method of average to aggregate the different opinion of fishery economists, the fuzzy importance weight w_i of the criteria c_1 is represented as follows

$$\widetilde{w}_i = \frac{1}{k}\left[\widetilde{w}_i^1 \oplus \widetilde{w}_i^2 \oplus \dots \oplus \widetilde{w}_i^k\right]$$

Where w_k^i is the fuzzy importance weight criteria c_i measured by k^{th} evaluator and $w_k^i = l_k^i, m_k^i, u_k^i$

Step 3: Determination of fuzzy best value (FBV) f_j^* and fuzzy worst value (FWV) f_j^0 using the following equation

$$f_i^* = {}^{MAX}_{j} X_{ij}, f_i^0 = {}^{MIN}_{j} X_{ij}, fori \in B$$

$$f_i^* = {}^{MIN}_{j} X_{ij}, f_i^0 = MAX\, X_{ij}, fori \in C$$

Where B is associated with benefit criteria and C is related to cost criteria

Step 4: The fuzzy difference d_{ij} between X_{ij} and the fuzzy best value f_j^* and the worst value f_j^0 are obtained by following equations respectively,

$$d_{ij} = \frac{(f_i^* - X_{ij})}{(u_i^* - l_i^0)} fori \in B$$

$$d_{ij} = \frac{(X_{ij} - f_i^*)}{(u_i^0 - l_i^*)} fori \in C$$

Where B is a set of benefit criteria and C is related to cost criteria.

Step 5: Computation of the values of S_i, R_i, and Q_i

This is to measure the separation of alternative A_j from the fuzzy best value f_j^* as well as to measure the separation of R_j of alternative A_j from the fuzzy worst value f_i^0. It calculated by using the following formula, respectively.

$$\tilde{S}_j = \sum_{i=1}^{n} (\tilde{w}_j \oplus \tilde{d}_{ij})$$

$$\tilde{R}_j = {}^{MAX}_{j} (\tilde{w}_j \oplus \tilde{d}_{ij})$$

Where $S_j = (S_j^l, S_j^m, S_j^u)$ is a fuzzy weighted sum referring to the separation measure of A_j from the fuzzy best value; similarly, $R_j = (R_j^l, R_j^m, R_j^u)$ is a fuzzy operator MAX denoting the separation of A_j from fuzzy worst value, w_i is the importance weight of criterion C_i.

Step 6: Computation of the value of Q_i

The value $Q_i = l_j, m_j, u_j$ can be calculated as

$$\tilde{Q}_j = \frac{v\,(\tilde{S}_j - \tilde{S}^*)}{(S^{0u} - S^{*l})} \oplus (1 - v)\, \frac{(\tilde{R}_j - \tilde{R}^*)}{(R^{0u} - R^{*l})}$$

Where $S^* = MIN_j S_j, S^{0u} MAX_j S_j^u, R^* = MIN_j R_j, R^{0u} MAX_j R_j^u$ and $v\ (v = n + {}^{1}/_{2n})$ is taken as a weight for the strategy of the majority of the criteria, whereas the 1-v is the weight of the individual regret. The best of S and R denoted by $S^* and\ R^*$ respectively.

Step 7: Defuzzify values of $S_i, R_i\ and\ Q_i$

De–fuzzification is a mathematical procedure to change the fuzzy value into crisp values

De fuzzification is a mathematical tool that changed the fuzzy value to crisp value. It was calculated by following Best Non-fuzzy Performance (BNP), which is a center of area approach that for a triangular fuzzy number $A = a_1, a_2, a_3$

$$A = \frac{a_1 + a_2 + a_3}{3}$$

Results and discussion

The economic and energy (fuel) performance conferred here are crucial to accomplish the sustainable motive of marine fisheries. These performances of fishing fleets increase the economic efficiency and reduce the greenhouse gas emission, especially CO_2, by resourceful management and optimization of fuel used, to make the fisheries more sustainable and environmentally friendly.

Technical and operational details of the fleet

The gear-wise technical specification of the three mechanized fishing fleets, namely; trawler, gillnetter and longliner has been shown in Table 1. The gillnetter has lesser fleet length (9-12 m) compared to trawler (11.0 – 19.2 m) and longliner (18.0 – 19.1 m) and the trawler has the highest engine power ranging between 90 and 270 hp. The longliner and trawler have better craft breadth, fuel and fish hold capacity than gillnetter (Table 1).

The technical characteristics are not directly proportionate to the operational characteristics of the fishing fleet which is detailed in Table 2. The fleet's operational distance to the fishing ground from the shore ranged between 30 and 80 Nm, the distance being directly proportional to the crew strength, number of days per fishing trip and number of hauls per fishing trip. The longliner had lesser number of annual fishing trips followed by trawler and gillnetter (Table 2).

Budgetary analysis

The average capital cost for the three mechanized fishing fleet has been given in Table 3. The capital cost also varied remarkably amidst the fleets; with the gillnetter showing the lowest average total capital invest (an approximately USD $ 62339) in contrast to trawler whose initial investment approximately amounted to USD $ 105161 ($F=27.16$, $P<0.001$). The trawler had the highest capital cost due to the maximum overall length of the fleet with higher engine power (Table 1). The gillnetter had the lowest engine cost followed by trawler and longliner ($F=13.14$, $P<0.001$), but no significant difference was found amidst the longliner and trawler. The operational and fixed cost varied widely among the three fleet segments and it has been specified in Table 3. The operating costs and direct cost are related to the type

Table 1. Technical specifications of the mechanized fleets

Items	Trawler	Gill netter	Longliner
Fleet overall length (m)	11.0 – 19.2	9 – 12	18.0 – 19.1
Fleet breadth (m)	2.5 – 5.1	2.5 – 4.0	4.5 – 5.1
Fish holding capacity in the fleet (t)	1.0 – 15.0	1.0 – 4.0	8.0 – 15.0
Fuel holding capacity of fleet (L)	100 – 4000	100 - 1000	1000 – 2000
Water holding capacity of fleet (L)	100 – 2000	100 - 500	1000 – 2000
Engine power (hp)	90 – 270	90 – 120	120 – 160
Gear mesh size (mm)	22 – 150	20 - 50	--

Table 2. Summary of fishing operations in mechanized fishing fleets

Items	Trawler	Gillnetter	Long liner
Distance to the fishing ground (Nm)	70	30	80
Crew size (numbers)	7	4	10
Number of days per fishing trip (days)	4	1	15
Number of hauls per fishing trip (numbers)	15	4	50
Number of fishing trips in a month (numbers)	5	20	2
Annual fishing days (days)	208	210	315
Annual fishing trips (numbers)	52	210	21

of gear used. The longliner had the highest operating cost in strong contrast to the gillnetters. A significant difference in operating cost has been observed between the fleets (F value=167.06; P<0.001) and Turkey pairwise comparison showed that the longliner had a significantly higher amount of operating cost compared to trawlers and gillnetters.

Fig 2 illustrates the fleet-wise comparative significance of operating cost of the fishing trips. Invariably, fuel was found to occupy the major cost in all the fishing fleets, accounting for 61.74%, 40.25% and 44.32% of the total operating cost for the trawler, gillnetter and longliner respectively, excluding diesel subsidies. There was a significant difference noticed between the fishing fleet (F=92.14, P<0.001). The second largest operating cost include labour cost with the trawler, gillnetter and longliner accounting for 29.59%, 38.01% and 47.37% respectively of the total operating cost and there were significant (F= 269.65, P<0.001) differences too. The inter-fleet comparison of annual costs has been depicted in Figure 3. Relatively higher operational and fixed cost has been recorded by longliner, along with highest profitability.

These mechanized fishing fleets generally operate under positive economic return, despite the open-access fisheries regime. This is indirectly influenced by the technical and operational attributes of the fleet primarily, length of the feet, engine power, fuel and fishing ground distance from the port. The magnitude of economic benefit largely varies between fisheries, countries and distance from port (Sala *et al.,* 2018).. Collectively, trawlers witnessed the highest economic return of US$ 40452 year^{-1} fishing at a distance of 70 Nm from the port whereas the longliners generated US$ 39738 year^{-1}. The magnitude of economic return was about 50% lesser in gillnetter, accounting to US$ 20,000 year^{-1}, possibly due to shorter fishing ground distance (an average of 30 Nm) from the port. The technical specifications and operational characteristics like; size of the fleet and engine capacity, fuel and fish-holding capacity of the fleet plays a crucial role to facilitate greater economic return.

Financial and economic performance

The trawler showed an estimated average profit of US$ 40452 year^{-1} followed by US$ 39738 year^{-1} for longliner and US$ 19645 year^{-1} for gillnetter (F= 39.66, P<0.001). The profit margin, ROI, economic efficiency and operating ratio have been portrayed in Fig 4. On

Table 3. Annual **e**nterprise budget for different fishing fleets in Palk Bay, India (1 US $ = ₹ 62)

Sl. No	Items	Trawler	Gill netter	Long liner
A	**CAPITAL INVESTMENT**			
	a. Craft and Engine	95242	56371	102581
	b. Gear and Accessories	9919	5968	815
	TOTAL CAPITAL INVESTMENT	105161	62339	103395
B	**FIXED COST**			
	a. Depreciation			
	(i) Craft & Engine (20%)	19048	11838	20516
	(ii) Gear (33% for trawl and gillnet)	3273	2068	0*
	b. Interest on Investment (18%)	18929	11782	18611
	c. Repair & maintenance	6332	16258	7655
	TOTAL FIXED COST	47583	41946	46782
C	**OPERATING COST**			
	a. Fuel	70678	21572	34108
	b. Ice	5120	1018	2869
	c. Water	1258	4200	479
	d. Oil	608	1143	226
	e. Food	2600	3952	2371
	f. Crew wages	32710	18065	33871
	Total operating cost, excluding subsidies	112974	49950	73924
	Value of subsided diesel realized	2419	2419	2419
	TOTAL OPERATING COST, INCLUDING SUBSIDES	110555	47530	71505
D	**TOTAL COSTS (B+C)**	158138	89476	118287
E	**GROSS REVENUE**	198590	109121	158025
F	**NET OPERATING INCOME**	88035	61591	86520
G	**NET PROFIT**	40452	19645	39738
H	**PROFIT MARGIN (%)**	20.37	18.00	25.15

**long line life has no depreciation cost due to the limited annual life span of the gear)*

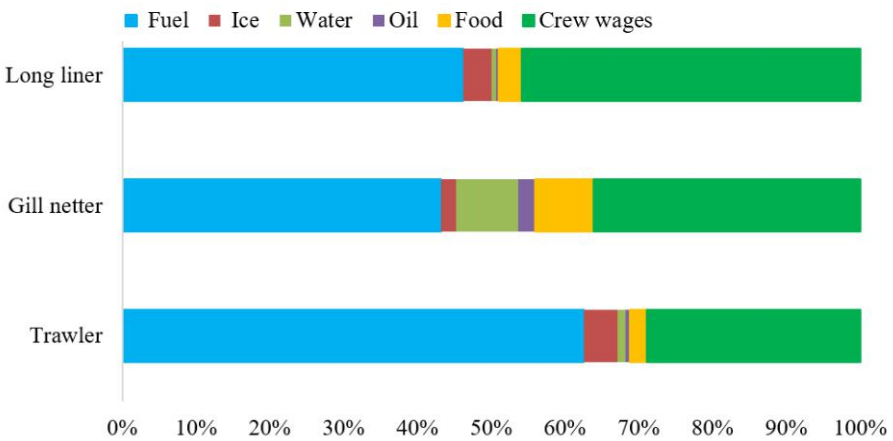

Fig. 2. Relative importance of the operating cost within each fishing fleet as calculated per trip, excluding diesel subsidies

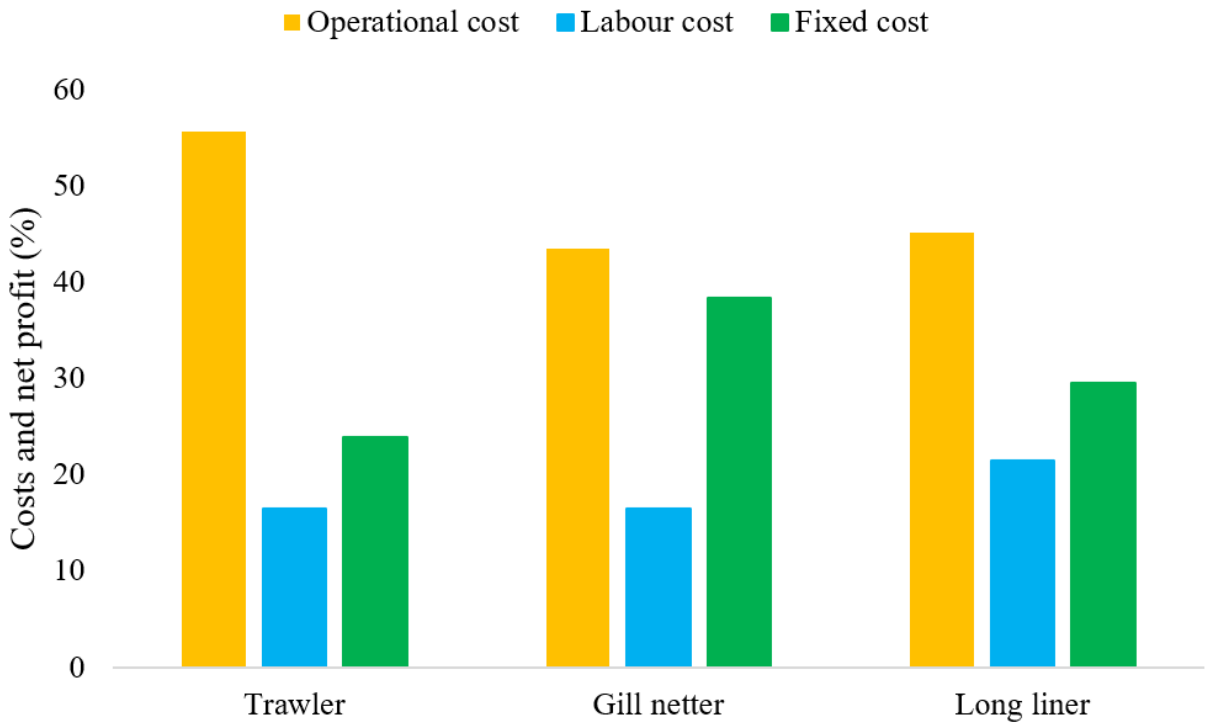

Fig. 3. Percent of cost and net profit for twaller, gillnetter and longliner

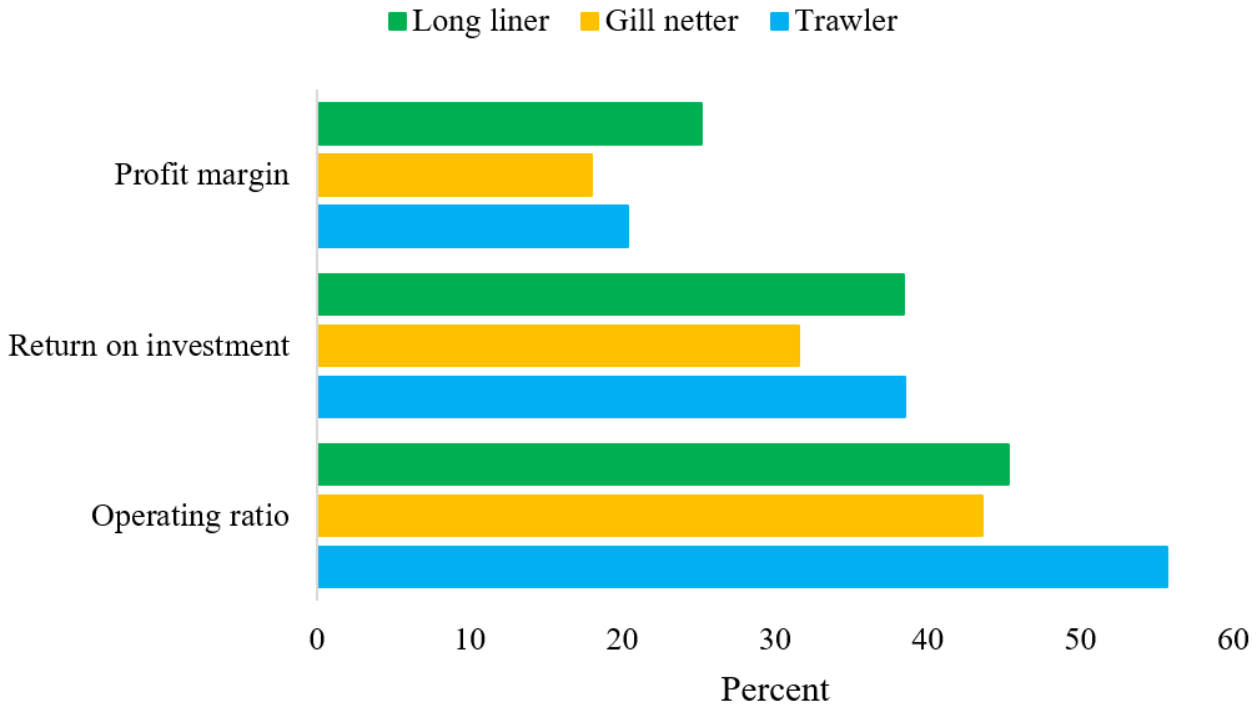

Fig. 4. Economic, financial and operational performance of the fishing fleets of the Palk Bay, India

average, longliner had significantly higher gross profit margin, including subsidies (25.15%) followed by trawler (20.37%) and gillnetter (18%). The economic efficiency was found to be lesser for gillnetter (1.22) compared to trawler (1.26) and longliner (1.34). ROI was found to be higher for longliner (38%) and trawler (38%) and lower for gillnetter (32%).

The gross profit margin reflects the percent of proceeds that a sector retains as profit (Rodrigues et al 2018). The annual profit margin substantially differed from as high as 25.15% in longliner to 20.37% in trawler and 18% in gillnetter. The industrial fishing fleet in France and Spain had reported a profit margin percent of 14.1 and 9.5 respectively (STEFC, 2015). The longliners were found to operate with the highest profit margin of 29.5% in Brazil than those that of pair bottom trawler (17.1%) and bottom gillnetter (13.6%) (Rodrigues *et al.*, 2018). In Vietnam, longliners operated at a profit margin of 12.1% (Long *et al.*, 2008) and gillnetters at 3.8% (Duy *et al.*, 2012).

The financial performance and efficiency level of the fleets were found analogous to profit margin. The tuna long liner had a higher rate of return from investment (27%) rather than stern trawler (17%) in India (Tietze *et al.,* 2005). The estimated profit margin and return on investment were more than 10% indicating better economic performance (Radhakrishnan *et al.,* 2018; Tietze *et al.,* 2005).

The study advocates longliner to be more economically profitable with lower percent of operating cost from gross revenue and higher catch of high value fish (seer fish = US $ 6.45 kg^{-1}, perches = US $ 2.90 kg^{-1}) compared to trawler and gillnetter. This is because, fast swimming fish, with a high market price, are usually targeted in line fishing in different parts of the world, including India (Radhakrishnan *et al.,* 2016), Brazil (Rodrigues *et al.,* 2018). Though, the trawlers also earned greater gross revenue, its major share (around 62%) was spent on operating cost of fuel. Although the quantum of fish caught in gillnetter was higher, the gross profit margin was smaller due to low-value realization per kg of fish. In addition, it is apparent that the fuel subsidy program has been more beneficial to the fleet owners than crew members, as crew rents are generally based on gross revenue minus operating cost, the subsidy cash not being shared with crew members (Rodrigues *et al.,* 2018).

Technical efficiency

The mechanized fleets were measured for their technical efficiency under variable returns to scale and have been depicted in Fig 5. The lowest mean technical efficiency was observed for trawler (81%) and highest for longliner (99.6%). While most of the trawlers (68%) were found to operate at a technical efficiency range of 0.5 to 0.9, both gillnetters (77%) and longliners (100%) operated at >0.9 technical efficiency range. The mean technical efficiency of trawlers at Palk Bay were found to be 78% indicating that the output could be elevated by 22% through efficient harvest practices, without raising the level of input use (Sathyapalan *et al.,* 2008). Only 10% of the MD trawling in Visakhapatnam had TE greater than 0.50, which is lesser than this study finding. The mean technical efficiency score of a single and multi-day trawler arrived at 78.2 and 94.5% respectively, with no vessels being technically inefficient (Narayanakumar and Sathiadhas, 2005). Higher technical efficiency score of 99.6% signified the optimal efficiency levels of long liners. The results of Swedish fishing vessel efficiency were consistent with the present findings in inferring that longer fleet had greater technical efficiency than smaller ones (Walden and Tomberlin, 2010).

Fuel use intensity and CO_2 emission

Fuel consumption significantly varies between the fishing fleets in terms of absolute fuel consumption, operating cost, fuel cost per kg of fish and relative carbon footprint (Parker *et al.,* 2015b). Fuel is the principal cost component of all the three-fishing fleet (Cambiè *et al.,* 2012; Radhakrishnan *et al.,* 2018; Sumaila *et al.,* 2008). Fuel usage within the mechanized fishing sector differs considerably due to various factors including the type of gear. Passive fishing gears invariably consumed lower quantity of fuel rather than active fishing gears due to less fishing distance to the port (Davie *et al.,* 2015; Thrane, 2004). The same was observed in this study, with trawler, being an active gear, incurring high fuel consumption cost compared (81149 L $year^{-1}$) to the passive gears; longliner (39161 L $year^{-1}$) and gillnetter (24768 L

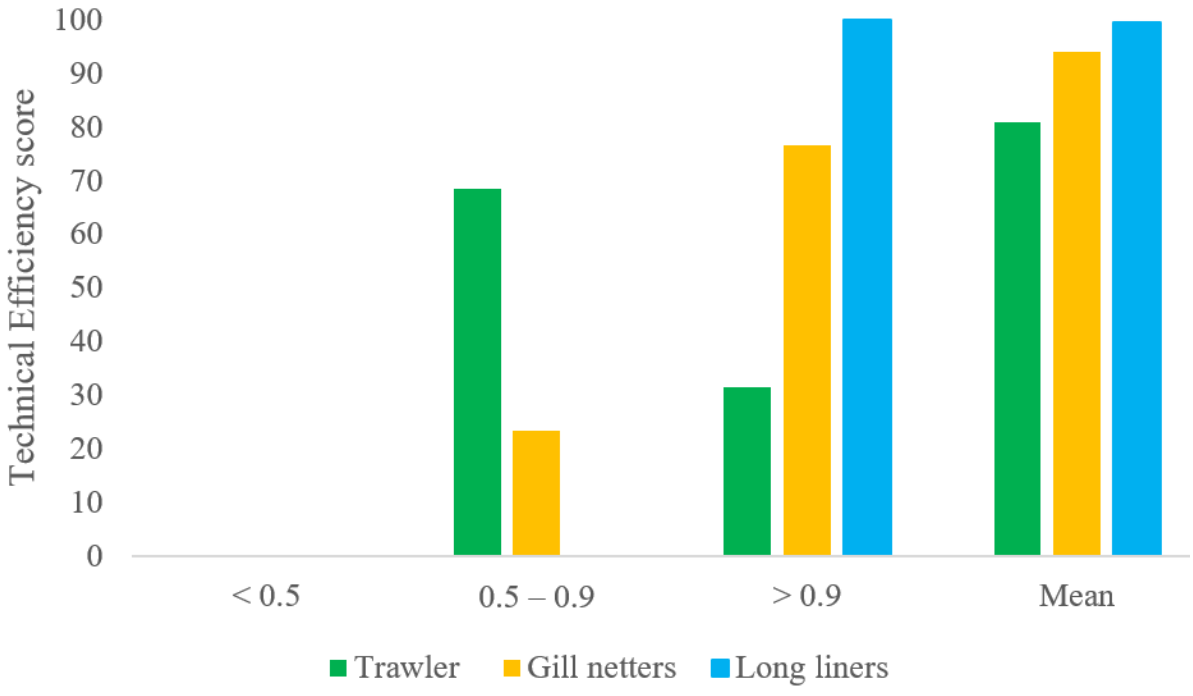

Fig. 5. Technical efficiency of sampled fishing fleets of the Palk Bay, India

year^{-1}.

Similarly, the amount of fuel used to produce one kg of fish (fuel use intensity) was also higher for active fishing gear than passive fishing gear. The current study has calculated FUI of 681 L t^{-1} in trawler followed by 256 L t^{-1} and 194 L t^{-1} in gillnetter and longliner respectively. The FUI was found to be 3.5-fold and 2.7-fold greater in trawler compared to longliner and gillnetter respectively, accounting for about 194 and 256 tons year^{-1}, respectively for one ton of fish production. The FUI generally varies with the fishing fleet and area; the tuna fishing with a purse seiner resulted in an average of 368 L t^{-1}, weighted by landing (Parker *et al.,* 2015b). Selected targeting of high market value fish such as tuna in longline fishing, consumed fuel of 1069 L t^{-1} of fish (Tyedmers and Parker, 2011). Further, optimizing the trawl design, running speed and reducing free-running duration could cut the fuel consumption by about 40% which further curbs the CO_2 emission (Amala Shajeeva *et al.,* 2017).

Contribution to the total fishing emission differs remarkably between fleets when they are disaggregated by species (Parker *et al.,* 2018). Whereas the FUI or litre of fuel consumed to land one ton of fish, is a relative and pertinent indicator of carbon footprint landed (Parker *et al.,* 2015b; Tyedmers and Parker, 2011). Trawlers were found to emanate the highest level of CO_2 (1823 tons year^{-1}) for every ton of fish produced and longliners, the lowest (520-ton year^{-1}). The relative fuel efficiency was significantly higher for longliner (0.520 t of CO_2 t fish production^{-1}) compared to gillnetter (0.684 t of CO_2 t fish production^{-1}) and trawler (1.823 t of CO_2 t fish production^{-1}). The better fuel efficiency resulted in lower amount of carbon emission in longliner compared to the other fleets studied which could have been attributed by longer fishing days and target fishing of sizeable fish. Generally, the trawls emit about 50% more of CO_2 rather the gillnet and longline (Vivekanandan *et al.,* 2013). The trawlers had the highest CO_2 emission of 1.823 t of CO_2 t fish production^{-1} in the study. In India, an average CO_2 emission of 1.43 t of CO_2 t fish production^{-1} has been reported for trawler rather than gillnetter (0.90 t of CO_2 t fish production^{-1}) and longliner (0.70 t of CO_2 t fish production^{-1}), possibly due to increased scouting time (Vivekanandan *et al.,* 2013) at farther distance of fishing from the port (an average of 70 Nm) and capturing of demersal and crustaceans. Globally, the crustacean fisheries have emitted highest (22%) CO_2 rather than pelagic fisheries (Parker *et al.,* 2018). The shrimp and crab harvest relatively occupy lower quantity for each trip of a trawler but consumed a considerable quantity of fuel in the process. The behavioral, technological, and managerial strategies improve the performance of the fishing industry. The relative effect of these varies among the fishing fleet where fuel significantly influences with no much impact on production. The degree of fuel use often differed with fleet size and engine power (Guillen *et al.,*

Table 4: Fuzzy weights

Items	fuzzy weights			weights	normalized weight
	l	M	r		
Net profit	0.096	0.156	0.253	0.168	0.154
Return on investment	0.100	0.160	0.253	0.171	0.156
Efficiency level	0.062	0.101	0.161	0.108	0.099
Operating ratio	0.061	0.106	0.176	0.114	0.105
Gross revenue	0.055	0.096	0.158	0.103	0.094
Fleet length	0.018	0.029	0.048	0.031	0.029
Engine power	0.024	0.042	0.071	0.046	0.042
Fuel holding capacity	0.011	0.017	0.028	0.019	0.017
Fishing distance from port	0.026	0.046	0.084	0.052	0.048
Crew number	0.009	0.014	0.024	0.015	0.014
Annual fishing days	0.019	0.032	0.055	0.036	0.033
Number of days per trip	0.023	0.041	0.078	0.047	0.043
Fuel used	0.016	0.027	0.054	0.032	0.029
Fuel use intensity	0.027	0.050	0.101	0.059	0.054
CO_2 emission / ton of fish	0.046	0.083	0.145	0.091	0.084

2016; Ziegler *et al.,* 2019; Ziegler and Hornborg, 2014). The behavioral characteristics namely; plummeting of fleet speed whilst steaming, proper planning of fishing location could considerably reduce the fuel consumption and can be easily applied by fishers (Abernethy *et al.,* 2010). Further, the provision of solar energy in the fleet can be utilized as an auxiliary power for lighting, net handling, etc. (Newspaper article). The fishery managerial effect assists to curtail fishing capacity and rebuild stock having a significant benefit. For instance, the vessel buy-backs system has been implemented for Australia's northern prawn fishery (Parker *et al.,* 2015a; Pascoe *et al.,* 2012) to remove the vessels which consumed greater fuel and emitted more CO_2.

VIKOR index

A total of 15 variables were used under four categories, namely; economic performance, technical specification, operational characteristics and sustainable key characters for the catch to glean the fuzzy weight and has been presented in Table 4. The attributes of the fishing fleets have been given in Table 5 with the best and worst value of each attribute.

The results of the VIKOR index suggested that utility measure was higher in case of gillnetter (0.684) and lower for longliner (0.132) (Table 6). And similar results were perceived for regret measure ranging from 0.048 to 0.156. The compromise solution, closest to the ideal was accomplished by longliner being the best performance fleet, satisfying the conditions, C1 and C2, with least VIKOR index value, ν = 0.5. This result was further validated with the lowest and highest index value of 0.2 and 0.8, resulting in a similar set of ranking, as presented in Table 6.

Table 5. Alternatives and attributes for fishing fleet, and their calculated best and worst value

	Particulars	A1	A2	A3	Best	Worst
		Trawler	Gill netter	Long liner		
Economic variables	Net profit	40452	19645	39738	40452	19645
	Return on investment	0.38	0.32	0.38	0.38	0.32
	Efficiency level	0.26	0.22	0.34	0.34	0.22
	Operating ratio	55.67	43.56	45.25	44	56
	Gross revenue	198590	109121	158025	198590	109121
Technical characteristics	Fleet length	17.1	10.4	18.7	18.72	10.36
	Engine capacity	129	105	136	136	105
	Fuel holding capacity	1293	708	1900	1900	708
Operational characteristics	Fishing distance from port	70	30	80	30	80
	Crew number	7	4	10	4	10
	Annual fishing days	208	210	315	315	208
	Number of days per trip	4	1	15	15	1
Energy efficiency	Fuel used	81149	24768	39161	24768	81149
	Fuel use intensity	681	256	194	194	681
	CO_2 emission / ton of fish	1823	684	520	520	1823

Table 6. Calculation of utility, regret measure and VIKOR index

	Si	Ri	Qi		
			0.2	0.5	0.8
Trawler	0.475	0.105	0.229	0.573	0.917
Gill netter	0.684	0.156	0.400	1.000	1.600
Long liner	0.132	0.048	0.000	0.000	0.000

Fig. 6. Fuel use intensity at different scenario of trawler replacement

The longliner exhibited the best performance; as highlighted in the findings, in terms of economic performance, technical efficiency and operational efficiency; apart from better economic returns and profit margin. ROI represents the profitability of capital invested and it proves the best value of fishing system. The higher economic performance of the longline fishery has been related to longer fishing days per trip at sea, significantly reducing the fuel consumption rate per trip. On another side, capturing of sizeable and high market value fish has significantly enhanced the gross revenue and net revenue of the longliner. The system with lowest performance level was gillnetter and it represents a robust artisanal character such as lesser labour (4 numbers) and lesser fishing distance from the port (30 Nm) and similar results have been reported in the fishing fleet of Italy (Romeo and Marcianò, 2019). Despite, lesser technical specifications and operational characteristics, economic performance is meagre with moderate sustainable indicator characters. The energy efficiency indicators namely; fuel, fuel use intensity and CO_2 (Parker *et al.,* 2015b) were higher leading to moderate overall performance. Though, trawl earned higher economic returns, exorbitant capital investment cost is inevitable, so the estimated profit margin is lesser than longline, and not remarkably higher than gillnet. Needless to mention, it consumes 2-fold higher amount of diesel and emits massive amount of CO_2 by engine combustion of fuel. Unlike gillnet and longline, it requires huge amount of diesel to operate the gear (for shooting, hauling and harvest) apart from propulsion. Further, bottom trawling also has a serious toll on the ecosystems, including coral reefs, due to its devastating damage on the seabed. Similar results were noticed in the marine fisheries of south Italy (Romeo and Marcianò, 2019). On the flip side, rising fuel price and higher fuel consumption has raised the total operating cost, as a consequence, the average fish price increase, but not in same proportion as the increasing fuel price (Cheilari *et al.,* 2013). Even some of the fishing fleet operate at less than its operating cost (Abernethy *et al.,* 2010).

Fig. 7. CO_2 emission per tons of fish at scenario of trawler replacement

The longline not only ensures fuel efficiency but also significantly contribute to cut down CO_2 emission. The quality of fish is ascertained in longline fishing compared to trawling and it generally focuses on sizeable and high market price fish apart from being environment friendly. Similarly, gillnet is also a selective fishing gear which does not damage the ecosystem, consumes less fuel and emits less Co_2.

The government of India and State Fisheries Department has joined hands to promote longline fishing by providing subsidies of about US$ 90323 (easing bank loan of US$ 25806 and US$ 14516 from fishers' side) for the conversion of existing trawlers. It was sanctioned for a total of 49 fleets, of which 28% of the fleet is being operated in Ramanathapuram district of India (the present study area). The average catch amounted to 10 to 12 tons per trip (15 days per trip), generating a net profit of US$ 8065 to 11290 for the same (Personal communication Sub–inspector of Fisheries, Ramanathapuram region). Therefore, we developed a scenario (5% interval) to understand the possibility of sustainable harvest by assuming conversion of trawler into longliner and gillnetter (20% for each). The projected FUI scenario proved to proportionality decrease the fuel usage per ton of fish harvested in trawl net (Fig 6). Similar result was also noticed in case of CO_2 emission (Fig 7) by replacing 40% trawler, reducing an amount of 9501515 CO_2 $year^{-1}$ and avoiding fuel combustion of 121.33 million litre of fuel $year^{-1}$.

Conclusion

This study provides adequate insight into increasing importance of the energy consumption and understanding of the environmental and economic sustainability of valuable fisheries. We had quantified the performance of the fishing fleets to identify the efficient fleet which operates under better economic returns, lesser environmental impact and low emission of CO_2. We have also attempted to simulate a scenario wherein the inefficient fleet (trawler) could be possibly swapped with the efficient (longliner/gillnetter) one, as a little step towards comprehending MSC (Marine Stewardship Council) standards of ensuring sustainability, curtailing environmental impacts and effective fisheries management. Needless to mention, this study is also a pre-emptive move obliging UN's #Envision2030 - Sustainable Development Goals (Goal 12: To ensure sustainable consumption and production patterns), towards which the entire world is marching ahead. The concerned authority for proper implementation, regulation and monitoring lies under the purview of the concerned State Fisheries Departments.

Evaluating the overall performance using the fuzzy VIKOR index has revealed that the longliner has higher return and efficient fuel utilization followed by gillnetter and trawler. The longliner fleet seem to operate under higher profit margin (25.15%) by capturing high market value fish (like seer fish,) rather than the trawler and gillnetter. Of the inputs, the fuel

consumption plays a crucial role which not only affects the income of the fishers, but also pollutes the environment by release of CO_2. For one ton of fish production, an average of 1.8 t of CO_2 is emitted by burning 680 L of diesel which is relatively larger compared to longliner that emanates 0.52 t of CO_2, burning 194 L of fuel. It is estimated that by replacing 40% of trawlers with gillnetter and longliner, we can save about 121.33 million litres of fuel $year^{-1}$ which significantly reduces the amount of CO_2 emitted (9501515) during harvest of fish per annum. These data suggest that the conversion of trawler to gillnetter/longliner would be economically viable and also diminish the CO_2 emission thus implying to curtail the climate change effects. In future, species–specific fuel use intensity and CO_2 emission assessment for different lengths of fleet are essential for gillnetter and longliner, to sustainably harvest fishery resources.

References

Abernethy, K.E., Trebilcock, P., Kebede, B., Allison, E.H., and Dulvy, N.K., 2010. Fuelling the decline in UK fishing communities? ICES Journal of Marine Science 67, 1076–1085. https://doi.org/10.1093/icesjms/fsp289

Aigner, D.J., Lovell, C.A.K., and Schmidt, P., 1977. Formulation and estimation of stochastic frontier. Journal of Econometrics.

Allsopp, M., Pambuccian, S.E., Johnston, P., and Santillo, D., 2009. State of the world's oceans, Springer Netherlands.

Amala Shajeeva, J., Neethiselvan, N., Sundaramoorthy, B., Masilan, K., Arunjenish, D., Rajakumar, M., Ravikumar, T., and Baiju, V., 2017. Carbon emission due to excess fuel consumption by the trawlers of Thoothukudi, Southeast Coast of India. Carbon Management 8, 393–398. https://doi.org/10.1080/17583004.2017.1386534

Amali Infantina, J., and Jayaraman, R., 2020. Is the operational dynamics of artisanal fishing fleet dawdling? A comprehensive study of palk bay, India. Indian Journal of Geo-Marine Sciences 49, 311–317.

Ashtiani, M., and Abdollahi Azgomi, M., 2016. Trust modeling based on a combination of fuzzy analytic hierarchy process and fuzzy VIKOR. Soft Computing 20, 399–421. https://doi.org/10.1007/s00500-014-1516-1

Banker, R.D., Charnes, A., and Cooper, W.W., 1984. Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. Management Science. https://doi.org/10.1287/mnsc.30.9.1078

Cambiè, G., Ouréns, R., Vidal, D.F., Carabel, S., and Freire, J., 2012. Economic performance of coastal fisheries in Galicia (NW Spain): Case study of the Cíes Islands. Aquatic Living Resources 25, 195–204. https://doi.org/10.1051/alr/2012010

Charnes, A., Cooper, W.W., and Rhodes, E., 1978. Measuring the efficiency of decision making units. European Journal of Operational Research 2, 429–444. https://doi.org/10.1016/0377-2217(78)90138-8

Cheilari, A., Guillen, J., Damalas, D., and Barbas, T., 2013. Effects of the fuel price crisis on the energy efficiency and the economic performance of the European Union fishing fleets. Marine Policy 40, 18–24. https://doi.org/10.1016/j.marpol.2012.12.006

Clark, M.R., Althaus, F., Schlacher, T.A., Williams, A., Bowden, D.A., and Rowden, A.A., 2016. The impacts of deep-sea fisheries on benthic communities: A review. ICES Journal of Marine Science 73, i51–i69. https://doi.org/10.1093/icesjms/fsv123

CMFRI, 2010. Marine Fisheries Census 2010.

Coelli, T., 1996. A Guide to DEAP Version 2.1: A Data Envelopment Analysis (Computer) Program. CEPA Working Paper 96/08 1–49.

Coelli, T., Rahman, S., and Thirtle, C., 2002. Technical , Allocative , Cost and Scale Efficiencies in Bangladesh Rice Cultivation : A Non-parametric Approach 53, 607–626.

Coelli, T.J., Prasada Rao, D.S., O'Donnell, C.J., and Battese, G.E., 1998. An introduction to efficiency and productivity analysis, Kluwer Academic Publishers. Boston. https://doi.org/10.1007/b136381

Davie, S., Minto, C., Officer, R., Lordan, C., and Jackson, E., 2015. Modelling fuel consumption of fishing vessels for predictive use. ICES Journal of Marine Science 72, 708–719. https://doi.org/10.4135/9781412953924.n678

Duy, N.N., Flaaten, O., Anh, N.T.K., and Ngoc, Q.T.K., 2012. Open-access fishing rent and efficiency-The case of gillnet vessels in Nha Trang, Vietnam. Fisheries Research 127–128, 98–108. https://doi.org/10.1016/j.fishres.2012.04.008

Esmaeili, A., 2006a. Technical efficiency analysis for the Iranian fishery in the Persian Gulf. ICES Journal of Marine Science 63, 1759–1764. https://doi.org/10.1016/j.icesjms.2006.06.012

Esmaeili, A., 2006b. Technical efficiency analysis for the Iranian fishery in the Persian Gulf. ICES Journal of Marine Science 63, 1759–1764. https://doi.org/10.1016/j.icesjms.2006.06.012

FAO, 2018. Summary of the FAO Fisheries and Aquaculture Technical Synthesis of current knowledge, adaptation and mitigation options.

FAO, 2005. Review of the state of world marine fishery resources, FAO Fisheries and Aquaculture Technical Paper 457.

FRAD CMFRI, 2020. Marine Fish Landings in India 2019.

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M.L.D., and Pauly, D., 2019. Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950 to 2016. Marine Policy 107, 103382. https://doi.org/10.1016/j.marpol.2018.12.001

Guillen, J., Cheilari, A., Damalas, D., and Barbas, T., 2016. Oil for Fish: An Energy Return on Investment Analysis of Selected European Union Fishing Fleets. Journal of Industrial Ecology 20, 145–153. https://doi.org/10.1111/jiec.12272

He, P., 2006. Gillnets: Gear design, fishing performance and conservation challenges. Marine Technology Society Journal 40, 12–19. https://doi.org/10.4031/ 00253320 6787353187

Herrero, I., and Pascoe, S., 2003. Value versus Volume in the catch of the Spanish South-Atlantic trawl fishery. Journal of Agricultural Economics 54, 325–341. https://doi.org/10.1111/j.1477-9552.2003.tb00066.x

Jamnia, A.R., Mazloumzadeh, S.M., and Keikha, A.A., 2015. Estimate the technical efficiency of fishing vessels operating in Chabahar region, Southern Iran. Journal of the Saudi Society of Agricultural Sciences 14, 26–32. https://doi.org/10.1016/j.jssas.2013.04.005

Jeya Girubha, R., and Vinodh, S., 2012. Application of fuzzy VIKOR and environmental impact analysis for material selection of an automotive component. Materials and Design 37, 478–486. https://doi.org/10.1016/ j.matdes. 2012.01.022

Jones, 1983. Mesh size regulation and its role in fisheries management, in: FAO Fisheries Report No. 289. p. 214.

Krueck, N.C., Ahmadia, G.N., Possingham, H.P., Riginos, C., Treml, E.A., and Mumby, P.J., 2017. Marine reserve targets to sustain and rebuild unregulated fisheries. PLoS Biology 15, 1–20. https://doi.org/10.1371/journal.pbio.2000537

Long, L.K., Flaaten, O., and Anh, N.T.K., 2008. Economic performance of open-access offshore fisheries-The case of Vietnamese longliners in the South China Sea. Fisheries Research 93, 296–304. https://doi.org/ 10.1016/j.fishres.2008.05.013

Maravelias, C.D., and Tsitsika, E. V, 2008. Economic efficiency analysis and fleet capacity assessment in Mediterranean fisheries. Fisheries Research 93, 85–91. https://doi.org/10.1016/j.fishres.2008.02.013

Mendoza, G.A., and Prabhu, R., 2003. Qualitative multi-criteria approaches to assessing indicators of sustainable forest resource management. Forest Ecology and Management 174, 329–343. https://doi.org/ 10.1016/S0378-1127(02)00044-0

Myers, R.A., and Worm, B., 2003. Rapid worldwide depletion of predatory fish communities. Nature 423, 280–283. https://doi.org/10.1038/nature01610

Narayanakumar, R., and Sathiadhas, R., 2005. Techno Economic Efficiency of resource use in Trawl Fishing in Andhra Pradesh-A Case Study in Kakinada 367–375.

Norse, E.A., Brooke, S., Cheung, W.W.L., Clark, M.R., Ekeland, I., Froese, R., Gjerde, K.M., Haedrich, R.L., Heppell, S.S., Morato, T., Morgan, L.E., Pauly, D., Sumaila, R., and Watson, R., 2012. Sustainability of deep-sea fisheries. Marine Policy 36, 307–320. https://doi.org/10.1016/j.marpol.2011.06.008

Opricovic, S., 2011. Fuzzy VIKOR with an application to water resources planning. Expert Systems with Applications 38, 12983–12990. https://doi.org/ 10.1016/j.eswa.2011.04.097

Opricovic, S., and Tzeng, G.H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research 156, 445–455. https://doi.org/10.1016/S0377-2217(03)00020-1

Parente, J., Fonseca, P., Henriques, V., and Campos, A., 2008. Strategies for improving fuel efficiency in the Portuguese trawl fishery. Fisheries Research 93, 117–124. https://doi.org/10.1016/j.fishres.2008.03.001

Parker, R.W.R., Blanchard, J.L., Gardner, C., Green, B.S., Hartmann, K., Tyedmers, P.H., and Watson, R.A., 2018. Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change 8, 333–337. https://doi.org/10.1038/ s41558-018-0117-x

Parker, R.W.R., Hartmann, K., Green, B.S., Gardner, C., and Watson, R.A., 2015a. Environmental and economic dimensions of fuel use in Australian Fisheries. Journal of Cleaner Production 87, 78–86. https://doi.org/10.1016/ j.jclepro.2014.09.081

Parker, R.W.R., Vázquez-Rowe, I., and Tyedmers, P.H., 2015b. Fuel performance and carbon footprint of the global purse seine tuna fleet. Journal of Cleaner Production 103, 517–524. https://doi.org/10.1016/j.jclepro.2014.05.017

Pascoe, S., Coglan, L., Punt, A.E., and Dichmont, C.M., 2012. Impacts of Vessel Capacity Reduction Programmes on Efficiency in Fisheries: The Case of Australia's Multispecies Northern Prawn Fishery. Journal of Agricultural Economics 63, 425–443. https://doi.org/10.1111/j.1477-9552.2011.00333.x

Pascoe, S., and Tingley, D., 2006. Economic capacity estimation in fisheries: A non-parametric ray approach. Resource and Energy Economics 28, 124–138. https://doi.org/10.1016/j.reseneeco.2005.06.003

Radhakrishnan, K., Kalaiarasan, M., Madan, M.S., Ananth, P.N., Umamaheswari, T., and Velmurugan, R., 2016. Economic analysis of the hook and line fishery in Kombuthurai coast, Tamil Nadu. Current World Environment 11, 926–933. https://doi.org/10.12944/cwe.11.3.28

Radhakrishnan, K., Prakash, S., Narayanakumar, R., Krishnan, M., Madan, M.S., and Kumar, N.R., 2018. Economic analysis of marine fishing crafts in Thoothukudi province, Tamil Nadu. Indian Journal of Geo-Marine Sciences 47, 653–659.

Reid, C., and Squires, D., 2007. Measuring fishing capacity in tuna fisheries : Data Envelopment Analysis , industry surveys and data collection, in: Methodological Workshop on the Management of Tuna Fishing Capacity. pp. 87–98.

Roberts, C.M., Hawkins, J.P., and Gell, F.R., 2005. The role of marine reserves in achieving sustainable fisheries. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 123–132. https://doi.org/10.1098/ rstb.2004.1578

Rodrigues, A.R., Abdallah, P.R., and Gasalla, M.A., 2018. Harvesting costs and revenues: Implication of the performance of open-access industrial fishing fleets off Rio Grande, Brazil. Marine Policy 93, 104–112. https://doi.org/10.1016/j.marpol.2018.04.008

Romeo, G., and Marcianò, C., 2019. Evaluating the economic performance of fishing systems using fuzzy multicriteria analysis in a Fishery Local Action Group in South Italy. Fisheries Research 218, 259–268. https://doi.org/10.1016/ j.fishres.2019.05.015

Sala, E., Mayorga, J., Costello, C., Kroodsma, D., Palomares, M.L.D., Pauly, D., Rashid Sumaila, U., and Zeller, D., 2018. The economics of fishing the high seas. Science Advances 4, 1–13. https://doi.org/10.1126/sciadv.aat2504

Sathyapalan, J., Srinivasan, J.T., and Scholtens, J., 2008. Maintaining a viable trawler fishery: A study of regulatory failures and over capitalization in the palk bay fishery.

Sesabo, J.K., and Tol, R.S.J., 2007. Technical efficiency of small-scale fishing households in Tanzanian coastal villages: An empirical analysis. African Journal of Aquatic Science 32, 51–61. https://doi.org/10.2989/AJAS.2007.32.1.8.145

Sreekrishna, Y., and Shenoy, L., 2001. Fishing gear and craft technology.

STEFC, 2015. Publications Office of the European Union, LuxembourgThe 2015 Annual Economic Report on the EU Fishing Fleet (STECF-15-07)2015.

Stephenson, R.L., and Smedbol, R.K., 2001. Small pelagic species fisheries. Encyclopedia of Ocean Sciences 503–509. https://doi.org/10.1016/B978-0-12-409548-9.11491-5

Stiasny, M.H., Mittermayer, F.H., Sswat, M., Voss, R., Jutfelt, F., Chierici, M., Puvanendran, V., Mortensen, A., Reusch, T.B.H., and Clemmesen, C., 2016. Ocean acidification effects on Atlantic cod larval survival and recruitment to the fished

population. PLoS ONE 11, 1–11. https://doi.org/10.1371/journal.pone.0155448

Sumaila, U.R., Teh, L., Watson, R., Tyedmers, P., and Pauly, D., 2008. Fuel price increase, subsidies, overcapacity, and resource sustainability. ICES Journal of Marine Science 65, 832–840. https://doi.org/10.1093/icesjms/fsn070

Thrane, M., 2004. Energy consumption in the Danish fishery: Identification of key factors. Journal of Industrial Ecology 8, 223–239. https://doi.org/10.1162/1088198041269427

Tietze, U., Thiele, W., Lasch, R., Thomsen, B., and Rihan, D., 2005. Economic performance and fishing efficiency of marine capture fisheries. FAO. Fisheries Technical Paper 77.

Tyedmers, P., 2004. Fisheries and Energy Use, in: Encyclopedia of Energy. https://doi.org/10.1016/b0-12-176480-x/00204-7

Tyedmers, P., and Parker, R., 2011. Fuel Consumption and Greenhouse Gas Emissions from Global Tuna Fisheries: A preliminary assessment, International Seafood Sustainability Foundation.

Vinodh, S., Varadharajan, A.R., and Subramanian, A., 2013. Application of fuzzy VIKOR for concept selection in an agile environment. International Journal of Advanced Manufacturing Technology 65, 825–832. https://doi.org/10.1007/s00170-012-4220-2

Vivekanandan, E., Singh, V. V., and Kizhakudan, J.K., 2013. Carbon footprint by marine fishing boats of India. Current Science 105, 361–366.

Walden, J.B., and Tomberlin, D., 2010. Estimating fishing vessel capacity: A comparison of nonparametric frontier approaches. Marine Resource Economics 25, 23–36. https://doi.org/10.5950/0738-1360-25.1.23

Wilson, J.D.K., 1999. Fuel and financial savings for operators of small fishing vessels, FAO. Fisheries Technical Paper 383. https://doi.org/10.1007/s13398-014-0173-7.2

Yao, S., and Liu, Z., 1998. Determinants of grain production and technical efficiency in China. Journal of Agricultural Economics 49, 171–184. https://doi.org/10.1111/j.1477-9552.1998.tb01262.x

Ye, Y., and Gutierrez, N.L., 2017. Ending fishery overexploitation by expanding from local successes to globalized solutions. Nature Ecology & Evolution 1. https://doi.org/10.1038/s41559-017-0179

Ziegler, F., Eigaard, O.R., Parker, R.W.R., Tyedmers, P.H., Hognes, E.S., and Jafarzadeh, S., 2019. Adding perspectives to: "Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950 - 2016". Marine Policy 107, 103488. https://doi.org/10.1016/j.marpol.2019.03.001

Ziegler, F., and Hansson, P.A., 2003. Emissions from fuel combustion in Swedish cod fishery. Journal of Cleaner Production 11, 303–314. https://doi.org/10.1016/S0959-6526(02)00050-1

Ziegler, F., and Hornborg, S., 2014. Stock size matters more than vessel size: The fuel efficiency of Swedish demersal trawl fisheries 2002-2010. Marine Policy 44, 72–81. https://doi.org/10.1016/j.marpol.2013.06.015