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A Review of Energy use and Carbon Footprint in Fishing with Special Reference to Life Cycle Assessment (LCA)

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Abstract

With over 4.1 million vessels operating worldwide the global fishing industry is critical for ensuring food security and supporting livelihoods. Asia leads in the total number of vessels globally with 2.68 million vessels which are operational, while India has about 0.166 million vessels (FAO, 2024). The fishing industry heavily depends on fossil fuels for fishing operations, which contributes significantly to greenhouse gas emissions. In 2011 alone, global fisheries consumed 40 billion litres of fuel, resulting in 179 million tonnes of CO_2 emissions, which is about 4% of total emission from global food production (Parker et al., 2018). In Indian scenario fuel consumption per tonne of fish landed, have increased from 0.50 tonnes in 1961 to 1.52 tonnes in 2024. Mechanized and motorized vessels contributed the most to emissions, with trawlers emitting up to 1.43 tonnes of CO_2 per tonne of fish. The economic challenges posed by rising fuel prices and inefficiencies in operations are highlighted in many fisheries, including India, where high fuel consumption and associated costs limits capacity utilization by up to 55% in many cases.

This review examines strategies used for reducing energy use and emissions in fisheries and explores best strategies to minimize emissions from fishing fleet. Innovations in vessel design, fuel-efficient engines, and advanced gear technologies can be effective solutions for reducing energy use and emissions. Additionally, practices such as conducting energy audits, optimizing routes, and transitioning to alternative fuels like LNG and biogas can significantly improve sustainability. While traditional approaches based on fuel consumption provide a comparative understanding of energy use, Life Cycle Assessment (LCA) frameworks offer deeper insights into environmental impacts, making them valuable for shaping policies and practices that promote both economic and environmental sustainability in the fisheries sector.

Key words: Fishing, fuel consumption, carbon emission, energy use, LCA

Introduction

Fisheries play a vital role in ensuring livelihoods and nutritional security. In 2022, global production from capture fisheries and aquaculture was estimated at 223.2 million tonnes, with capture production contributing 80 million tonnes and supporting the livelihoods of 61.8 million people (FAO, 2024). Marine fishing, heavily depends on fossil fuels to power vessel propulsion and other related activities during fishing, leads to greenhouse gas emissions, which is primarily constituted by carbon dioxide (Greer et al., 2019).

In 2011, the marine capture fisheries sector was estimated to have consumed 40 billion litres of fossil fuel, resulting in 179 million tonnes of CO_2 emissions, which is approximately 4% of the total global emissions from food production (Parker et al., 2018). Over the past five decades, the increased effort and also the improved efficiency of fishing operations have significantly raised fuel consumption levels. In India, CO_2 emissions, which was estimated as 0.30 million tonnes (mt) in 1961, increased to 3.60 mt by 2010, and concurrently, CO_2 emissions per tonne of fish caught increased from 0.50 to 1.02 tonnes during this period (Vivekanandan et al., 2013) and the recent estimates place this value

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at 1.52 tonnes of eq. CO_2 per tonne of fish landed (Dineshbabu et al., 2024).

Although the direct effects of fishing on fish populations and marine ecosystems frequently garner significant attention, the collateral impacts and costs associated with fishing, especially fuel use, are typically underexamined. Research has consistently demonstrated that fuel use by fishing vessels is a key contributor to environmental impacts associated with climate change (Avadí & Fréon, 2013). Though marine capture fisheries have reached a plateau, the fishing effort continues to increase, and this is more pronounced in the Asian and African countries (FAO, 2024). Thus, it is understood that studies on energy use patterns in fisheries and their changes, both in terms of fuel use and catch per unit effort, over time, can serve as valuable tools to assess the health of fish stocks (FAO, 2015).

Most global studies that have analyzed fuel use patterns have depended on limited data inputs, focusing primarily on fuel consumption data alone (Tyedmers, 2001; Ziegler & Hanssen, 2003; Thrane, 2004). Although the contribution from combustion of fuel contributes significantly to the emissions, other factors, that are indirectly required for fishing operations, for instance the building of the vessel, cooling mechanism etc. which involve significant energy inputs are often overlooked in studies deriving carbon footprint of fisheries (Høyli & Aarsæthe, 2023). However, recent studies have adopted approaches such as life cycle assessment, which is an advanced method for estimating both direct and indirect emissions, related to fisheries (Hill, Keefe, & Snape, 1995; Ellingsen & Aanondsen, 2006; Thrane, 2006; Ziegler & Valentinsson, 2008; Vázquez-Rowe, Moreira, & Feijoo, 2010; Ramos et al., 2011; Svanes, Vold, & Hanssen, 2011; Ziegler et al., 2018).

Systematic methods, such as Life Cycle Assessment (LCA), evaluate the carbon footprint of seafood products by assessing the environmental impacts throughout their life cycle. This approach offers a detailed analysis and understanding of the actual energy use in fisheries. Such studies that account for all relevant factors, assist industries in developing frameworks aimed at minimizing environmental impact and enhancing sustainability (Cao, Diana, & Keoleian, 2013; Farmery, Gardner, Green, Jennings, & Watson, 2015). However, it is felt that there is a notable gap in the systematic compilation of information on both direct and indirect energy use in fishing systems, and the need for better documentation of strategies, including the role of direct and indirect cost of fishing, to reduce energy consumption and the associated carbon footprint, particularly beyond the fuel component. Against this backdrop, this review aims to achieve the following objectives:

1. To provide an overview of energy consumption, particularly related to fossil fuel use, and the resulting carbon emissions at both global and Indian fisheries contexts.
2. To identify key challenges and explore potential approaches for reducing fuel use and carbon emissions in the fishing sector using various strategies, with a focus on LCA.

Global overview of energy use and carbon footprint

It is estimated that the total energy content of fuel used by global fisheries is 12.5 times greater than the energy content of the edible protein in the landed catch (Tyedmers, Watson, & Pauly, 2005), and numerous other studies worldwide have estimated greenhouse gas emissions in terms of landed catch (Table 1). The type of fishing method plays an important role in determining fuel consumption, and among these, trawl gear is considered the most energy-intensive fishing gear, requiring significantly more fuel per kilogram of landed catch compared to other methods of fishing. For instance, Ziegler and Valentinsson (2008) reported that trawling requires nearly twice the amount of fuel for the same catch as other methods. Similarly, Vázquez-Rowe et al. (2010) estimated that trawling for horse mackerel uses 64% more fuel per ton of landed catch than purse seiners for the same species. Shrimp trawls, which are often mandated to use species-selective grids result in reduced bycatch and lower capture rates, which in turn increases fuel consumption per kilogram of landing. Conversely, fish trawling requires less fuel per kilogram of landing but results in higher bycatch (Ziegler et al., 2014).

Ziegler and Hansson (2003) assessed the Swedish cod fishery and found that 38 megajoule (MJ) of energy was required per kilogram of landed cod, with gillnet fisheries accounting for 38% of the energy use and trawl fisheries for 62%. Driscoll and Tyedmers (2010) reported that purse seiners emitted approximately 65 kg CO_2 equivalent per tonne of catch, while mid-water trawlers operating in pairs or as single vessels released 337 and 365 kg CO, equivalent per tonne, respectively. Among fishing methods, pelagic trawls and purse seines/ring seines required the least amount of fuel per kilogram of fish caught (Schau, Ellingsen, Endal, & Aanondsen, 2009; Lee, 2013).

Purse seines and beach seines are among the most energy-efficient fishing systems, with energy inputs ranging between 0.05 and 0.08 kcal per kilogram of catch landed (Watanabe & Okubo, 1989). Purse seines also stand out in terms of fuel efficiency, requiring only 0.25 kg of fuel per kilogram of fish landed. Auxiliary boats, which are smaller boats that assist in purse seining operations, use as little as 0.07 kg of fuel per kilogram of fish landed. However, when considering carbon footprints, Ceballos-Santos et al. (2023) estimated that purse seines emit 1.0 kg CO_2 equivalent per functional unit, whereas auxiliary boats emit a much lower 0.34 kg CO_2 equivalent per functional unit, which highlights the need for deeper understanding of the energy use within the fishing systems. In small pelagic fisheries, the carbon footprint is typically low, often less than 1 kg CO_2 equivalent per kilogram of whole fish landed. A life cycle assessment (LCA) comparing pelagic fisheries to other seafood operations revealed that one kilogram of catch landed by the Scottish pelagic trawl fleet has a carbon footprint of 0.4 kg CO_2 equivalent. Notably, 96% of the total carbon footprint was attributed to fuel burned during fishing operations (Sandison et al., 2021). There is however a consensus that fuel use accounts for the largest share of the environmental burden in fishing operations, contributing 60-80% to the overall environmental impact (Ziegler & Hansson, 2003; Thrane, 2006; Ziegler & Valentinsson, 2008).

Studies related to energy consumption in fisheries in the Indian context

In the Indian context, a large number of studies have tried to understand the direct and indirect energy use in different fisheries since 1990s and notable among these are Edwin and Hridayanathan (1997); Boopendranath (2000); Mathai (2000); Boopendranath and Hameed (2009, 2010, 2013); Vivekanandan et al. (2013); Ghosh et al. (2014); Jha, Antony, Baiju, Yasmi, and Edwin (2021); Devi et al. (2021); Asokan et al. (2023); Dineshbabu et al. (2024) & Jenish et al. (2024). Boopendranath (2000) & Boopendranath and Hameed (2009, 2010) correlated emissions with the power of vessels in traditional motorized fishing sector of Kerala. The trend from these studies indicates that the energy requirement in fisheries is primarily by the harvest sector, with the post-harvest phase contributing significantly less. Ghosh et al. (2015) studied fuel consumption of harvest and post-harvest phases and reported that, out of 0.48 litres of fuel and 0.255 kWh of electricity used, the harvest phase used 0.45 litres of fuel and 0.13 kWh of electricity. The associated CO_2 emissions were recorded as 1.2 kg CO_2 for harvest phase and 1.4 kg CO_2 for harvest and post-harvest phase together. Fuel use during the harvest phase was found to contribute the most to abiotic depletion, primarily due to production of fuel and lubricating oil, which accounted for 96% of the environmental burden (Abdou et al., 2018). Vivekanandan et al. (2013), reported significant variations in emissions among different types of vessels, with mechanized landings characterized by higher fuel and energy use, thus resulting in higher emissions compared to the motorized vessels. The smaller motorized boats with outboard motors emitted on an average, 0.59 tonnes of CO_2 per tonne of fish caught, while mechanized boats with inboard engines released 1.18 tonnes of CO_2 per tonne of fish. Among mechanized vessels, trawlers recorded the highest emissions at 1.431 tonnes of CO_2 per tonne of fish, whereas emission calculated for gillnetters, bag netters, seiners, liners, and dol netters, were lower and ranged from 0.56 to 1.07 tonnes of CO_2 per tonne of fish. The trend however was not concurrent with bulk catching methods like ring seines; where each tonne of oil sardine caught and landed by motorized vessels powered by kerosene resulted in 402 kg of CO_2 emissions, whereas the emissions from mechanized vessels with diesel engines was calculated at 300 kg CO_2 (Edwin & Das, 2016).

Fuel use and economics of fishing operations

Fuel costs represent a significant portion of the total fishing expenses, making fleet economics highly dependent on fluctuations in fuel prices. The excessive use of fossil fuels, coupled with rising fuel prices, are reported to have negatively impacted the economic performance of fishing fleets and case studies indicate fleets adopting cost-cutting measures, reducing fishing activities, and, in some cases, changing operational strategies (Quintana, 2023), to reduce the impact of price hikes. The impact of fuel prices is seen to vary across geographies and based on the economic conditions, and therefore analysing fuel consumption data, give valuable insights about fleet characteristics, fuel usage patterns, other associated costs and return on investments (Catherine & Cleveland, 1993; Floc'h et al., 2007; Kapodar & Liu, 2022).

It is also noted that rising fuel prices, low fish prices, declining vessel productivity, and depleting fish stocks have significantly reduced the profitability of the fishing sector, often leading to lower capacity utilization (Guillen & Maynou, 2016). Additionally, the energy required to harvest seafood has steadily increased over time, resulting in a declining energy return on investment (Catherine & Cleveland, 1993). In the absence of external interventions, such as fuel subsidies or market support mechanisms, rising fuel prices is found to drive unprofitable fishing operations into losses, leading to a reduction in fleet size or lower utilization of capacity which results in reduced trips. An estimated 33% reduction in profitability was observed in one-fourth of the vessels by number and one-third of the vessels by the volume of landed catch, in the European Union between 2002 and 2008 (Cheilari, Guillen, Damalas, & Barbas, 2013). In Kerala, India, a 55% reduction in capacity utilization was reported, primarily attributed to high fuel prices and increased fuel consumption (Unnithan, Gopal, Nair, & Nasser, 2005).

The economic implications of fuel expenses in fisheries differ as the ratio of fuel costs to overall revenues do not consistently correspond with the level of fuel usage. Fuel costs can represent a significant portion of total cost in various fisheries, ranging from 2% to 50%. Furthermore, it is observed that patterns of fuel consumption in fisheries are influenced by a variety of other factors. A study conducted along the west coast of India by Devi et al. (2021) indicated that in single-day fishing trips, management-related factors are more influential, while for multiday trips, technological factors emerge as the main drivers. Assessing and outlining fuel consumption in fisheries offers an essential understanding of the economic stability and ecological sustainability of these businesses (Solakivi, Paimander, & Ojala, 2022).

Eayrs, Wanchana, and Suuronen (2017) performed a two-tier audit on 94 single-boat trawl fleets, revealing that fuel expenditure constituted the predominant operational expense across all vessel size categories, followed by labour and provisions. They subsequently chose six trawlers for a 10-day fishing expedition to assess fuel consumption and, following audit suggestions, projected that fuel usage might be reduced by 40%. Wakeford and Bose (2013) proposed a three-tiered energy audit procedure for fishing vessels, integrating recurrent neural networks (RNNs) with route optimization algorithms for weather routing, demonstrating considerable potential for fuel savings. Consequently, performing energy audits in fisheries has demonstrated efficacy in pinpointing inefficiencies and matching practices with climate change goals. Energy audits of trawl fisheries underscore the necessity of lowering energy usage and mitigating environmental impacts along the entire product chain (Lee, Han, & Wang, 2017; Sala et al., 2022). Iribarren, Vázquez-Rowe, Hospido, Moreira, and Feijoo (2010) assessed the carbon footprints linked to the Galician fisheries sector, encompassing coastal fishing, offshore fishing, deep-sea fishing, extensive aquaculture, and intense aquaculture. The individual carbon footprints were utilized to compute the carbon footprint for each Galician fishery, establishing a standard for assessing and disseminating emission reductions, hence facilitating the prioritization of initiatives aimed at reducing greenhouse gas emissions. Parker, Vázquez-Rowe, and Tyedmers (2014) indicated that purse seine vessels targeting yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*) constituted 28% of the global landings of these species in 2009, consuming approximately 368 litres of fuel per tonne of wet weight landed, resulting in a fuel-related carbon footprint of 1.1 kg CO_2 per kilogram of tuna landed, thereby illustrating the environmental impact of these fisheries.

Asokan et al. (2023) analyzed fuel consumption and greenhouse gas (GHG) emissions from small-scale fishing vessels along southeast coast of India, focussing on longline-cum-gillnetters, seine-netters, longliners, and drift-gillnetters, and reported that these vessels collectively contributed 65% of the annual GHG emissions of the sector. Another study by Edwin and Das (2016), reported that the carbon footprint of motorized ring seine fleets was higher than that of mechanized ring seine fleets, except for abiotic depletion potential (ADP) and ozone depletion potential (ODP), where mechanized fleets performed worse due to their reliance on lead weights and polyamide webbing. Studies to understand fuel consumption patterns and estimate the total fuel usage of motorized fishing vessels operating along east coast of India during 2004-05, showed that the average fuel utilization by the motorized fishing craft was 14.15 l/day and measures like using fuel-efficient engines and optimizing fishing fleet were suggested (Jeeva, Gopal, Unnithan, & Sreedhar, 2009). Jenish et al. (2024) assessed fuel consumption and CO_2 emissions associated with different motorised fishing practices in the Pulicat region. The study categorised the Pulicat region into the Pulicat coast and Pulicat lake, and the carbon emissions from the Pulicat coast and Pulicat lake (inland) were approximately 1.37 and 0.3 tonnes per tonne of catch landed, respectively and the total average carbon emission was reported to be 1.08 MT of CO_2 per tonne of catch landed. The overall outcome of this study and other studies confirms that inland fishing practices have a lower carbon footprint than marine fisheries (Avadí & Fréon, 2013).

The role of LCA in analysis of environmental Impact due to emissions

The life cycle of a product involves examining its processes and activities, starting from raw material extraction to manufacturing, distribution, usage, and, where applicable, recycling and waste treatment (ISO, 14044). The environmental impact of fishing operations, including the construction of implements and their usage, can be effectively estimated using Life Cycle Assessment (LCA) approaches, and thus can play a crucial role in estimating the environmental consequences of fishing operations and identifying opportunities to reduce indirect emissions associated with fuel use (Avadí & Fréon, 2013). LCA offers several advantages over other methods for assessing environmental burdens, such as those using CO_2 emissions alone for calculations. The advantages of LCA include accurate and precise results, flexibility in defining system boundaries based on the scope of the study, universal acceptance as a reliable method, and the ability to analyse results component-wise or sub-component-wise.

An essential element of the LCA approach is the functional unit, which acts as the fundamental link between inputs and outputs, that is crucial for establishing and limiting the system boundaries of the study. Life cycle inventory (LCI) analysis, which focuses on the collection and quantification of inputs and outputs within the system, is another important aspect in which all aspects related to production is collected. LCA thus acts as a key tool in sustainability assessments, helping to identify areas for improvement and enabling informed decision-making (Guinée, de Koning, & Heijungs, 2022). The step-by-step, objective-driven approach involved in LCA to assess environmental impacts across categories such as human health, ecosystem quality, and natural resource use makes it a great tool in impact assessment (Azapagic, 1999). Beyond carbon dioxide, the combustion of fossil fuels by fishing vessels releases other greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and halogenated compounds including chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and perfluorinated carbons (PFCs), which are also major contributors to climate change (IPCC, 1996, 1997). The most used metric for comparing different scenarios is the Global Warming Potential (GWP), which measures the ability of a gas mixture to trap additional heat in the atmosphere over time, relative to carbon dioxide (CO_2). The potential environmental impact categories evaluated through LCA, other than GWP include:

- Abiotic depletion (AD): Kilograms of antimony equivalent (kg Sb eq)
- Acidification (AC): Kilograms of sulfur dioxide equivalent (kg SO_2 eq)
- Eutrophication (EP): Kilograms of phosphate equivalent (kg PO_4^{3-} eq)
- Ozone layer depletion (ODP): Kilograms of trichlorofluoromethane equivalent (kg CFC-11 eq)
- Human toxicity (HT): Kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DB eq)
- Freshwater ecotoxicity (FE), marine ecotoxicity (ME), terrestrial ecotoxicity (TE): Kilograms of 1,4-DB equivalent
- Photochemical oxidant formation (PO): Kilograms of 1,4-DB equivalent (Hauschild, Rosenbaum, & Olsen, 2017).

Factors affecting fuel consumption and measures for reduction

Unscientific vessel designs, such as poorly constructed hulls, over-speeding, improper nozzle installations (Tadros, Ventura, & Soares, 2023), improper propeller design (Nasser, Lalitha,

Table 1. Comprehensive list of studies in the field of fuel consumption and associated emissions in the fisheries sector

S.N.	Author(s)	Objective/Area/Object investigated	Findings/outcome/recommendations
Estimation of energy use/carbon footprint/environmental burden in marine capture fisheries			
1.	Abdou et al. (2018)	Estimation of environmental burden due to fishing	Abiotic depletion during the harvest phase came from the manufacture of fuel and lubricating oil production (96%).
2.	Asokan et al. (2023)	Estimation of fuel consumption and related greenhouse gas emission due to operation of small-scale fishing vessel	Fuel consumption and GHG emissions for effective management with a focus on longline-cum-gillnetters, seine-netters, longliners, and drift-gillnetters, which contribute to 65% of annual GHG emissions.
3.	Boopendranath & Hameed (2009, 2010, 2013)	Energy analysis of different mechanised and motorised fishing systems along Indian coast	Estimated fuel and energy use in fishing operation of different mechanised and motorised fishing systems.
4.	Ceballos-Santos et al. (2023)	Estimated impacts associated with greenhouse gas (GHG) emissions	The value of global warming potential (GWP) was 1.44 kg CO_2 equivalent per functional unit, and emissions were in the upper range for fishery species caught with seine nets.
5.	Devi et al. (2021)	Fuel use of different categories of mechanised trawl fishing vessels based on L_{OA}	Fuel utilized in kg per kg of fish landed varied between 0.42 (single day trawler) and 0.70 (multiday large trawler).
6.	Edwin & Das (2016)	Carbon emission in Ring seine fishing operation	Kerosene powered motorized vessel, emit 402 kg of CO_2 per tonne of oil sardine landed, whereas diesel powered mechanized vessel emit 300 kg of CO_2 per tonne.
7.	Ghosh et al. (2015)	Estimation of fuel and electricity demand in mechanised fishing (harvest and post-harvest phase)	Fuel and electricity requirement in fishing operation was 0.48 l/kg and 0.255 kWh/kg of fish landed.
8.	Greer et al. (2019); IPCC (1996, 1997)	Fossil fuel consumption in fishing operation and CO_2 emission	Greenhouse gases mainly carbon dioxide (CO_2) is an environmental burden globally.
9.	Guinée et al. (2022)	LCA and its different methods	Described different methods of LCA it is a method used to evaluate the environmental impacts of a product or process.
10.	Hornborg et al. (2012)	Fuel efficiency in trawler	Most energy-efficient method was Skagerrak conventional trawling, which required almost twice as much fuel per landing as grid trawling.
11.	Parker (2016)	Carbon emission and economic analysis due to fish harvest	Global wild-capture of marine fisheries is a significant contributor to greenhouse gas emissions and is the second highest cost to fishers globally after labour.
12.	Parker et al. (2018)	Quantification of fuel inputs and greenhouse gas emissions for global fishing between 1990 and 2011	Estimated the fishing industry used 40 billion lt of fuel and produced 179 million tonnes of CO_2 equivalent greenhouse gases in between 1990 and 2011.
13.	Parker & Tyedmers (2015)	Estimation of relative energy performance and median fuel consumption intensity of global fisheries	Relative energy performance and median fuel consumption intensity of global fishery since 1990 is 639 lt per tonne.

14.	Sala et al. (2022)	Fuel consumption and associated emission due to mechanised fishing operation	Fuel consumption rates greatly varying depending on the kind of gear and vessel size. On an average 2.9 l of fuel are consumed per kilogram of landed fish, correspond to each kg of fish has an average carbon impact of about 7.6 kg CO_2.
15.	Schau et al. (2009); Lee (2013)	Fuel use comparison between two fishing system	Shrimp trawl in Norway, uses 1.04 kg fuel per kilogram of capture, whereas pelagic trawl and purse seine/ring seine, both of which weigh 0.09 kg of fuel per kilogram of catch.
16.	Shajeeva et al. (2017)	Eq. carbon estimation study in mechanised fishing sector	Proper design is required to build stable vessel with fuel efficiency.
17.	Sumaila et al. (2008)	Investigation on fuel price, subsidies, overcapacity and resource sustainability.	Excess number of fishing fleet, increased subsidy on fuel are linked to increased emission
18.	Tadros et al. (2023)	Study on hull and propeller characteristics and fuel consumption	Unscientific design of hull and Propeller can lead to more fuel consumption.
19.	Vázquez-Rowe et al. (2010)	Fuel use estimation by purse seine	Purse seiners harvesting horse mackerel use 64.5% less fuel per ton of harvest.
20.	Ziegler & Hansson (2003)	Estimation of environmental burden due to fisheries	The fisheries contribute to environmental impact, including the potential for global warming, eutrophication, acidification, photochemical ozone creation, and aquatic ecotoxicity.
21.	Ziegler et al. (2018)	Estimation of potential impact categories of environmental assessment through LCA approach	Estimation of abiotic depletion, acidification, eutrophication, global warming potential, ozone layer depletion, human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and photochemical oxidant formation etc.
Fuel and economics of fishing operations			
22.	Catherine & Cleveland (1993).	Study on energy return on investment and seafood harvest over period of time.	The energy requirement is increasing with time resulting reduced energy returns on investment.
23.	Floc'h et al. (2007)	Fishermen's behaviour with economics of fuel component in mechanized fishing sector.	Fleet contribution to total earnings is appreciated according to fishing methods used.
24.	Solakivi et al. (2022)	Relationship between maritime fuel surcharges and economic growth with an estimate of when low-carbon fuels will be competitive against fossil fuels.	Impact of surcharges on financial planning in the industry and need to identify surcharge development in relation to economy.
25.	Unnithan et al. (2005)	Economic analysis and fuel use patterns of more than 3000 number of mechanized fishing vessels (small category: LOA less than 40 feet; medium category: LOA 40-48 feet and large category: LOA more than 48 feet)	Fuel use pattern of mechanized fishing sector of Kerala (India) is only 55% of the fishing capacity.
Measures to reduce fuel consumption and GHG emission			
26.	Eayrs et al. (2017)	Energy audit of shrimp trawler.	Energy audit is an important step for estimation of the fuel use during fishing and opportunity to reduce it.

27.	Edwin & Das (2016)	Analysis of different environmental burdens due to mechanised and motorised seine net operation	Impact of catch landed by motorized ring seine fleet is higher than that of mechanized ring seine fleet, except abiotic depletion potential (ADP) element and the ozone depletion potential (ODP).
28.	Korican et al. (2022)	Methods/apparatus to estimate Fuel consumption	Demonstrated different methods to estimate, monitor and evaluate fuel consumption viz. sounding, fuel flow meter, modern fuel measurement system etc.
29.	Lee & Lee (2010)	Effect of improved trawl gear design through simulation on gear resistance and fuel efficacy	Improving the fuel economy of trawlers and highlighted the importance of gear to improve the efficiency of mechanized fishing vessel.
30.	Parker et al. (2017)	Investigation on fuel consumption rates and impact of managerial, behavioural, and technological factors (engine power and vessel size).	For one-day excursions, managerial factors had the greatest impact on fuel use, but multi-day trips were significantly impacted by technological factors.
31.	Percic et al. (2023)	Investigation on economics and environmental performance of various alternative fuel in purse seiner	Methanol was the best option for the purse seiner as it reduces costs by 23.3% and greenhouse gas emissions by 22.4% compared to a diesel.
32.	Sala et al. (2022)	Study on energy audit in trawl fishing system	Energy audits of trawl fisheries helps in lowering energy usage and mitigating environmental impacts
Dual fuel/eco-fuel in fisheries			
33.	Baiju (2019); Baiju et al. (2024)	Potential of alternate energy for higher fuel efficiency in fishing activity	Energy efficiency of fishing vessels can be increased with use of alternate fuel
		Investigation on different fuels in context with cost and emission in fishing vessel.	Dual-fuel engines that combine diesel with LNG or CNG offer significant reductions in fuel consumption and emissions.
34.	Bilgili (2021)	Study on environmental impacts of the different fuels of to be used in marine transportation through LCA	Out of four fuels studied; methanol, ammonia, biodiesels and biogas, biogas is shown to be the most environmentally friendly fuel.
35.	Ghosh et al. (2023)	Study on impact of renewable source of energy on fisherfolk's income in small scale fisheries	Solar-assisted electric boats can empower to livelihoods with decreased fuel cost.
36.	González-García et al. (2015)	LCA based study was conducted to comprehend the eco-efficiency of purse-seiner.	There is correlation between skipping less efficient vessel and Important environmental benefits including fuel efficiency.
37.	Kim et al. (2023)	Comparision and evaluation of environmental impact of different fuels in small scale fisheries through LCA approach	Greenhouse gas emissions are produced less over the course of a vessel's life cycle when LPG fuel is used in place of gasoline and diesel fuel.
38.	Lee et al. (2024); Ismail & Omar (2016)	Importance of dual fuel use in fishing operation to reduce GHG, compared to single fuel.	Reduced fuel consumption in Malaysian offshore fishing vessels by introducing dual fuel diesel and compressed natural gas (CNG) engines.
39.	Percic et al. (2020)	Applicability of different energy source/marine fuels on environmental performance of Croatian vessel.	Out of all the energy sources for propelling vessel electricity for powering was found the most environmentally friendly.
40.	Ziegler & Hansson (2003)	Energy use per unit (kg) of cod landed by large mechanized fishing vessels in Swedish waters.	Energy utilisation of Swedish cod fishery and found approximately 38 MJ of energy are utilized per kg of landed cod.

Ashaletha, & Geethalekshmi, 2014), and overcapacity contribute significantly to increased fuel consumption (Sumaila, Teh, Watson, Tyedmers, & Pauly, 2008). Operational inefficiencies like, higher engine RPM (revolutions per minute) (Wilson, 1999), irregular maintenance schedules and fouling (GEF-UNDP-IMO GloFouling Partnerships Project, 2022), are reported to further exacerbate fuel use. Compared to inboard diesel engines of equivalent power, outboard two-stroke petrol engines consume more fuel. These inefficiencies not only increase environmental impacts but also compromise vessel safety and stability during fishing operations (Boopendranath, 2000, Boopendranath & Hameed, 2013; FAO, 2015). Shajeeva et al. (2017) have reported that efforts to improve vessel efficiency must prioritize constructional inputs and systematic design to create stable, fuel-efficient vessels, for which the key considerations should be to optimize engine power and vessel size, which directly influence fuel consumption rates. Studies conducted on rock lobster fisheries in Australia and New Zealand have shown that managerial, behavioural, and technological factors, such as vessel size and engine power, significantly affect fuel consumption rates (Parker, 2016; Parker, Gardner, Green, Hartmann, & Watson, 2017). Using large propellers with reduction gears or optimized gear designs are found to reduce drag resistance, leading to substantial fuel savings (Mathai, 2000; Lee & Lee, 2010).

Fishing gear design also plays an equally important role in fuel efficiency, particularly for trawl nets where the resistance of the towed net contributes significantly to the drag and higher fuel consumption. Innovations such as knotless webbing, thinner twines, square mesh panels, large mesh sizes, and modified accessories like otter boards have shown to reduce drag and fuel consumption significantly (Boopendranath, 2002). Similarly, attempts to substitute construction material, like wood, in place of steel has been found to lower CO_2 emissions for vessels of similar dimensions (Jha et al., 2021). Route optimization, that determines ideal travel speeds and paths between fishing grounds is another attempt where significant fuel savings are attempted (Granado, Hernando, Uriondo, & Fernandes-Salvador, 2024). Changes in the operational parameters have shown to positively influence on fuel savings, for example reducing vessel speed by 10-20%, could save 35-61% of fuel, while a 3% reduction in engine RPM was found to lower fuel consumption by up to 10% (Wileman, 1984; Gulbrandsen, 1986; Aegisson & Endal, 1993). Studies have also highlighted the role of numerical modelling in optimizing fuel use by recommending suitable gear designs and materials for improved efficiency (Lee & Lee, 2010). Recently, energy audits, , which highlight ways to minimize energy consumption throughout the product chain have proven to be effective tools for identifying inefficiencies and optimizing fuel use in fisheries and trawl fisheries (Lee, Han, & Wang, 2017; Sala et al., 2022). Modern technologies, such as speed profile calculations and disturbance correction coefficients, have also helped in accurate fuel consumption estimates (Lee et al., 2017). Similarly, integrating artificial intelligence (AI) tools, such as recurrent neural networks (RNNs), with weather routing and optimization algorithms has demonstrated their potential for reducing fuel consumption, and there by total emissions, including operational costs (Kaklis et al., 2022).

Alternative fuels, such as liquefied natural gas (LNG), compressed natural gas (CNG), methanol, and biogas, are emerging as practical solutions for reducing fuel costs and emissions in fisheries. Dual-fuel engines that combine diesel with LNG or CNG offer significant reductions in fuel consumption and emissions (Baiju et al., 2024). Methanol, when used in purse seiners, have shown to lower operating costs by 23% and reduce greenhouse gas emissions by 22% compared to diesel engines (Perèiæ, Vladimir, Korièan, Jovanoviæ, & Haramina, 2023). Biogas, identified as the most environmentally friendly fuel, produces only 0.9 tons of CO_2 per ton of fuel burned, compared to higher emissions from methanol, biodiesel, and liquefied biogas (Bilgili, 2021). Transitioning to these cleaner fuels not only enhances environmental performance but also reduces the dependence of the fishing industry on traditional fuels, which can help in mitigating rising global fuel prices (Korièan et al., 2022). Brynolf, Fridell, and Andersson (2014) compared the life cycle environmental performance of liquefied natural gas (LNG), liquefied biogas (LBG), methanol, and bio-methanol. They suggested that transitioning to LNG or methanol produced from natural gas could significantly enhance overall environmental performance. However, the impact on climate change remains comparable to that of heavy fuel oil.

The energy return on investment in fisheries varies significantly depending on the species and fishing methods. Generally, the capture of sardines and mackerels requires less energy compared to species like marlins and tunas, which are considered more energy intensive (Watanabe & Okubo, 1989). Parker and Tyedmers (2015) analyzed more than 1600 published and unpublished literature on fuel use for capture of different species, using different gear and from different regions of world since 1956, for compilation of Fisheries and Energy Use Database (FEUD). They reported small pelagic fisheries are among the most fuel-efficient, while crustacean fisheries as the least efficient, (fuel use intensity values are up to, and even over, 10,000 L/ton) with median global fuel consumption intensities of 639 liters per ton of landed fish in terms of energy use.

The integration of renewable energy sources, such as sail-assisted fishing and electric propulsion systems, are found to offer long-term solutions for sustainable fishing operations (Perèiæ, Vladimir, & Fan, 2020; Ghosh, Soman, Kaur, & Jain, 2023). Renewable energy reduces dependence on fossil fuels while lowering emissions, making it a viable option for small-scale and large-scale fisheries. For example, using liquefied petroleum gas (LPG) in place of diesel has been shown to cut greenhouse gas emissions by over 30% for small fishing vessels (Kim, Jeong, Choi, & Lee, 2023).

Practices such as using turbocharged diesel engines, smart navigational equipment, and smaller, more efficient fishing gear can significantly reduce fuel use and emissions (Boopendranath & Hameed, 2009; Cochrane, Andrew, & Parma, 2011; Rakopoulos, Dimaratos, Giakoumis, & Rakopoulos, 2011). Additionally, implementing clear policies, and use of advisories on potential zones for fishing to enhance the overall efficiency are other steps in this direction. Establishing benchmarks for fuel use intensity (FUI) to provide a framework for monitoring progress and identifying opportunities to improve environmental performance is critical (Asokan et al., 2023). Calisal (1985) developed a computer program based on fishing operation profile, including the actual fuel consumption estimates of major popular engines. Adhering to standard operating procedures for marine engines, like reducing service speeds, lowering engine RPM, and performing regular maintenance, such as cleaning the underwater portions of vessels, not only conserves fuel but also ensures the smooth operation and longevity of marine engines (Molland, 2008).

Innovative, energy-efficient fishing technologies such as solar-powered sun boats (Baiju, 2019), hybrid trawls, high-opening trawls, large mesh off-bottom trawls, optimized hull designs with bulbous bows (Baiju, 2019; Tadros et al., 2023), fuel-efficient propeller systems (Nasser et al., 2014), and lightweight superstructures are other promising solutions to reduce energy consumption and improve sustainability in the sector (EC, 2011; Gulbrandsen, 2012; Hussein, Elsayed, & Yehia, 2021; Szelangiewicz, Abramowski, ¯elazny, & Sugalski, 2021).

Sustainable exploitation of marine fisheries resources will remain a viable option when supported by robust regulatory management systems and coordinated policy efforts, tailored to specific species and locations (Hornborg, Nilsson, Valentinsson, & Ziegler, 2012; Hashim, Ramlan, & Wang, 2017). Policy measures play a crucial role in managing non-renewable resources, and many countries have already implemented initiatives to address these challenges. For instance, in the European Union, the potential removal of fuel tax exemptions for fishing fleets has been studied to assess its impacts on small-scale, large-scale, and distant-water fleets. In 2021 the gross profit by EU fishing fleets was 850 million EUR, and in 2022, when fuel prices increased to EUR 0.93/litre, profitability decreased to 670 million EUR. This implies that a 10-cent increase in the fuel price per litre resulted in about a EUR 185 million loss for the EU fishing sector (Guillen, Carvalho, Carpenter, Borriello, & Santos, 2023). Such efforts would offer decision-makers and stakeholders, significant insights into the implications of fuel tax modifications while examining strategies to alleviate these impacts.

Conclusion

The fishing industry in India and around the world is vital to maintaining both economic stability and food security. However, the reliance of the fishing industry on fossil fuels has raised environmental concerns globally and measures to reduce the impact areof utmost importance. Due to both increased fishing effort and operational inefficiencies, emissions per unit of fish landed have significantly increased over the past few decades. Emissions from mechanized and motorized vessels, particularly trawlers, are significant, highlighting the need for focused research in this area.

It is widely acknowledged that methods for lowering carbon emissions and enhancing energy efficiency in fisheries are essential to meet the larger goal of sustainable development. Energy consumption has been shown to be reduced by technological advancements in fishing gear, fuel-efficient motors, and vessel design. Practical ways to improve sustainability include energy audits, route optimization, and the use of alternative fuels like methanol, biogas, and LNG. Furthermore, switching to hybrid systems and renewable energy sources can lessen economic susceptibility to changes in fuel prices while also having long-term positive environmental effects.

Using Life Cycle Assessment (LCA) frameworks has become a reliable method for thoroughly assessing how fisheries affect the environment. LCA facilitates well-informed decision-making for operational and policy enhancements by evaluating both direct and indirect emissions across the production chain.

Notwithstanding these developments, there are still issues, such as the requirement for improved records of energy consumption trends, especially in small-scale fisheries. To reduce the environmental impact of fisheries and maintain their economic sustainability, these gaps must be filled by targeted research and policy changes. To ensure that fisheries continue to contribute to global food security in an environmentally responsible way, all the stakeholders must work together to strike a balance between resource use and economical and ecological sustainability.

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