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Comparing the end-of-life circularity potential of commercial fishing gear deployed in Norway by applying multi-criteria decision analysis (MCDA)

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ABSTRACT

Abandoned, lost, or otherwise discarded fishing gear is one of the most harmful types of marine litter globally, causing irreversible damage to ocean life and ecosystems. Therefore, global and regional policies are currently being designed and implemented to limit the influx of fishing gear into the marine environment, emphasizing the importance of circular end-of-life management of fishing gear. This study compares the end-of-life circularity potential of the six most used commercial fishing gears in Norway to identify how the heterogeneity of gears impacts their management alternatives. The main findings of the multi-criteria decision analysis (MCDA) applied in this study are that considering the economic and environmental sustainability, as well as technological feasibility of the gears' end-of-life management, purse seines have the most significant circularity potential, followed by trawls and Danish seines, while gillnets, longlines, and traps and pots are most challenging to manage according to circularity principles. Finally, some policy implications of these findings are discussed, considering especially the role of the Extended Producer Responsibility policy in the accommodation for fishing gears' circularity.

1. Introduction

Currently, there exists a minimal understanding of the life cycle and end-of-life (EOL) management alternatives for synthetic fishing gear (FG) (Gilman et al., 2021). The use of plastics in short-term applications in highly linear economies, including most marine fisheries, contributes to a variety of ecological and socio-economic issues (ibid). Abandoned, lost, or otherwise discarded fishing gear (ALDFG) is one of the most common and harmful types of plastic marine litter due to ghost fishing (Macfadyen et al., 2009). Ghost fishing occurs when gear discarded or lost at sea continues to catch fishes and invertebrates, resulting in crowding, cannibalism, starvation, injuries, and predation (Thorbjørnsen et al., 2023).

Ghost nets not only entangle commercially essential fish species but also entangle a diverse array of marine species, including sea turtles, dolphins, porpoises, birds, sharks, and seals (Do and Armstrong, 2023). These animals often swim into the nets, unable to detect them visually or through sonar. The entanglement restricts their movement, inflicts injuries, and prevents mammals and birds from surfacing for air (Stelfox et al., 2016) Additionally, ghost nets cause significant damage to coral reefs by breaking corals, exposing them to diseases, and obstructing essential sunlight (Do and Armstrong, 2023). Furthermore, the degradation of plastics generates microplastics, which, when ingested by organisms, can deliver contaminants across trophic levels (Andrady, 2011; Stelfox et al., 2016).

To the total 500 kt of yearly buoyant marine plastic influx, FG is the main contributor at 45–48 %, i.e., 220–260 kt, followed by unspecified plastic litter from coastlines (38–42 %) and from rivers (12–13 %) (Kaandorp et al., 2023). Further, a study by Richardson et al. (2022) estimates that annually, 2 % of all legal, commercial FG is lost in the oceans due to adverse weather, interactions with wildlife, snagging on a bottom obstruction, and gear and vessel conflicts (Richardson et al., 2021). However, estimates of gear losses, accumulation, and impact of ALDFG vary between gear types and geography. In Norway, the country of focus in this study, fisheries-related items dominate the litter recovered through beach clean-ups, along the whole coastline (Falk-Andersson et al., 2019), as well as the marine litter bycatch registered in the Fishing for Litter (FFL) scheme (Johnsen and Narvestad, 2023). The prominent commercial fisheries reportedly resulted in the cumulative annual loss of 780 tons of plastics from fishing gears and ropes in the

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Norwegian waters demanding urgent need to prevent and manage the fishing gear resources (Deshpande et al. 2020a, and 2023).

Stopping the influx of FG into oceans is urgent due to the negative impacts these largely non-biodegradable gears have on the ocean ecosystems. ALDFG impacts the oceans not only through ghost fishing and entanglement but through, e.g., hindering gas exchange between the seafloor sediments and seawater, damage of habitats, bioaccumulation of toxins from plastics, decline in food uptake, and reduction in the reproductive rate and mortality due to consumption of litter fractions (Urban-Malinga et al., 2018). Over 800 species are affected by marine plastic pollution globally, including all sea turtle species, more than 40 % cetacean species, and 44 % marine bird species (The PEW Charitable Trusts and Systemiq, 2020).

The urgency to transform the management methods of FG is highlighted by the increase in fishing activity and the transition to synthetic and more durable materials for FGs in the last decades (Deshpande et al., 2020a). Commercial FGs are primarily made of three plastic polymers; polypropylene (PP), polyethylene (PE), and Nylon, constituting between 60 and 90 % of materials used in production (ibid). These robust materials are ideal for catching marine life, which is beneficial when the gears are active. The robustness of the materials becomes a negative factor when gears are left unmanaged in the marine environment, as they can keep ghost fishing for decades. ALDFG also impacts fisheries and the maritime industry through, e.g., reduced catch, navigation issues, gear collisions, and entanglement with active gear and fishing vessels (Richardson et al., 2019). In addition, leakage of FG into nature contributes to the linear material use of FG, thus increasing the production of new raw materials, which leads to increased emissions from production.

The FGs used in commercial fishing in Norway vary significantly with respect to size, method of use, material composition and contamination (e.g., use of lead, copper, or other metals), repairability, cost, and ghost fishing potential (Deshpande et al., 2020b). In this study, we compare the repairability, durability when in use, threat potential to marine ecosystems, and feasibility of material recycling of the six most used commercial FGs in Norway, considering the environmental and economic sustainability, the current technological capacity, and feasibility of material recycling. We use a Multi-Criteria Decision Analysis (MCDA) framework to answer the question, "As per the current end-of-life management practices, which of the six fishing gear types demonstrates the most sustainable and circular pathways and why?"

The goal of this study is to provide knowledge to enable science-based decision-making and to assist the fishing industry in responding to regulations based on circular principles, ultimately contributing to improving the economic and environmental sustainability of FG management in Norway and other fishing nations.

2. Background

2.1. Management of fishing gear in Norway

This study investigates the EOL circularity potential of the six most typical FGs used in commercial fishing in Norway; trawls, purse seine, Danish seine, gillnets, longlines, and traps or pots. These FGs are divided into active gears that dynamically hunt the targeted species (seines and trawls) and passive gears designed to attract active fish (longlines, gillnets, and traps/pots). Norway is a major fishing nation, accounting for approximately one-third of the total annual landings in Europe (Deshpande et al., 2020a). The European Union (EU) is Norway's most important market, accounting for 60 % of Norwegian export value (FAO, 2022).

2.1.1. Fishing gear management during the use-phase

There were 9591 full-time fishers and 1226 part-time fishers, divided between 5611 fishing vessels, most of which are small-scale fishing vessels (SSF), i.e.,15 m and under, in Norway in 2022 (The Norwegian Fisheries Directorate, accessed 23.04.2024). However, while being in the majority compared to large-scale fisheries, the SSF only accounted for 10 % of the total volume of landings and 18 % of the total value of fish landings in 2013–2017. All vessels and fishing trawlers over 400 gross tons must report produced and delivered waste, while the majority of smaller vessels are exempt from reporting (Nogueira et al., 2022).

Norway has a highly complex coastline reaching over 25,000 km and manages one of the world's richest fishing grounds making Norway the European leader in commercial fishery and aquaculture (Olsen et al., 2020). There are 4443 registered ports in Norway, only 1514 of which currently have a plan for waste reception and handling (Deshpande et al., 2020a). Norway is thus failing to fulfill the obligations under the EU Directive 2000/59/EC that mandates that all EEA member states should ensure the availability of Port Reception Facilities (PRF) and waste management and handling plans in all ports (ibid).

The lack of standardized waste management in ports makes waste deliveries and sorting more difficult for fishers as they are not incentivized to sort waste onboard, and the majority end up having to dispose of everything in the same container quayside (Olsen et al., 2020). However, end-of-life fishing gear (EOLFG) with recycling potential can be separated from other waste fractions and delivered to recycling containers and sacks provided by e.g., the logistics company Nofir (ibid). While the management of waste onboard fishing vessels has improved in the last decades, due to increased awareness (ibid), some materials are still lost at sea.

Fishers are obliged to search for and attempt to retrieve lost FG or parts of FG and, if unsuccessful, report losses via an online platform called FiskInfo. The Norwegian Fisheries Ministry (NFM) conducts annual clean-up missions to collect lost gear reported by fishers. In 2023, the clean-up by NFM retrieved 1339 gillnets, 42,000 m of longline, 25,000 m of rope, 229 traps, 8000 m of trawl line, and 5000 m of Danish seine ropes. In addition, approx. 250 square meters of trawl and miscellaneous trawl parts were collected during the action, resulting in the largest ALDFG catch since NFM started the collection 40 years ago (The Norwegian Fisheries Directorate, 2023). Over 500 gillnets and 100 traps were returned to fishers, while the rest of the litter was recycled or landfilled (ibid). The rate of recycling versus landfilling of these gears is unknown. Fishers also contribute to the cleanup of the marine environment through the voluntary Fishing for Litter (FFL) scheme. Here, fishers registered in the scheme can deliver marine litter caught under regular fishing activity in assigned ports without a fee. Through FFL, 229 tons of marine litter was removed from fishing sites in 2023, 96 % of which is registered as fisheries-related litter, measured in weight (Johnsen and Narvestad, 2023).

2.1.2. End-of-life options for fishing gear

Norway's plastics economy is 78 % linear, relying mainly on petroleum-based plastic manufacturing and incineration EOL, creating 2.8 million tons of CO_2eq. annually (Systemiq et al., 2023). Due to the carbon-intensive plastics life cycle, the plastics value chain is responsible for approximately 7 % of Norway's annual Greenhouse gas (GHG) emissions (ibid). The majority of the GHG emissions from the Norwegian plastics economy come from two processes: use of petroleum-based plastics and incineration EOL. The high GHG emissions from incineration of plastic waste are partly explained by the export of waste from Norway, as approximately 50 % of plastic waste for incineration is exported out of Norway to countries relying relatively highly on fossil fuels, compared to Norway that has a 98 % renewable energy production domestically (ibid). When using 100 % renewable energy throughout the process, mechanical recycling of plastics could reduce GHG emissions by 77 %, compared to virgin plastic production (Ford et al., 2022). Thus, improving the domestic capacity to recycle EOLFG could reduce the carbon footprint of the lifecycle of FG, as well as capture the value from the waste fractions locally (Havas et al., 2022).

Due to a lack of political support, logistical challenges, lack of raw material availability (e.g., lack in pooling of resources between fisheries, aquaculture, and leisure fishing), and immature markets, the domestic recycling of FG has not been established as a competitive alternative to the other EOL pathways (Deshpande et al., 2020a). Ideally, FG would be reused, redistributed, remanufactured, and recycled as many times as sustainably possible after its first useful life before final disposal. Some pilot attempts are successfully demonstrated in Norway, where EOL plastics from FGs are recycled and used as replacements for virgin polymers in producing components for the aquaculture sector, thereby creating the business case of sustainable circularity.

In 2016, approximately 4000 tons of plastic waste were created from commercial fisheries in Norway, 55 % of which was segregated for recycling, 26 % was landfilled, and 19 % incinerated (Deshpande et al., 2020a). An MCDA study by Deshpande et al. (2020b) concluded that domestic recycling of plastic from fisheries is the most sustainable EOL alternative with respect to economic and environmental sustainability. The second most sustainable method is incineration, followed by landfilling and, finally, exporting materials for recycling. Therefore, this study considers the domestic feasibility and availability of material recycling capacity for managing FG.

In addition, while the total leakage of plastic pollution is relatively low in Norway, compared to countries with less developed waste management systems, approximately 2 % of all plastics used in Norway were estimated to leak into nature in 2020 (Systemiq et al., 2023). A scientific quantification of fisheries-related flows revealed that commercial fishing annually loses up to 380 tons of plastic in Norwegian waters (Deshpande et al., 2020a). Additionally, 383 tons of ropes are lost or discarded during operations (Deshpande et al., 2023), making the cumulative annual loss of 760 tons from commercial fishing in Norway alone. Thus, informed system interventions are needed along the whole life cycle of FG to increase the circular management of gears, the most significant impact potential being within extending product lifetime and material recycling (Systemiq et al., 2023).

3. Methodology: sustainability assessment using multi-criteria decision analysis (MCDA)

The integration of sustainability assessments into management issues is the subject of numerous case studies, guidelines, and methodologies, in which the criteria and indicators are taken into consideration, the overall goal of the assessment, and the assessment type (qualitative, semiquantitative, or quantitative) vary according to the assessment framework (Deshpande et al., 2020a). According to current sustainability theories, sustainability assessment should consider both universality and the context (Hou et al., 2018).

Accordingly, the present study aims to assess the sustainability of commercial FGs based on their ability to conserve resources upon available EOL management strategies. The evaluation will then be used to devise individual management strategies for ensuring sustainable and circular management of FGs in the region. For the assessment, we define sustainable circularity as: "*The current circular management pathway for end-of-life fishing gears which is technologically feasible, environmentally beneficial, economically profitable and socially acceptable to recover optimum material*".

Evaluating the EOL sustainability of various types of FGs is a multicriteria problem, considering the variety of dimensions pursuing diverse and frequently incompatible goals. In this sense, MCDA is an essential tool that allows the evaluation of the sustainability of different alternatives, considering the significance and/or relevance of each criterion, and the degree of uncertainty in the data. In the present investigation, we consider an approach for evaluating the EOL sustainability of different types of FGs using MCDA as the base. A number of MCDA methods are proposed in the literature, distinguished by particular mathematical properties that have different implications (Deshpande et al., 2020b). Multi-Attribute Value Theory (MAVT) was chosen among several MCDA methods due to its suitability for the participatory process, its flexibility, simplicity, transparency, robustness in eliciting stakeholder preferences, ability to handle both quantitative and qualitative data, as well as its successful application in other sustainability assessments (Deshpande et al., 2020b; Ferretti et al., 2014; Osterwalder et al., 2014).

The MCDA framework proposed in this study adopts the method proposed by (Deshpande et al., 2020b), and adjusts it to the local situation and the relevance of the case. Fig. 2 shows the steps that will be followed to address the sustainability of the alternatives. The MCDA is applied here to define and prioritize indicators using an expert's judgment. The six FGs were assessed to determine which are most sustainable in recovering the material while preserving selected sustainability criteria. Additionally, the analysis will be explored further to understand the barriers and opportunities to improve the overall sustainability of the FG system in Norway.

The data collection started on 31st of January 2023 and lasted for 17 months, including interviews with the significant recyclers (both chemical and mechanical recyclers of EOL FGs), surveys with fishers, data analysis, application of the MCDA framework and presentation of results.

3.1. Definition of the goal and system boundaries

This step involves the definition of the main goal of the decision-making process and the boundaries of the system to be evaluated. The goal of the study is to rank the six most used FGs available in commercial fishing in Norway in terms of their potential for sustainable downstream management. The main focus is on how gears are managed when they lose some or all of their catch capacity, e.g., whether they are repaired during use, and recycled, reused, incinerated or landfilled after their first useful lifetime. Moreover, Norway as a geographical territory was selected as the system boundary for the analysis, which implies that all monetary and material flows outside Norway are not considered in the assessment. Similarly, the analysis is adapted specifically to commercial fishing in Norway and the gears used within the territory.

3.2. Definition of the alternatives to evaluate

This step considers the definition of the alternatives that will be evaluated and ranked. The alternatives are context-dependent and must be within the system boundaries. Six different alternatives were considered in the present study: trawl, purse seine, Danish seine, longlines, gillnets, and traps or pots. Figures related to each of the FG types considered in this study can be found in Appendix 1.

3.3. Selection of the sustainability pillars and assessment criteria

This step requires first the identification of the sustainability pillar that would be considered in the approach. When holistically analyzing the sustainability of a system, the triple-bottom-line approach with the environmental, economic, and social dimensions is to be considered (Elkington, 1998). However, for this assessment, technical capacity is added as one of the dimensions, as this is considered a central factor when designing and implementing management alternatives for FG. For the present study, the social dimension was not considered, as the social aspects that related to e.g., health and safety or employment levels were considered as irrelevant when comparing the management of gears within Norway. These social aspects would have been relevant e.g., a comparison of plastic waste management between geographical regions with heterogeneous health and safety regulations. Each of these pillars must have associated assessment criteria, and usually, a balance between the number of indicators is recommended (Lund et al., 2023).

Moreover, considering that the alternatives are ranked and evaluated based on the assessment criteria, performing an extensive and balanced criteria selection process is important. A review of the literature served as the foundation for the initial criterion selection, which was then improved through stakeholder interviews. It is standard procedure in

Table 1
The selected assessment criteria.

Assessment criteria	Question and information that defined the assessment criteria	Unit	Goal	Method of data collection	Scale of measurement considered	Reason for selection of scale
T1. Effectiveness of the recycling process	How would you rate the six gears according to how effectively they can be processed for recycling, with respect to energy and resource use?	Rating number	Maximize	Interviews with recyclers	1 (impossible to recycle) – 5 (easy to recycle)	Limits of rating exercise
T2. Annual recycling capacity covered	What is the annual recycling capacity of the different gears? This information was further divided into the expected plastic waste generated by each type of fishing gear, considering the 4000 plastic waste generated from commercial fishing, and the relative weight of gears according to the quantities purchased by commercial fishing fleets (Deshpande et al., 2020b).	%	Maximize	Interviews with recyclers, literature review	0 to 100 %	Percentage limits
T3. Efficiency of transportation according to volume per weight	Which gear can be relatively efficiently transported with respect to volume per weight?	Rating	Maximize	Interview with recyclers	1 (least efficient) – 5 (most efficient)	Limits of rating exercise
T4. Fishing gear repairability	On average, what % of the following fishing equipment (that you use yourself) is repaired annually?	%	Maximize	Fisher's survey (combined with the fishers' survey of Deshpande et al., 2020b)	0 to 100 %	Percentage limits
EN1. Threat potential to marine ecosystems	On average, what type of fishing gear do you pick up during normal fishing activity, such as marine litter? Adjusted my multiplying with data from average adverse ecological and socio-economic outcomes from ALDFG (Gilman et al., 2021).	Number	Minimize	Fishers' survey, literature review	0.07 to 24.5	A local scale was used, considering the highest value calculated for one of the gears as the upper level.
EN2. Risk of FG loss during operation	On average, what type of fishing gear do you catch as marine litter during normal fishing activity?	%	Minimize	Fisher's survey (combined with the fishers' survey of Deshpande et al., 2020b)	0 to 5 %	5 % was selected as upper limit based on Richardson et al. (2022)
EN3. Efficiency of the recycling process	What is the estimated percentage of material recycled when processing the different gears? (Material that is not loss)	%	Maximize	Interview with recyclers	37 % to 95 %	Limits of the scale were established according to the ranges set for the questions to recyclers.
EN4.Durability of FG (life span)	What is the typical lifespan of the different fishing gear you use?	Years	Maximize	Fisher's survey (combined with the fishers' survey of Deshpande et al., 2020b)	1 to 10	Expected range of durability of fishing gears
EC1. Cost of processing into new materials	What is the cost of processing the gear to new materials	Rating	Minimize	Interview with recyclers	1 (very low relative cost) – 4 (very high relative cost)	Limits of rating exercise
EC2. Average revenues from recyclables	What is the average revenue from sale of materials recycled from the used gear?	Rating	Maximize	Interview with recyclers	1 (very low relative revenue) – 4 (very high relative revenue) 0: No revenues expected, as it is no possible to recycle	Limits of rating exercise

MCDA studies to select and rank assessment criteria based on expert knowledge (Deshpande et al., 2020b; Tsai, 2018; Tsai et al., 2018). As a result, a questionnaire was created and disseminated.

The selected criteria, broken down into the technical (T1–4), environmental (EN1–4), and economic (EC1–2) pillars, are shown in Table 1. The criteria are defined in terms of the name of the assessment criteria, description of question used to define the assessment criteria, unit of measure, goal, method of data collection, scale of measurement considered, and reason for selection of scale.

3.4. Assignation of weights based on stakeholder responses

Using the same questionnaire for criteria selection, responses were gathered and condensed, and further transformed into weights for both the sustainability pillars and the specific assessment criteria considered, based on the following equation:

$$W_i = \frac{S_i}{\sum_{i=1}^{n} S_i}$$

where n is the number of criteria being weighted within that specific group of criteria or sub-criteria, Wi is the weight of criterion i, and Si is the score in points assigned to criterion i.

3.5. Data collection and quantification of indicators

Both qualitative and quantitative criteria were considered in this investigation. The specifics about the data collection used and estimation for the different indicators are elaborated in the Supplementary Materials.

Table 2
Weights of sustainability dimensions and assessment criteria.

Assessment criteria	n	Mean	St. dev	Weight
Technical capacity	18	4.56	0.51	34.34 %
Environmental sustainability	18	4.44	0.62	33.43 %
Economic sustainability	18	4.28	0.67	32.23 %
T1. Manageability of the recycling process	18	3.78	0.94	22.84 %
T2. Annual recycling capacity covered	18	4.44	0.62	26.83 %
T3. Efficiency of transportation according to volume per weight	18	4.22	0.88	25.50 %
T4. Fishing gear repairability	18	4.11	1.18	24.83 %
EN1. Threat potential to marine ecosystem	18	4.17	0.86	25.44 %
EN2. Risk of FG loss during operation	18	4.61	0.5	28.13 %
EN3. Efficiency of the recycling process	18	4.11	0.58	25.08 %
EN4.Durability of FG (life span)	18	3.5	1.34	21.35 %
EC1. Cost of processing into new materials	18	4.17	0.99	51.04 %
EC2. Average revenues from recyclables	18	4	0.77	48.96 %

3.6. Normalization of indicators

Values obtained from the indicators were normalized using either a global or a local scale (see Table 1) and adapted to the goal related to each indicator. Taking into consideration the goal of the indicator (maximize or minimize), the best-performing alternative was given the higher score (1), while the lowest-performing alternative received the lowest score (0). The normalized values should be viewed in relation to one another within each criterion rather than being added together to produce a meaningful value (Lund et al., 2023).

3.7. Application of the MCDA methodology and final ranking of alternatives using MAVT

This step considers the application of the MCDA methodology. Every criterion in MAVT has a goal that is specified (see Table 1). DECERNS (Decision Evaluation in ComplEx Risk Network Systems) software was used for the analysis (Deshpande et al., 2020b). The application of DECERNS in the mapping and resolving multi-criteria problems in the context of environmental and sustainability assessment was effectively demonstrated by Linkov and Moberg (2011).

For applying this method, it is necessary to establish value functions to quantify each alternative's overall performance by combining the results of all criteria into a single total value (Belton and Stewart, 2002). This study uses a linear additive function to rank the alternatives by summing the scores and weights of the various criteria, adapted according to Belton and Stewart (2002).

$$V(A) = \sum_i W_i V_i(A_i)$$

where *Wi* is the weight that the stakeholder group assigned to criterion *i*, *Vi(Ai)* is the performance of alternative *A* on criterion *i*, and *V(A)* is the overall value function for alternative *A*.

3.8. Sensitivity analysis to interpret the results

A sensitivity analysis of the three primary dimensions was carried out to evaluate the degree to which the results were dependent upon modifications in the weights. Sensitivity analysis is recommended by Pesce et al. (2018) to verify if the results are robust to weights. In order to maintain the weighted total of 100, each criterion was modified independently, and the other weights were automatically adjusted proportionately. Moreover, in the Supplementary Materials, we present a further sensitivity analysis of changes in each indicator.

4. Results

4.1. Assessment of stakeholder responses

A group of experts was invited to contribute to the process of defining and weighing the indicators. All experts work within the development of circular solutions for fishing and fish farming gear, as the questionnaire (to be found in Supplementary Materials) was presented at the SHIFT-Plastics project workshop in Bodø 2nd of May 2023. After the presentation, the survey was sent out, and the attendees filled it out anonymously. A total of 18 responses were received, 10 from researchers within life cycle analysis, EOLFG management, FG technology, fisheries technology, and biology, while eight represent industries (i.e., FG recyclers, pollution control, circular industrial plastic systems, and aquaculture management).

Firstly, the stakeholders were asked to rate the importance of the three dimensions of sustainability namely, environmental sustainability, economic sustainability, and technological feasibility, for achieving EOL circularity for FG. While not differing vastly, the stakeholders evaluated technological feasibility as the most critical factor at 34.34 %, environmental sustainability as the second most important factor at 33.43 %, and economic sustainability as the least essential factor at 32.23 %. Further, the stakeholders were asked to evaluate the existing indicators defined by the authors, add comments on any missing indicators, or suggest changes to the existing ones. Additionally, the sub-criteria for each main criterion were shortlisted using stakeholder input, and then these sub-criteria were weighted using the MAVT equation specified in the Methodology section. Table 2 shows more detailed data on the weights assigned by stakeholders for the criteria. According to stakeholders, the sub-criteria 'Annual recycling capacity covered' (26.83 %) was the most important among the technical capacity dimension, while less importance was assigned to 'Manageability of the recycling process' (22.84 %).

Meanwhile, for the environmental dimension, the highest importance was assigned to 'Risk of FG loss during operation' (28.13 %), while the lowest weight was allocated to 'Durability of FG (life span)' (21.35 %). For the economic dimension, relative uniform weights were obtained, with slightly more importance placed on costs over revenues. To visualize this process and its results, the MAVT model tree was developed as shown in Fig. 3.

4.2. Performance assessment of alternatives

The data collected from different stakeholders was used to quantify the diverse indicators. Firstly, in-depth interviews were conducted face-to-face with two local gear recyclers. Here, the recyclers were interviewed based on a survey with open-ended and multi-choice questions. Secondly, a survey was sent to 120 Norwegian fishers by email. The autonomically filled survey with open-ended and multi-choice questions received 32 responses. The surveys can be found in the Supplementary Materials. Moreover, the survey results of fishers were combined with the previous survey by Deshpande et al. (2019).

Table 3 and Fig. 4 show the performance of the six different FGs against the criteria. Regarding the technical indicators, using the inputs from recyclers, it was found that trawls and purse seines have the best performance in the manageability of the recycling process (T1) and the efficiency of transportation according to volume per weight (T3). Meanwhile, considering the annual recycling capacity determined by recyclers for each FG with the expected plastic waste generated by each

Table 3
Performance of alternatives.

Assessment criteria	Unit	Trawl	Purse seine	Danish seine	Gillnet	Longline	Traps/pots
T1. Manageability of the recycling process	Rating number	4.5	4.5	4.0	3.5	2.5	2.0
T2. Annual recycling capacity covered	%	0.1	0.3	0.6	0.6	0.0	0.0
T3. Efficiency of transportation according to volume per weight	Rating	4.5	4.5	4.0	1.0	1.0	1.0
T4. Fishing gear repairability	%	64.7	46.4	35.6	24.1	36.9	24.9
EN1. Threat potential to marine ecosystem	Number	2.6	0.1	0.3	24.5	5.6	11.2
EN2. Risk of FG loss during operation	%	3.8	0.5	1.2	1.1	4.2	4.1
EN3. Efficiency of the recycling process	%	82.0	95.0	75.3	86.3	37.0	37.0
EN4.Durability of FG (life span)	Years	2.8	8.9	4.1	2.2	2.9	6.1
EC1. Cost of processing into new materials	Rating	2.5	1.5	3.0	3.0	4.0	4.0
EC2. Average revenues from recyclables	Rating	2.3	3.7	2.0	1.7	0.0	0.0

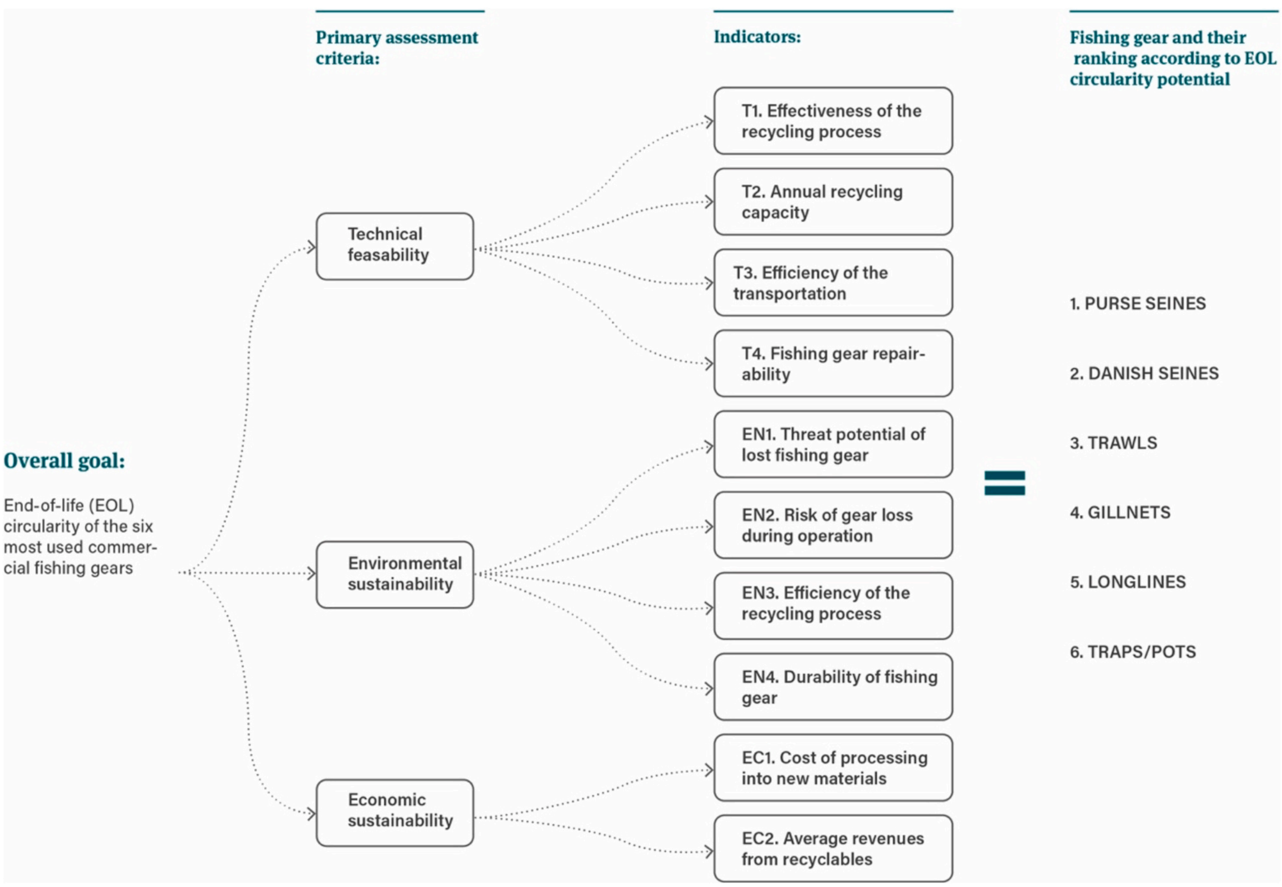

Fig. 1. The graphic abstract presents the MCDA decision tree, including the ranking of the six most used commercial fishing gears. The ranking shows that purse seines have the highest EOL circularity potential, while pots or traps have the lowest.

of them, it was found that gillnets are the gears offering the highest annual recycling capacity covered (T2). Further, from input from fishers, it was found that trawls offered the highest relative FG repairability (T4).

Regarding the environmental criteria, we found that purse seines overperform all the other FGs in all the indicators. The information filled by fishers suggests purse seines have the lowest risk of FG loss during operation (EN2) and the highest life span (EN4). Additionally, purse seines have the lowest threat potential to marine ecosystems (EN1) according to fishers and literature and the best efficiency in the recycling process (EN3) according to recyclers.

Finally, for the economic criteria, we also found that purse seines overperform other FGs, as according to recyclers, they offer the lowest cost of processing into new materials (EC1) and the highest average revenues from recyclables (EC2).

4.3. Final ranking of alternatives

Every alternative was assigned a linear value function evaluation following the recording of weights, the performance of each alternative against the assessment criteria, and the scales defined for each indicator. Fig. 5 shows the final ranking of EOL alternatives based on the DECERNS software output using the MAVT method. Purse seines turned out to be the best performing option among the different FGs, while longlines and traps or pots came in last place.

4.4. Sensitivity analysis

Considering the possible subjectivity assigned to the weights of the different criteria, the ranking of the alternatives found might also be subjective (Deshpande et al., 2020b). As a result, we analyzed the robustness of the model by performing a sensitivity analysis that

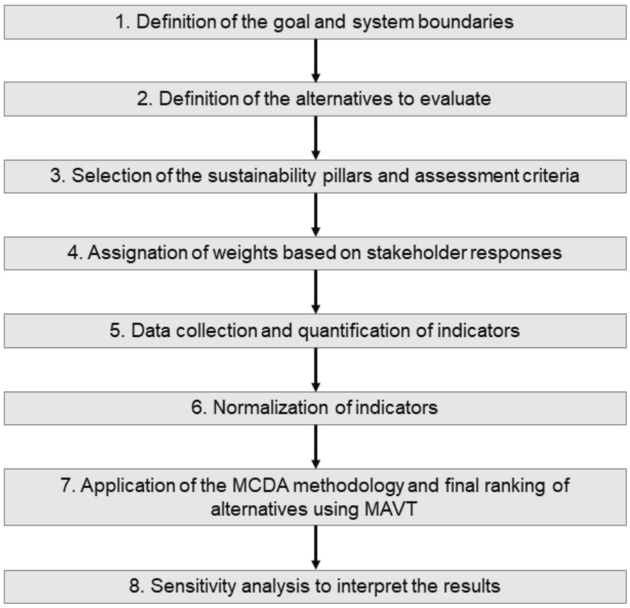

Fig. 2. Proposed stepwise method for MCDA (from Deshpande et al. (2020b)).

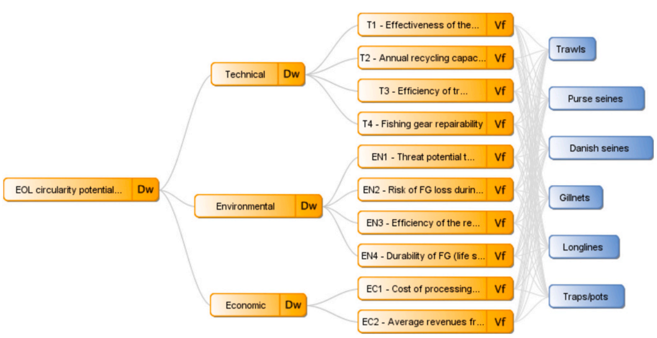

Fig. 3. The MCDA model tree depicting the overall goal, primary assessment criteria, indicators, and the six fishing gears chosen for comparison.

considers the effect of changes in the weights assigned by stakeholders. For this, we independently varied each of the three pillars sustainability dimensions considered (technical, environmental, and economic) while leaving the other two to vary in proportion to their original scores. The results of this analysis are presented in Fig. 6. The sensitivity performance of sub-criteria was also evaluated, and the results are available in the Supplementary Materials.

The sensitivity of the alternative outcomes is evaluated by varying the importance of the technical criteria in the first chart (Fig. 6a). The chart shows that irrespective of the weight assigned to the purse seines, they dominate all other gears, and only small differences emerge if weight is set to close to 1 (only technical criteria considered), as trawls and Danish seines seem to tie with purse seines. Minor differences are also observed for the lowest performance alternatives, as with the current weight of 0.34 for the technical dimension, longlines perform slightly better than traps or pots, while with a higher weight on the technical dimension, this gap increases slightly.

Moreover, Fig. 6b shows the sensitivity outcomes when the weight importance of the environmental dimension is considered. The figure reveals that regardless of the weight assigned, purse seines emerge as the best alternative. More relevant changes occur for the second position, in which trawls become a better alternative than Danish seines if the importance of the environmental criteria is lowered. Slight differences are also observed for the lowest performance alternatives, as traps/pots emerge as a better alternative than longlines after the environmental dimension is given a weight of around 0.54.

Finally, Fig. 6c shows the sensitivity of the results against changes in the weight of the economic dimension. Similar to the other two dimensions, purse seines perform better regardless of changes in the weights of the economic dimension. However, for the second most preferred alternative, we found that trawls outrank Danish seines if the weight of economic criteria is above 0.4.

In summary, the sensitivity analysis revealed that purse seines are the most favorable FG in terms of circular EOL management of the six most used commercial gears deployed in Norway, regardless of the weights allocated to the three dimensions. However, trawls may outrank Danish seines as the gear with the second highest circularity potential is of higher importance to the economic dimension (weight above 0.4), or less weight is assigned to the environmental dimension (weight below 0.25). In addition, the robustness of the presented rankings is reaffirmed by the sensitivity analysis of the sub-criteria in the Supplementary Materials.

5. Discussion

The results from this study can be applied to management strategies as a response to policies that require increased EOL circularity of FGs, or even contribute to the development of knowledge-based policies to sustainably manage FG, as described under.

5.1. Relevance to global policies on EOLFG and ALDFG

Currently, there are several international agreements that focus on eliminating ALDFG influx, listed in e.g. James (2023), but a lacking national focus on incentivization of circular value chains for FG in Norway (Deshpande et al., 2020b). However, the European Commission's (EC) Circular Economy Action Plan (CEAP), adopted in early 2020, supported by the European Union's (EU) Single-use Plastics Directive, and including an Extended Producer Responsibility (EPR) scheme for FG, puts pressure on Norway to adopt EPR policies for FG. This scheme directs responsibility for covering the cost of separating, transporting, and treating plastics FG onto producers, potentially impacting the EOLFG recycling market in Norway (James, 2023). The EPR scheme for FG is to be implemented by the end of 2024, at the same time as the potentially first international Treaty to End Plastic Pollution, which is to be implemented by the United Nations member countries. The development process of the treaty is ongoing, and FG is mentioned in the revised Zero Draft e.g., in relation to the need for environmentally responsible disposal or recycling of EOLFG (UNEP, 2023). While the final formulation regarding requirements for EOLFG management is expected to be in place by the end of 2024, the revised Zero Draft of the treaty pointing to the importance of sound EOL management of synthetic FG, including recycling, suggests that fisheries can proactively begin planning for increased focus on management of gears according to sustainable circularity.

5.2. Strategies for sustainable circularity of EOLFG

While the introduction of global standards for FG management set the framework for ALDFG reduction, the successful improvement of FGs' EOL circularity, and thus reduced ALDFG influx, requires the consideration of local conditions, such as maturity of the market for recycled materials and fishers' awareness the importance of circular management of gears. The creation of circular value chains for FG in Northern Europe calls for stakeholder cooperation, taxation to support recycling and reuse, and regulatory interventions to stop the mismanagement of materials (James, 2023). Recycled plastic materials, especially sourced from marine industries or through marine litter cleanups, have traditionally been relatively costly to process into new, high-quality raw materials, due to e.g. material complexity (Dijkstra, 2023), highlighting the need for regulation that supports circularity and discourages linear

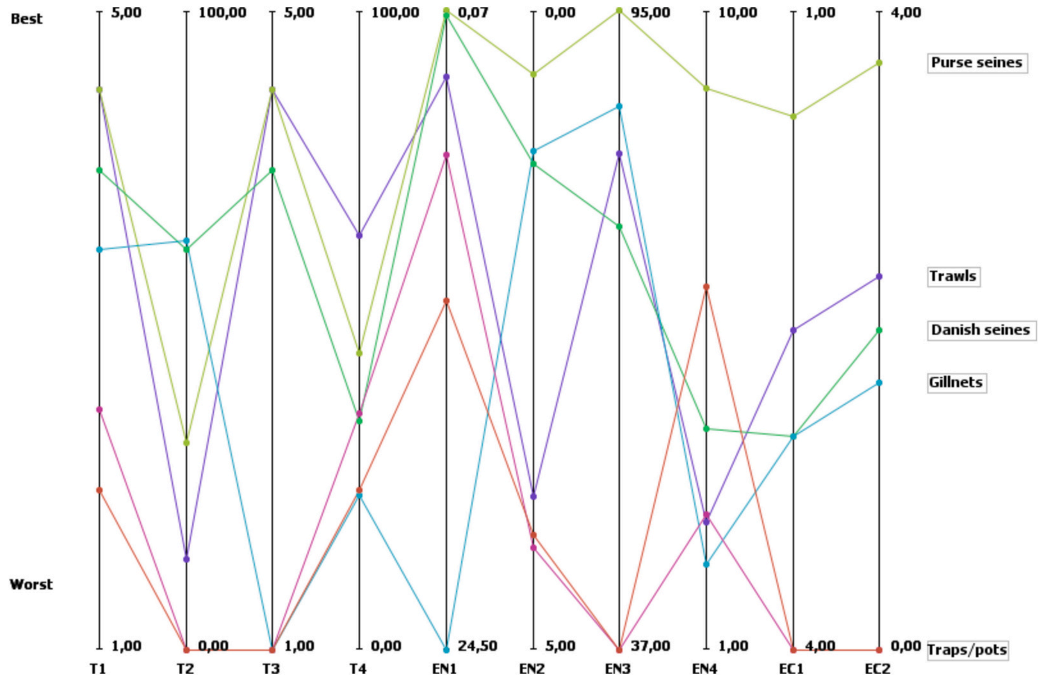

Fig. 4. Performance of alternatives according to the scale.

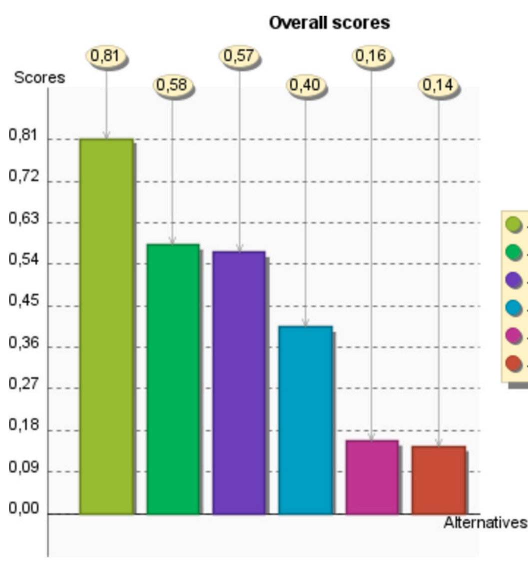

Fig. 5. Overall ranking of the end-of-life circularity potential of the six most used commercial fishing gear deployed in Norway.

material management of FG in Norway (James, 2023; Deshpande et al., 2020b; Olsen et al., 2020). Implementation of EOL circularity incentives for FGs in Norway is already underway, mainly driven by the private sector. Private recycling and logistics companies have begun developing EOL solutions for FG, based highly on increased material recycling. There is a lack of academic understanding of these private initiatives, or "sustainable plastic business models" (Dijkstra, 2023), which is why broad industry analyses are needed. Such analyses will contribute to the understanding of the drivers and barriers of developing sustainable business models around plastics (ibid), including commercial EOLFG. The MCDA conducted in this study continues from the work of Deshpande et al. (2020b) and shows that there is significant heterogeneity within the EOL circularity potential of the commercial FGs deployed in Norway, thus contributing to the knowledge to streamline circularity strategies for these gears, based on the assumption that domestic recycling is the environmentally and economically most sustainable EOL strategy for Norwegian FG in general (Deshpande et al., 2020b).

According to the analysis conducted in this study, Purse seines have the highest circularity potential EOL, considering even adjusted weights for the environmental, economic, and technical dimensions, suggesting that Purse seines need relatively little adjustments, e.g., material composition and management methods to achieve full circularity potential. Thus, making adjustments to, e.g., repairability of these gears might improve their circularity, aligning also with the recommendations made by Systemiq et al. (2023) that describe recycling and increased life span as the preferable circularity strategies for FGs in Norway. In contrast, longlines and traps or pots have relatively low EOL circularity potential, signaling a need to consider more profound changes along the gears' life cycle. According to the recyclers interviewed in this study, there are currently no recycling alternatives for these gears in Norway, and they pose a significant threat to the marine environment due to their ghost fishing potential.

It is important to note that while purse seines, Danish seines, and trawls can be managed in line with the principles of a circular economy, there is minimal separation of waste FGs in Norway. Collection and transport of mixed waste gear fractions that are often laden with dirt, biomass, and rotten fish/fish oil are among the critical barriers to effective recycling (Deshpande et al., 2020a). Furthermore, the mixed EOLFGs and ropes often consist of diverse materials such as PP, PE, and PA, with some secondary gear parts containing metal cores or coatings. Waste managers often lack insight into material properties. The unfamiliarity with a material composition causes stakeholders to lack knowledge, resulting in lower recycling rates and an inability to recycle FGs into high-quality recycled pellets with significant economic value (Deshpande et al., 2023). Such knowledge gaps on EOLFG waste handling result in the sub-optimal recycling of 'recyclable fractions' of FGs such as purse seine, Danish seine, and trawl nets, as discussed in this study. Therefore, the findings in this study can provide inputs on designing new facilities to ensure the recyclable fractions are segregated and managed effectively to recover materials, aligning with the upcoming EPR. At the same time, alternative design approaches or management methods are considered for the difficult-to-recycle gears, such

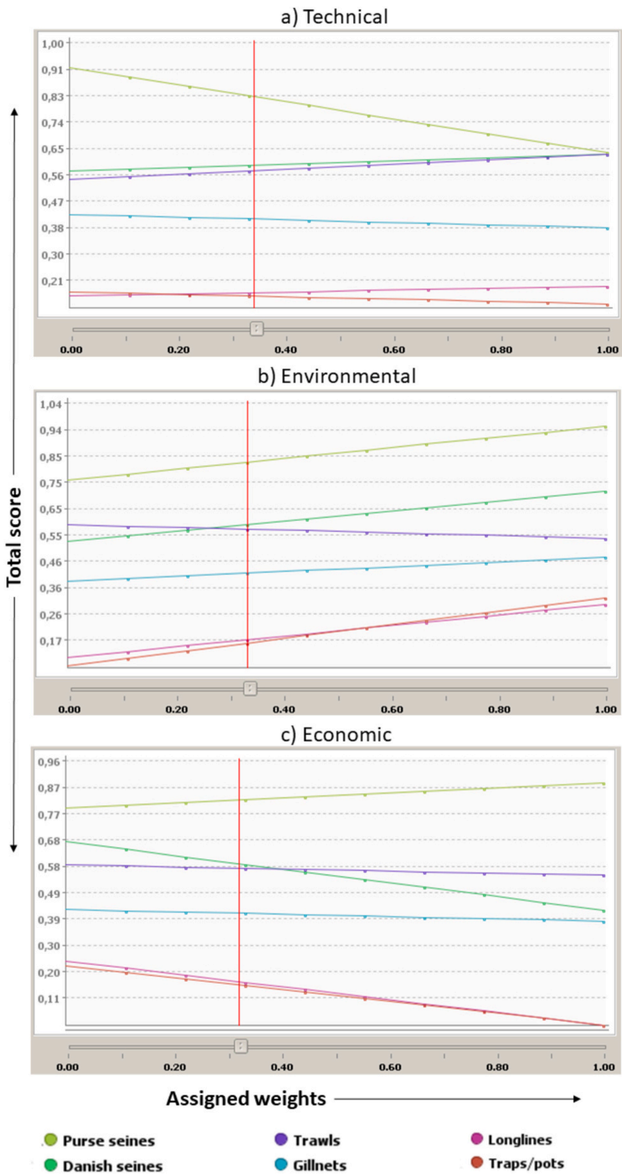

Fig. 6. Sensitivity analysis based on changes in a) Technical, b) Environmental, and c) Economic impact criteria.

as longlines and traps. In Taiwan, attempts are made to encourage fishers to recycle their fishing nets rather than discard them, and the Ocean Conservation Administration also collaborated with local governments on setting up segregating, sorting, and recycling stations in ports and increase recycling values to provide the economic incentives (Su et al., 2023), similarly working with fishers can be pivotal in improving the source segregation of recyclable fishing gears to improve material recycling.

Fig. 7 below presents the ranking of FGs based on the MCDA results. As these results are obtained by including a practical assessment of the system through relevant expert stakeholders, they offer valuable insight into which FGs should be marked and tracked from purchase to the end of their useful life to facilitate material recovery, as mentioned in the EPR regulation. Furthermore, these results could support the Food and Agriculture Organization's (FAO) draft of gear marking and encourage the inclusion of “Recyclability” criteria to highlight the economic benefits of recovered FGs (Einarsson et al., 2023). The ranking is not just a list, but it can be used as a practical tool by authorities to create the priorities for efficient collection, handling, pre-treatment, segregation, and delivery of recyclable FGs to improve the resource efficiency of the fishing sector. The ranking can also be used to prioritize ports across the Norwegian coastal region to establish Port Reception Facilities (PRF), which can act as a first step to meeting requirements set-up by the EU's PRF directive (Osmundsen, 2023) and to ensure fishing boats have regulated facilities to dispose of the EOL FGs, leading to better collection and recycling of the recyclable gears.

5.3. *Limitations and future work*

Considering these results in a greater context of fisheries management, a discussion of whether there is a need to accept the potential increased cost of gear, reduced functionality, and/or reduced catch potential of gear to improve the design-for-recycling and to reduce gear losses and ghost fishing might be relevant. For example, a consideration of whether there is too much fishing activity in general and if fishers should be paid not to fish in certain areas using specific methods (e.g., bottom trawling in vulnerable areas or areas prone to bottom snagging) to remove pressure and improve the long-term sustainability of fisheries?

In developing this study, we investigated, e.g., the profitability of the different gears when they were in use to determine the value of these gears according to the service they deliver. While this assessment landed outside the scope of this study, such an analysis of the different FGs added value through e.g., catch-per-unit-effort combined with the least negative impact on the environment throughout the gears' life cycle could be an interesting research focus on contributing to more sustainable fisheries management. Related questions have been discussed in the literature previously and are very relevant with respect to future systems analyses on FG management and regarding holistic policy development (Loris, 2023; Pauly et al., 2002; Aanesen et al., 2018). The social aspect of limiting fishing activity is also highly relevant, as a fifth of the world's population relies on fish for their daily protein intake (Cai and Leung, 2022).

Acknowledging such holistic considerations for sustainable gear management from production to sustainable use, and responsible disposal, rather than isolating the management of synthetic fishing gear in its sustainability strategy, can assist in finding ways to transform the currently wasteful and linear plastics economy within which FGs are managed to a fair and sustainable, circular economy where fisheries operate sustainably, improving not only the rate of recovery of the world's oceans, but the future access to sustainable fish and seafood, and thus the industry's own long-term survival. Simultaneously, to understand requirements for a systemic change from linear FG management to a circular system, literature on plastics' management suggests the application of “managing sectors, while monitoring compartments” (Erdle and Eriksen, 2023), as all plastic use sectors and even product groups within, as shown by this study, require customized circularity strategies.

6. Conclusion

In this study, we have compared the EOL circularity potential of the six most used commercial FGs deployed in Norway, considering the technological capacity and environmental and economic sustainability of managing the different gear. By conducting an MCDA, we found that purse seines have the highest EOL circularity (recyclability) potential and overperform other gears, considering all three aspects. Purse Seines' lead was not threatened even in the sensitivity analysis. However, they tied with trawls and Danish seines when the technical dimension was only considered (i.e., weight ca. 1). Longlines and traps or pots displayed the poorest EOL circularity potential, imposing the highest threat to marine ecosystems and lacking any recycling alternatives. Thus, EOL circularity can be improved through some specific design and management improvements, such as the top three gears, i.e., purse seines, trawls, and Danish seines. In contrast, the improvement of longlines, traps, and pots' circularity EOL requires changes along their life cycle

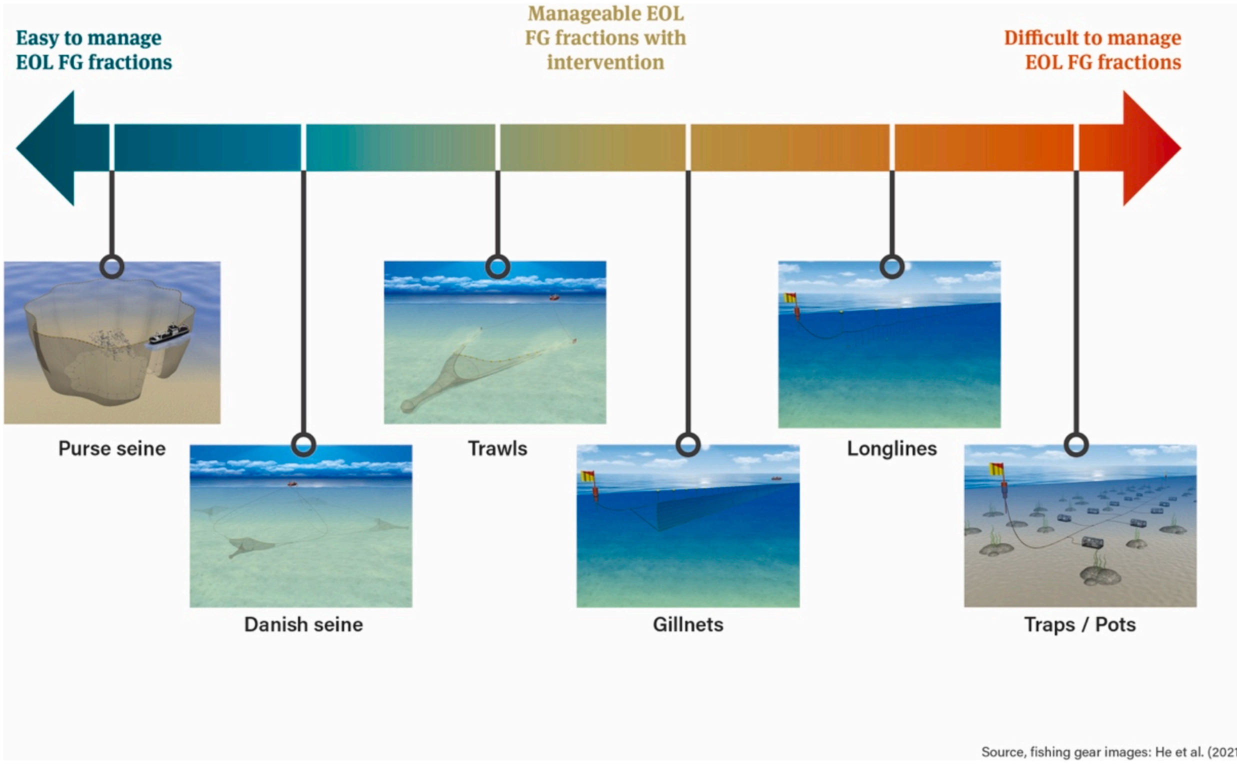

Fig. 7. Ranking of fishing gears as per circularity potential and ease of management upon end-of-life phase based on the Multi-Criteria Decision Analysis study results for the commercial fishing gears deployed in Norway.

from design for durability to more stringent regulations and better management strategies to avoid material losses into the sea and, thus, ghost fishing.

The results of this analysis potentially contribute to the increasingly effective development and implementation of policies based on circularity principles and targeted management strategies that respond to policy requirements according to the circularity potential of the specific gears. While we highlight the need to consider the local and gear-specific challenges and opportunities with respect to circular development, more knowledge is needed to holistically manage gears within the industry that has an increasing environmental and socio-economic impact. In addition to the fisheries management discussion above, gear-specific system improvements are needed, such as increased traceability of gears globally, i.e., tracking and monitoring of the production, use, and disposal of gears more accurately - and as a result, measurement of changes in gear use over time and across locations. Also, future research should consider the quality of recycled FGs and the potential for multiple recycling cycles, thus expanding from the results of this study.

CRediT authorship contribution statement

Vilma Havas: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Javier Cantillo:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Paritosh C. Deshpande:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vilma Havas reports financial support was provided by Research Council of Norway. Paritosh Deshpande reports financial support was provided by Research Council of Norway. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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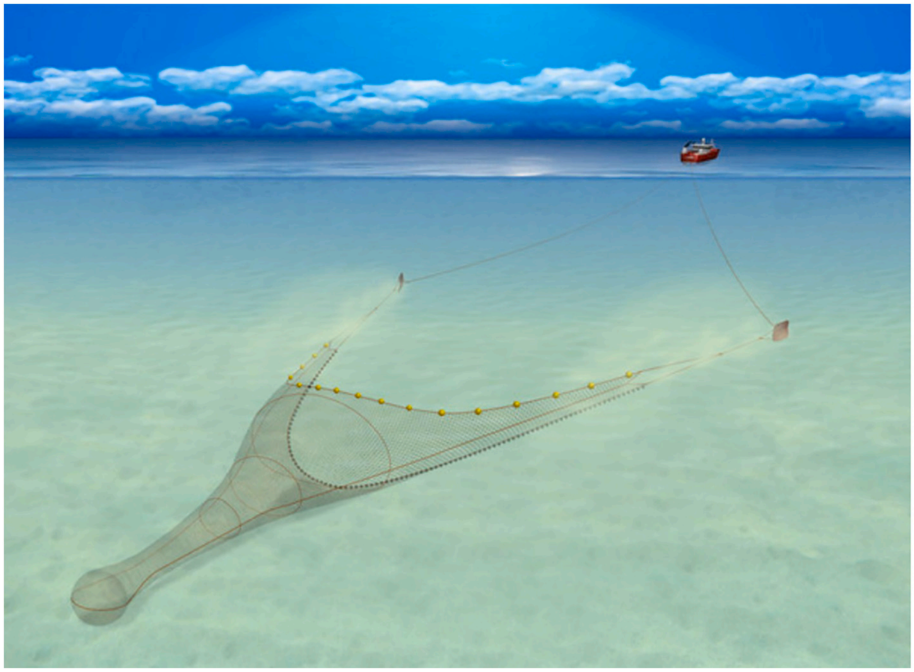
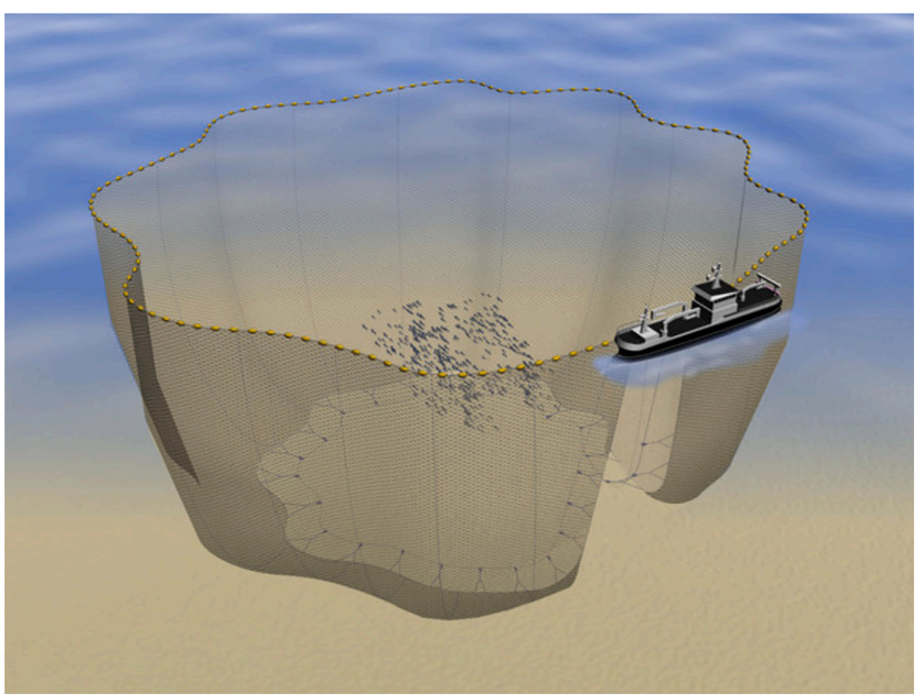
Appendix 1. The FG analyzed in this study

1. Trawl



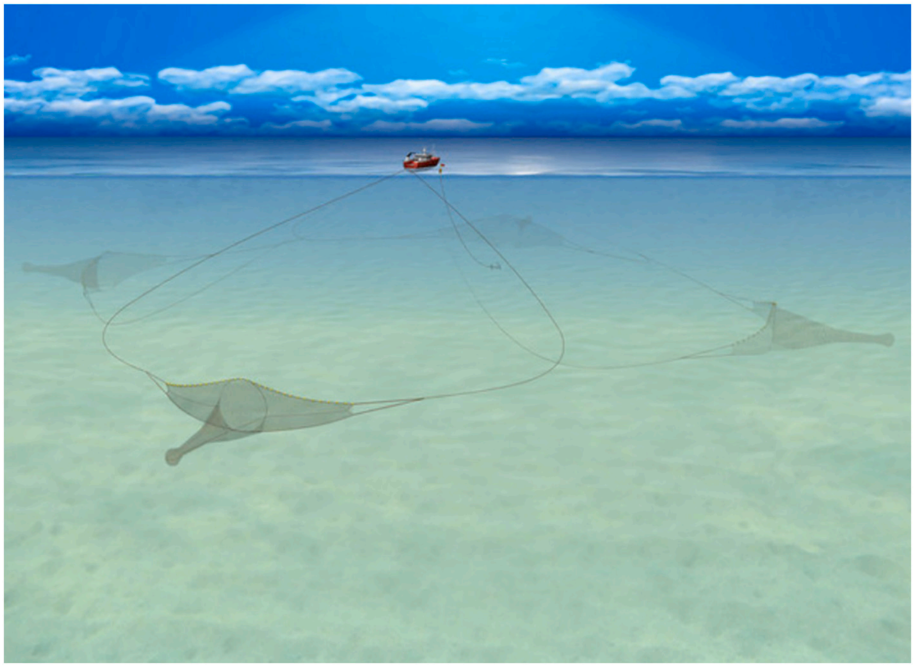
Source: He et al. (2021).

2. Purse seine



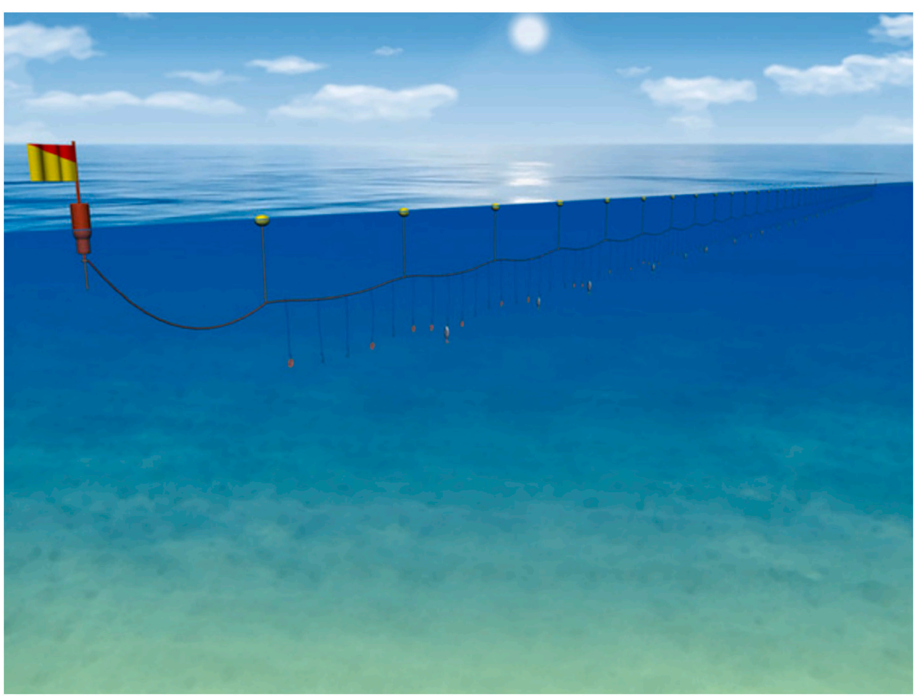
Source: He et al. (2021).

3. Danish seine



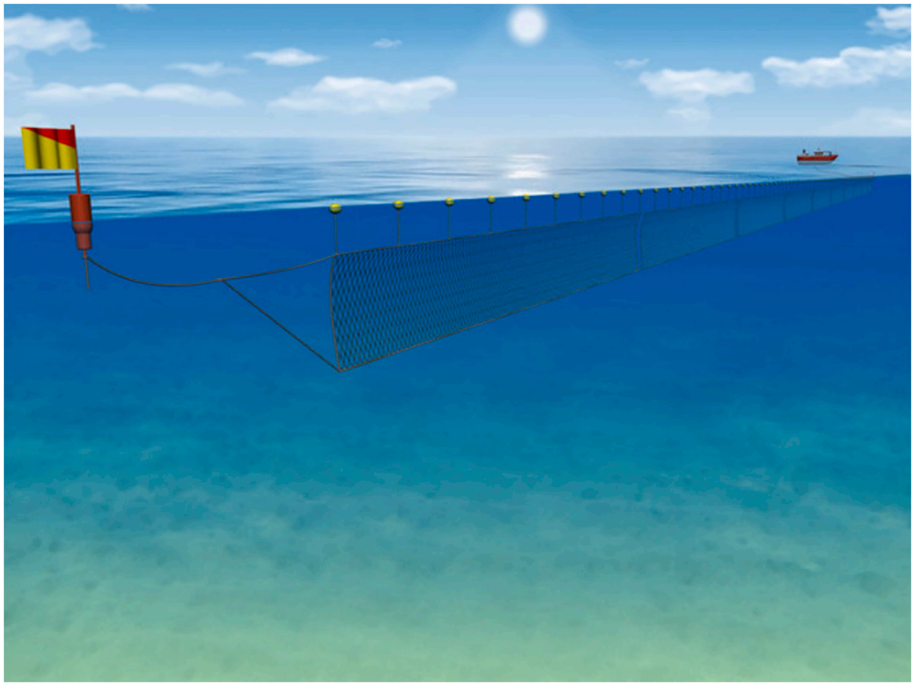
Source: He et al. (2021).

4. Longlines



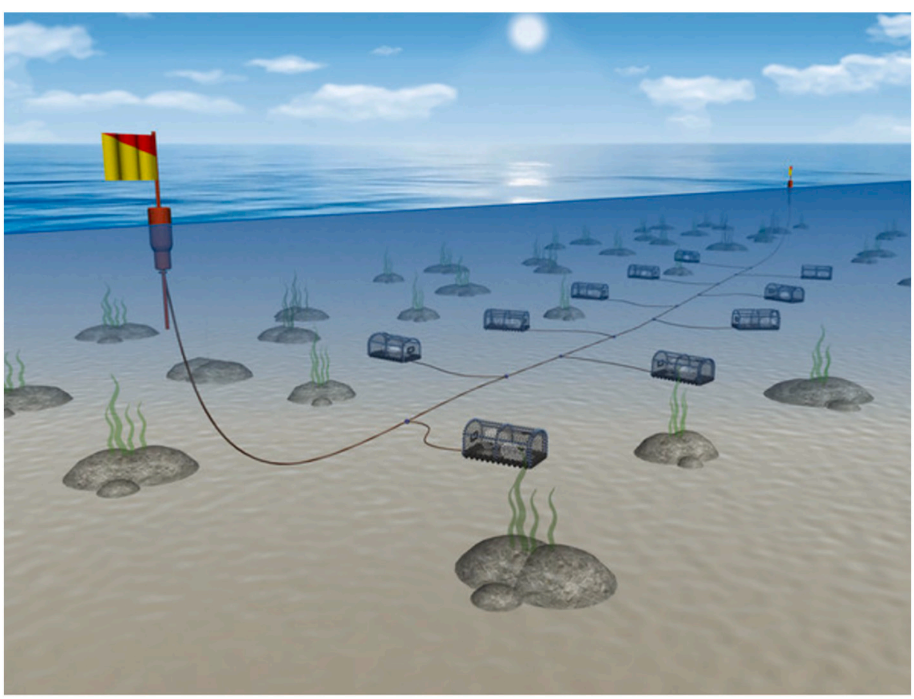
Source: He et al. (2021).

5. Gillnets



Source: He et al. (2021).

6. Traps/pots



Source: He et al. (2021).

Appendix 2. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117066.

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