Marine Pollution Bulletin 197 (2023) 115798

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Multi-stakeholder perspective to generate evidence and strategies for sustainable management of ropes from the fishing sector of Norway

Paritosh C. Deshpande [a,*], Sidra Tul Muntaha [a], Ragnhild Bjerkvik Alnes [b]

[a] *NTNU Norwegian University of Science and Technology, Department of Industrial Economics and Technology Management, Norway*
[b] *NTNU Norwegian University of Science and Technology, Department of Energy and Process Engineering, Norway*

ARTICLE INFO

Keywords:
Fishing gear
ALDFG
Circular economy
Ropes
Gear marking
Sustainable fisheries
Plastic recycling
Marine pollution

ABSTRACT

Marine plastic pollution is a growing stressor affecting both marine and terrestrial life. Plastic polymers are widespread in oceans, including sparsely populated Nordic countries. Norway, a fishing-dominant region, faces substantial plastic pollution from fishing ropes, which often end up incinerated, landfilled, or lost in the ocean, contributing to the ghost fishing problem.

This research employs a static material flow analysis (MFA) to assess plastic mass flows and the recyclability of 15 rope types used in Norway's commercial fishing sector. Findings reveal that approximately 383 tons of ropes are lost annually in Norwegian waters, endangering fish species. Furthermore, only one-third of the rope types can be efficiently recycled using available recycling technologies, highlighting the need for circularity.

The MFA and inventory-based ranking approach shows significant potential as a holistic decision support tool for industry and policymakers in exercising sustainable and circular management for ropes.

1. Introduction

Sustainable fisheries are vital contributors to global food security and economies. Fisheries face both challenges and opportunities on the way to becoming a sustainable and climate-neutral food production system. Marine plastic pollution is one of the significant environmental stressors alongside climate change and overfishing (FAO, 2020; Lebreton et al., 2018). While it is broadly recognized that most global marine plastic litter originates from land-based sources, sea-based sources, including fisheries, aquaculture, shipping, dredging, and offshore oil and gas activities, introduce substantial amounts of litter to the world's oceans (GESAMP, 2021). Among the studies estimating global plastic loads to the marine environment, plastic entering the marine environment directly from the fishing sector, such as abandoned, lost, or otherwise discarded fishing gear (ALDFG), is excluded owing to a lack of data availability (Deshpande and Haskins, 2021).

In 2021, FAO (2021) reported an annual use of 2.1 million tonnes of plastic products in the fisheries and aquaculture industries, although it is not known what fraction of this total plastic use can result in marine litter. Debris can disperse far and wide from its origin, becoming widely distributed throughout the oceans, even in remote areas (Derraik, 2002; Lebreton et al., 2018). In the marine environment, debris can impact various organisms, from crustacea and fish to apex predators such as marine mammals and seabirds, mainly through ingesting microplastic and getting entangled (Gall and Thompson, 2015; Laist, 1997). Several studies reported other problems caused by ghost fishing i.e., lost gear in the aquatic environment, including entrapment of target (Gilardi et al., 2010) and non-target marine species (Duguy et al., 1998; Phillips, 2017), physical impacts on the benthos (Edinger et al., 1998), disruption in coastal areas (Phillips et al., 2010; Smith et al., 2014), a navigational risk to vessels and ships (Hong et al., 2017), potential human exposure to microplastics and chemicals through the food chain among others (Huntington, 2019).

Prevention and mitigation of the impacts from ALDFG are essential to sustainable fisheries, preserving aquatic food web, and supporting marine flora. The risk of ALDFG accumulation is ever pertinent to countries characterized by a long and productive coastline (Deshpande, 2020). Norway's geographic location and strong dependence on fishing activity make it among the most vulnerable countries in the EU-EEA region to the detrimental effects of ALDFG pollution (Deshpande and Haskins, 2021). Ropes are among the most versatile and widely used part of fishing gears (FG) (Oxvig and Hansen, 2007). In Norway, fragments of abandoned and lost ropes and FG are prevalent across all the water bodies, including beaches, fjords, coastal and deep waters (Buhl-

---

* Corresponding author.
E-mail address: paritosh.deshpande@ntnu.no (P.C. Deshpande).

https://doi.org/10.1016/j.marpolbul.2023.115798
Received 28 September 2023; Received in revised form 11 November 2023; Accepted 13 November 2023

Mortensen and Buhl-Mortensen, 2018). Fig. 1 demonstrates the example of prevalence of ropes and netting plastic fibers used as nesting material by northern gannets in Runde bird sanctuary, Norway. O'Hanlon et al. (2019) studied two sites in Norway, namely Runde, and Syltefjord, and concluded that almost 98 % and 97 % respectively, of the observed bird nests, are contaminated by plastic debris from ropes and mismanaged FG.

The lack of scientific evidence has resulted in a strong dependence on precautionary principles or conservative methods to manage FG and associated ropes in coastal countries. Previously, Deshpande et al. (2020a) provided a first estimate on plastic pollution from commercial FGs in Norway; however, the ropes were excluded from that study owing to the unavailability of refined data. Consequently, there is a pressing need to build a holistic and systemic understanding of the sources, sinks, and end-of-life (EOL) management alternatives for the ropes from the fishing sector. Pursuing the transition to green and sustainable fisheries will be in jeopardy without the sustainable handling and management of ropes. Therefore, this study presents the first quantification and rapid analysis of rope types used by commercial fishers in Norway. Using the information from producers, suppliers, fishers, material experts, and rope recyclers, we present the classification suggesting the recyclability and handling pathways to manage different rope types used in Norway. This research will thus fill the knowledge gap by answering the following research questions:

1. What is the current status of managing ropes used in the Norwegian commercial fishing sector?
2. What are the current barriers and opportunities in applying sustainable and circular management of end-of-life ropes?

The paper is structured into six sections; Section 2 details the case of the application of ropes in commercial fishing practices in Norway and reviews associated challenges. Section 3 provides insights into mixed methods used for this study, whereas Sections 4 and 5 present the results and associated discussion.

2. Case: ropes in the fishing sector of Norway

Norway is a northern European country surrounded by water to the south (Skagerrak), the west (the North Sea and the Norwegian Sea), and the north and northeast (the Barents Sea). With a more than 25,000 km marine resource-rich coastline, Norway is a European leader in commercial fishery and aquaculture (Lawson, 2015). Commercial fisheries have always played a critical social and economic role, both nationally and regionally, and have been the basis for settlement and employment along the Norwegian coast (FAO, 2013). The commercial capture fishery sector is segmented into the coastal and ocean fishing fleet. The coastal fishing fleet comprises smaller vessels operated by 1–5 fishers with sizes ranging from 10 to 20 m. The ocean fleet is known for its sophisticated deep-water fishing practices, where fishing vessels are generally more than 28 m in size, and crew members can vary up to 20 persons or more (Deshpande et al., 2019). In 2021–2022, 5503 vessels were registered in Norway, of which approximately 93 % are coastal vessels, and the rest belong to ocean fishing fleets (Fisheries, 2022).

The commercial fishers in Norway use such commonly used FG types: trawls, purse seines, Danish seines, gillnets, longlines, and traps/pots (Fisheries, 2010). All the FGs are typically connected or supported by variety of rope and chain types. This study focuses on ropes, as they are one of the primary supporting part for FGs. Ropes are commonly made of polymers or polymers with metals (Sundt et al., 2018). The most used polymers are Polypropylene (PP), Polyethylene (PE), Polyamide or Nylon (PA), polyester, Ultra-High Molecular Weight Polyethylene (UHMWPE), and High-Density Polyethylene (HDPE) (Sundt et al., 2018; APEM, 2020). Sometimes, these polymers have the addition of lead, steel, and copper as metals (Sundt et al., 2018; Huntington, 2019). The density of the rope material decides its application based on its floatability and sinkability. PE, PP, and HDPE float while metal and PA sink (Stolte and Schneider, 2018; APEM, 2020).

The heterogeneous nature of materials in the ropes determines their designated properties, which vary in each rope type. Some of these properties are related to strength, floatability, wear and tear, weight, or specific gravity (Sundt et al., 2018). Further, ropes are categorized into two types that are either twisted or braided. In twisted ropes, there are different twisting levels, and the direction of twisting is vital in determining the desired property. In contrast, braided ropes are structured with a crisscross pattern in a diagonal direction (Oxvig and Hansen, 2007). The fibers may have been pre-twisted. These ropes are often used to replace metal wires (Oxvig and Hansen, 2007).

Fig. 1. Fibers of plastic from fishing gears and ropes used as nesting material by northern gannets in Runde bird sanctuary, Norway, where 98 % of the sampled nests were contaminated with plastic fibers and debris (O'Hanlon et al., 2019).

The variation in rope materials is an essential factor in deciding the fate of the rope at the EOL. The complexity of the design meant that segregation or pre-sorting is required to remove the metal and heavy fractions of rope parts to prevent damage to mechanical recycling unit blades (Stolte and Schneider, 2018; Deshpande et al., 2020a). The complex mixture of polymers and other metals may provide specific applications to the ropes; however, these mixed polymers result in operational challenges in recycling the ropes, reducing the feasibility of recycling operations (Stolte and Schneider, 2018). As a result, material composition and properties are crucial information that dictates the recyclability of ropes and associated technology for recycling (chemical or mechanical).

In view of the upcoming Extended Producer Responsibility (EPR) scheme for fishery-related waste in Norway (Environment, 2022) and the EU's circular economy directive for plastics (Deshpande and Haskins, 2021; Huntington, 2019; EC, 2018b), there is a growing need to manage FGs and ropes sustainably. Therefore, this study aims at addressing the research questions by *a)* modeling the mass flows of ropes across their life cycle stages and *b)* developing the holistic inventory and ranking the significant rope types used in commercial fishing activities according to their recyclability upon the EOL stage.

3. Methodology

The study uses mixed methods to obtain the qualitative and quantitative information necessary to address the presented research aims. The Material Flow Analysis (MFA) is used to quantify the ropes across the life cycle phases. Stakeholder interviews, expert opinions, and literature reviews were used to obtain the data for MFA and information on the material composition, and recyclability of the ropes. The research methods applied are discussed here.

3.1. *Material flow analysis*

MFA is a method that accounts for flows and stocks of goods or substances within a set system boundary in time and space (Brunner, 2016). The method has vast applications and is frequently used within environmental engineering for assessing resource efficiency and guiding resource management, waste management, and policymaking (Deshpande and Tippett, 2023). Materials can refer to both goods and substances, and the system consists of both flows and processes (Cencic and Rechberger, 2008). Previous studies demonstrate the successful application of MFA to map the plastic flows from the fishing sector of Norway (Deshpande et al., 2020a) and monitor the FGs deployed by commercial fishing in Taiwan (Su et al., 2023), making it a robust choice for this study. The initiation point for MFA is defining the problem after which processes, goods, and system boundaries are set. The mass flow of goods is then set in addition to their balance and concentration levels within the system, using transfer coefficients (Paul and Helmut, 2004).

The commercial fishing sector in Norway and ropes used for fishing applications in the year 2020 constituted the system boundary for the MFA system. Fig. 2 demonstrates the typical processes in the life cycle of ropes used in commercial fishing practice. Fishing companies purchase FGs and ropes annually to equalize the stock after annual losses from deployment or disposal after EOL. In the use phase, fishers deploy FG and ropes in the ocean to catch a target species. Deployed ropes, or their parts, may get lost during operation due to various reasons listed by Richardson et al. (2018). There are efforts to find lost ropes in the ocean that are retrieved from the oceans (Fiskeridirektoratet, 2022) and the beaches through clean-ups (Rent, 2021). Collected ropes from the clean-up activities are sent to waste management facilities (WMF), where the mixed waste fractions are segregated between recyclable rope and non-recyclable rope fractions. Non-recyclable ropes are either sent to landfills or incineration plants for energy recovery, while recyclable fractions are sent to recycling facilities.

Additionally, the EOL phase for certain rope types is further extended to the recycling process within Norway based on communication with the regional mechanical recyclers. The recyclable EOL rope fractions are mechanically recycled or sent abroad for further treatment. Moreover, talking to stakeholders, the repair part is removed as ropes are not majorly repaired, unlike the system of FGs studied by Deshpande et al. (2020a).

After mapping the life cycle phase for ropes (Fig. 2), the MFA was modeled with seven processes and seventeen variables in the MFA system. The data and insight from WMF are obtained from surveys and interviews. Uncertainty from parameters and constants has been assessed using the tool Simulaci'on in Excel and followed by STAN v.2.6.801 software for error propagation (Brunner, 2016). Data uncertainties are calculated using the Gaussian error propagation, assuming a normal distribution. Additionally, an expert's opinion is used to verify assumptions and estimations before finalizing the results. The system equations are altered in line with the understanding that ropes are not repaired, and the main difference from the FG system is that the flow of worn equipment to EOL management is calculated with the mass balance of the fishery process. The uncertainty is simulated with 10,000 iterations. The resulting MFA on ropes for 2020 is represented with a STAN illustration. The calculation procedures for processes and flows, data sources and equations used for mass balance are presented in Table 1.

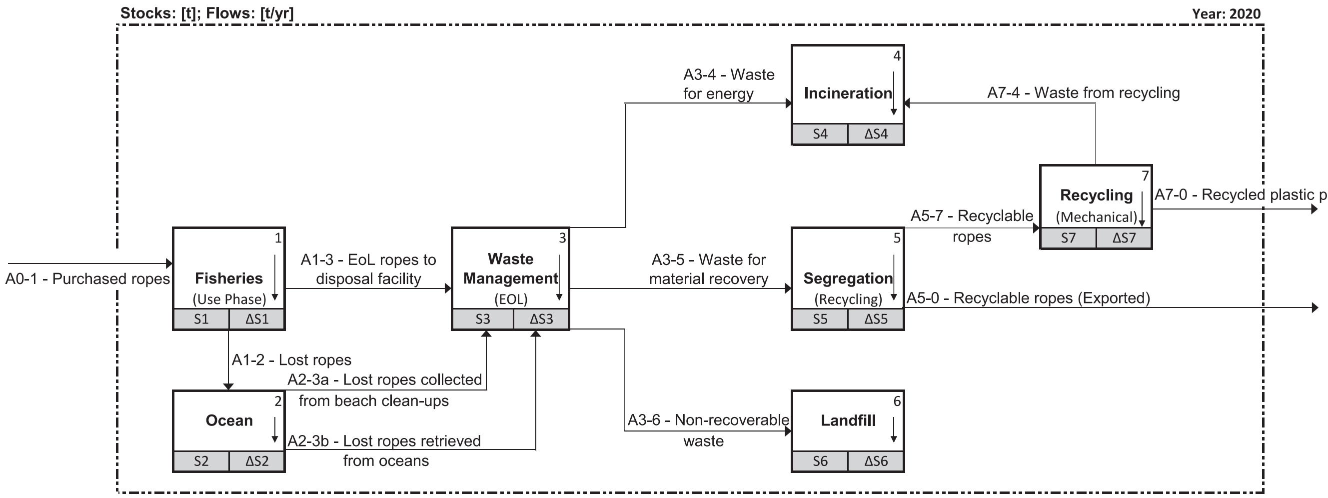


Fig. 2. Processes involved in the system life cycle of ropes used in commercial fishing in Norway.

Table 1

Description of flows, respective data sources, and flow equations used in the MFA model.

Variable symbol	Variable name	Data source	Equation
A_{0-1}	Purchased ropes (t/yr)	Rope Suppliers	$A_{01} = \sum \text{purchased ropes}$
A_{1-2}	Lost ropes (t/yr)	Fishers survey and (Deshpande et al., 2020a)	$A_{12} = \sum C_{lost} \cdot (A_{01} + A_{01} \cdot C_{stock})$
A_{1-3}	EOL ropes to disposal facility (t/yr)	(Deshpande et al., 2020a)	$A_{13} = \sum C_{dispose} \cdot (A_{01} + A_{01} \cdot C_{stock})$
$A_{2\text{-}3a}$	Lost ropes collected from beach clean-ups (t/yr)	Data in units: Rydde portal/Hold Norge Rent (Rent, 2021) Mass conversion factor: (Deshpande et al., 2020a)	$A_{23a} = \sum \text{Collected ropes at beach (unit)} \cdot \text{MoP in ropes at the beach (kg/unit)}$
$A_{2\text{-}3b}$	Lost ropes retrieved from oceans (t/yr)	Data in units: The Norwegian Fishing for Litter (Johnsen et al., 2020) and Directorate of Fishery (Fiskeridirektoratet, 2022) Mass conversion factor: (Deshpande et al., 2020a)	$A_{23b} = \sum \text{Retrieved ropes from ocean (unit)} \cdot \text{MoP in ropes from ocean (kg/unit)}$
A_{3-4}	Waste for incineration (t/yr)	Survey of waste management facilities (WMF)	$A_{34} = \sum C_{incineration} \cdot (A_{13} + A_{23a} + A_{23b})$
A_{3-5}	Waste for material recovery (t/yr)	Survey of WMF	$A_{35} = \sum C_{Segregation} \cdot (A_{13} + A_{23a} + A_{23b})$
A_{3-6}	Non-recoverable waste (t/yr)	Survey of WMF	$A_{36} = \sum C_{Landfill} \cdot (A_{13} + A_{23a} + A_{23b})$
A_{5-7}	Recyclable ropes (t/yr)	Recyclers survey	$A_{57} = \sum C_{Recycle} \cdot A_{35}$
A_{5-0}	Recyclable ropes (Exported) (t/yr)	Mass Balance	$A_{50} = A_{35} - A_{57}$
A_{7-4}	Waste from recycling (t/yr)	Recyclers survey	$A_{74} = \sum C_{waste} \cdot A_{57}$
A_{7-0}	Recyclable plastic pallets (t/yr)	Mass Balance	$A_{70} = A_{57} - A_{74}$
$S1 + \Delta S1$	Stock and stock change of total ropes owned by fisheries (t)	(Deshpande et al., 2020a)	$S1 + \Delta S1 = \sum C_{Stock} \cdot A_{01}$
$\Delta S2$	Stock change of ropes in the ocean (t)	Mass Balance	$\Delta S2 = A_{12} - A_{23a} - A_{23b} - A_{23c}$
$\Delta S4$	Stock change of ropes in the incineration plant (t)	Mass Balance	$\Delta S4 = A_{34} + A_{74}$
$\Delta S6$	Stock change of ropes in the landfill (t)	Mass Balance	$\Delta S6 = A_{36}$

3.2. Survey and interviews

Due to the lack of information on ropes, the research mainly relied on stakeholders' information. A questionnaire, face-to-face, and digital interviews were used to obtain data from key stakeholders. The details on survey design, administration, and analysis of responses are presented in Supplementary material. Apart from the structured questionnaire, site visits to the recycling facility were used in this research to gather additional information from various stakeholders.

3.3. Inventory – material and recyclability

The inventory identifies the rope types sold in Norway mainly for fishing activities. Since the brand names of the ropes were not always similar, this study classifies rope types as per their material and application. The ropes used for aquaculture and other maritime sectors are excluded from the study. The inventory further analyses the rope types based on twisted or braided strands, applications within the fisheries sector, and their properties. The information was identified by reviewing the product catalogs of the significant rope suppliers in the region and the literature. The inventory information was further extended by involving expert stakeholders, including material scientists, and chemical and mechanical recyclers in the region, to determine the recycling process and ease of recyclability for the selected rope types. Field visits and interviews of expert stakeholders were used to obtain information on the material composition of the ropes. Finally, waste managers and recyclers in the region were contacted through field visits to obtain information on the recyclability of different rope types and polymers. The data collection routines and interviewed stakeholders are detailed in Fig. A1 and Tables A2 and A3 of Supplementary material.

The circularity potential of ropes is determined through qualitative ranking. Three criteria were selected for ranking the ropes: material composition, recycling technology, and technology readiness. The criteria are developed and modified to test the feasibility of the recycling technology to manage the rope type upon its EOL. The three criteria are ranked *(from 1 to 3, 1 being the best alternative and 3 being the least preferred)* as presented in Table 2.

In the material composition (A) criteria, the highest rank (1) is given to the ropes made of homogeneous polymers, whereas ropes made of heterogeneous or mixed polymers are ranked (2), while the last rank (3) was assigned to ropes with mixed polymer and material, including metals. These material composition rankings are defined based on their recyclability ease and financial viability. Composite material requires different recycling methods due to their varied composition, melting temperature and mechanical properties (Krauklis et al., 2021). Therefore, recycling technology (B) was compared based on its economic feasibility and technology availability. Relevant studies on chemical and mechanical recycling of plastics (Gu et al., 2017; Huntington, 2019; Kubiczek et al., 2023) revealed that chemical recycling is economically intensive and technologically complex compared to mechanical plastic recycling, yet can recycle PA into high-quality recycled polymers which retain the properties and give high economic value. Therefore, mechanical recycling was scored together with chemical recycling in the ranking criteria that has the highest rank (1). The ropes that need severe pre-treatment before recycling are rated second on the scale, as pre-treatment and segregation is both time and cost-intensive. While ropes that cannot be recycled due to their design and material composition are rated the lowest. Finally, technology readiness (C) was selected as the last criterion to evaluate both availability of the recycling technology and/or technology enablers in the region. The availability and capacity of technology for industrial-scale recycling were ranked highest (1), while the absence of technology for recycling was ranked the lowest (3). Technology in the pilot project scale was ranked in between (2).

Each rope type has been assessed and ranked individually using the simple summation technique:

$$\begin{aligned} \mathit{Recyclability\ rate\ of\ rope\ type} = \sum \Big(& \mathit{Material\ composition}\ (A) \\ & + \mathit{Recycling\ technology}\ (B) \\ & + \mathit{Technology\ readiness}\ (C) \end{aligned}$$

The rankings are refined and confirmed through experts' opinions. Finally, the color coding of green-yellow-red is used to conclude that green is easiest to recycle, red deemed unsuitable for recycling, and yellow is moderately challenging to recycle.

4. Results

The results are divided into three parts. First, the plastic accounting across the life cycle of rope types is presented using an MFA. The second part presents the inventory of ropes majorly used by commercial fishers. Finally, the ranking of rope types is presented based on their recycling potential at the EOL phase.

Table 2
Criteria to assess and rank the recyclability of the selected rope types.

Rating **Criteria**	**1**	**2**	**3**
Material Composition (A)	Homogeneous polymer	Heterogeneous (mixed) polymers	Polymer with metals and other materials
Recycling Technology (B)	Mechanical or Chemical Recycling	Intensive Pre-processing Required	Not available
Technology Readiness (C)	Available	Upcoming (pilot scale)	Not available

	Polymer Composition (A)	**Recycling Technology (B)**	**Technology Readiness (C)**
Rating	1-3	1-3	1-3
Sum/Rank	3-4 (Recyclable)	5-6 (Recyclable with interventions)	7-9 (Non-recyclable)

4.1. *MFA of ropes in fisheries*

A static MFA of ropes deployed by commercial fisheries in Norway in 2020 is given in Fig. 4, and the input values in the tabular format can be found in the Supplementary material. According to the mass balance principle, all input values and uncertainties are adjusted automatically based on error propagation in STAN v.2.6.801.

As per Fig. 4, in 2020, 1614 ± 271 tons of ropes per year were imported within the fisheries sector. Among ropes in stock of fisheries and purchased ropes, 383 ± 96 tons of ropes per year are lost in the ocean in 2020, while 2607 ± 209 tons per year of ropes are sent to waste management facilities directly after usage. Efforts are made to retrieve the waste from the ocean and land through clean-up activities. Approximately 59 ± 48 tons per year are recovered from beach and ocean clean-up operations and sent to WMFs. Among the waste collected at WMFs, 48 % is sent for incineration, 45 % for recycling, and 7 % for landfill. Out of 45 % of ropes segregated for recycling, only 7.5 % are recycled within Norway using mechanical recycling technique i.e., 87 ± 7 tons per year (as of 2020), and the rest of the recyclable ropes are either unclean, mixed, made of polymers that are unsuitable for mechanical recycling or have metal inside. These rope types are currently sent abroad for further treatment and processing to be recycled. Of the recycled ropes in Norway, around 2 % to 3 % of the waste from the recycling plant is sent to an incineration plant for energy recovery.

4.2. *Ropes inventory*

From the product catalogs and semi-structured interviews with rope producers in the region, 15 commonly used rope types for fishing sectors are identified and shortlisted for the study. Due to a lack of in-depth information on material composition, aggregated methods were used to determine polymer types and other materials in the selected rope types. The selected ropes are classified based on their material composition, application, and properties and presented in Table 3.

The inventory information was further extended by involving expert stakeholders, including material scientists and chemical and mechanical recyclers in the region, to determine the recycling process and ease of recyclability for the selected rope types. Table 4 demonstrates the classification of selected ropes with the material composition. The type of polymers present, metals, and other materials used in ropes were marked in classifying the ropes as these factors influence the EOL treatment.

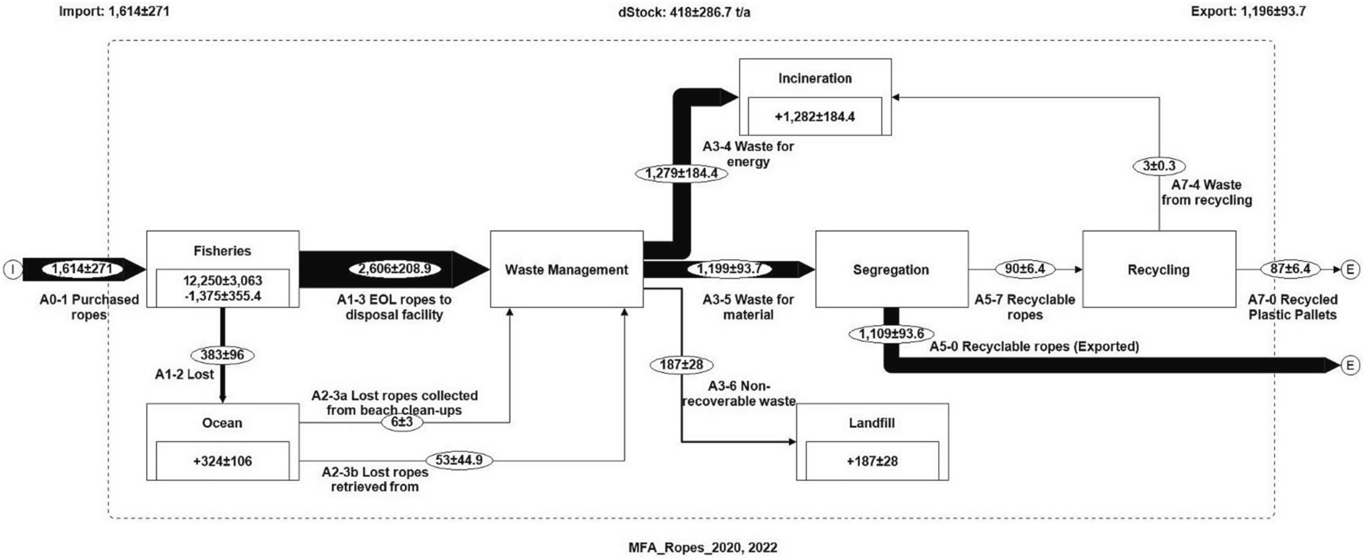


Fig. 4. Material Flow Analysis of ropes used by the commercial fishing fleet of Norway in 2020 (tons/yr).

Table 3

Inventory of key rope types, material composition and applications in the fishing sector.

Rope	Rope type	Applications	Properties
Dolly Rope	Twisted	Trawls	High wear and tear resistance, protective buffer for nets
Danline Rope	Twisted, Braided, Braided and twisted	Mooring, Towing, Lifting	Floats, very good UV and chemical durability, high strength and wear resistance, melting point: 165 °C
Polyethylene Rope	Twisted, Braided	Fishing, Sailing	Low breaking strength, floats, high chemical and abrasion resistant
Nylon Rope	Twisted, Braided	Mooring, Anchoring, Towing, Straps, Sailing, Self-tensioning winches	Sink, UV-resistant, melting point: 250 °C, very strong, elastic, high breaking load
Polyester Rope	Twisted	Fishing	Sink, very good UV and wear resistant
Silver Rope	Twisted	Longline and end rope, Yarn mounting and pots, Mooring	Sink, melting point 130–260 °C, high tensile strength, abrasion, UV and chemical resistant
Ultra-High Molecular Weight Polyethylene Rope	Braided	Sweeps, Mooring, Towing, Winch, Seismic, Anchor, Lifting slings, Grommets, Tugboats	Melting point: 145 °C, lightweight, highest strength to weight, low elongation, abrasion, fatigue, UV rays and chemical resistant
Danline with lead	Twisted, Braided and twisted	Seine netting	Sink, high strength, good abrasion resistant
Polypropylene Rope	Twisted	Fishing gear, mooring, Yarn mounting and pots	Float, low elongation, wear-resistant
Mixed Rope (Poligareta)	Twisted	Demersel fishing	Very resistant to abrasion or friction
Polirex Rope	Twisted	–	–
Seine Rope with Steel	Twisted	Demersel fishing, Seine fleet	Good UV resistant and wear property
Terylene with Lead Rope	Braided and twisted	Sinking ropes	–
DURA - Float	Twisted	Mooring, Winch	High breaking load, good elongation, float, UV stabilized, abrasion resistant
Nylon rope with copper coating	Twisted	Trawling	–

4.3. Ranking of ease of recyclability

The inventory was used to rank the 15 rope types on the scale of easiest to hardest to recycle within Norway (Fig. 5). The criteria-based ranking method elaborated in Table 2 was used to rank the rope types based on the three criteria i.e., material composition, recycling technology and technology readiness. The recyclability ranking shows the highest ease of recyclability of ropes with PP and PE, whereas ropes with composite materials are the most difficult to recycle.

The ropes made of homogeneous polymers such as PE/HDPE and PP are relatively easier to mechanically recycle. Though there is an exception of Ultra-High Molecular Weight/High Modulus PE (UHMWPE) rope which has the highest strength. Otherwise, even the mixture of PE and PP can be recycled mechanically, which is simpler than chemical recycling, while PA and polyester are recycled chemically. PA is recycled on a pilot scale in Norway through pyrolysis, unlike polyester. Many rope types with complex designs comprising mixed polymer are considered challenging waste fraction for recycling e.g., if PE/PP are mixed with PA/polyester then it is difficult to recycle as two different processes of recycling are required. Most challenging are composite materials ropes that include metals (copper, lead, steel) along with the polymer. The recyclers in the region confirm the findings. The detailed calculation of the ranking of each type of rope is given in the Supplementary material.

5. Discussion

5.1. Challenges to EOL management of ropes

Ropes are an essential component in fisheries, and the wide range of applications include mooring, towing, aiding in the sinking or floating of attached gears, anchoring, and lifting, among others. The MFA results indicate that annually 2700 tons of waste ropes are collected in Norway from commercial fishing practices alone, and around 383 tons of ropes are reportedly lost in the ocean contributing to the ghost fishing problem in Norwegian waters.

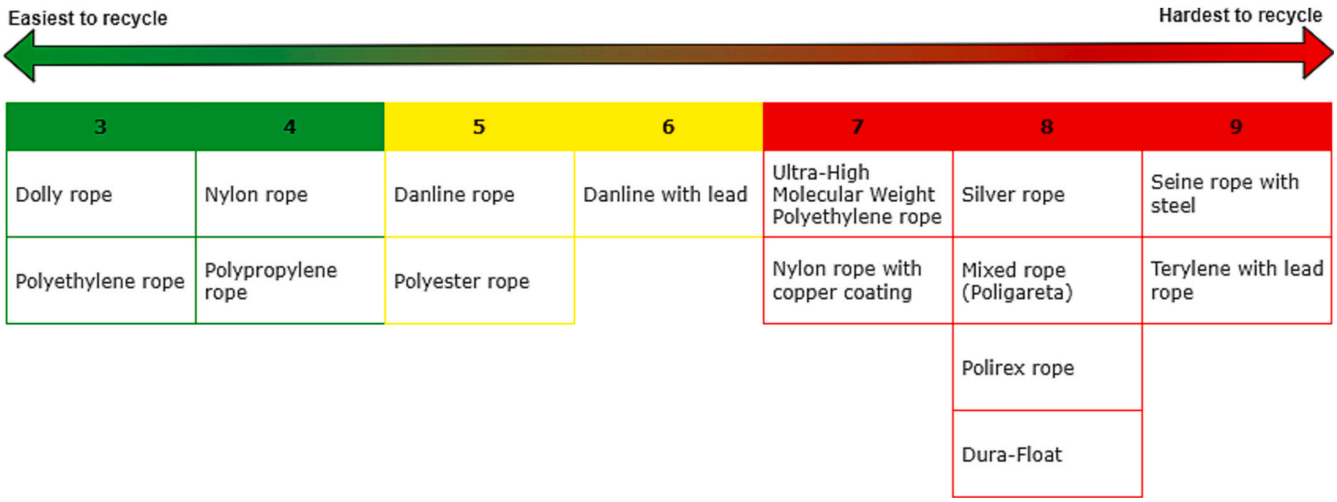
As illustrated in Fig. 6, the EOL ropes are often collected at WMFs in a mixed form and are laden with rotten biomass, fish oil, and dirt (Deshpande et al., 2020b). Since many WMFs lack the facility to clean such waste, the result is elevated rates of incineration or landfill within the waste fraction, as reflected in MFA, where more than 50 % of the collected EOL ropes are incinerated or landfilled in Norway. Furthermore, an absence of industrial-scale recyclers in the region results in an export of a significant recyclable fraction out of Norway, thereby missing an opportunity to extract the optimum value from locally generated waste ropes (Havas et al., 2022). The MFA model for ropes develops an understanding of the scale of mismanaged resources from the fishing sector. The knowledge of the life cycle phases of ropes guides the regulatory actors in identifying areas for improvement in the system to ensure sustainable fisheries and realize the targets for the circular economy (CE).

Together with MFA, this study provides the classification and ranking of rope types used in the fishing sector. The classification included 15 rope types distinguished based on the material composition, application, and existing methods for EOL management. The rapid ranking system developed in this study was based on the material composition, recycling technology, and technology readiness to determine the recyclability of the studied ropes. Based on the results of ranking, only one-third of the selected ropes are considered fit for recycling. Two rope types, namely, seine ropes with steel (also called typhoon ropes) and terylene ropes with lead, have metal as a core inside or coating outside. These ropes are considered the hardest to recycle on the ranking scale (9) of recycling ease. The ropes with metal need intensive pre-treatment, sorting, and cleaning to remove the metal coatings or inner metal core to make them suitable for material recycling. Separating metal is an extensive task; metallic rust on the rope makes the ropes challenging to recycle, and they are usually sent to incineration plants after shredding. Fig. 7 shows the ropes with steel wire and the lead inside, making them economically cumbersome to recycle.

The ropes ranked 8 on the ranking scale contained a mix of high and low-density polymers (Polyester, PP, PE, and PA). These mixes are challenging to recycle together as their recycling processes are different. PE and PP can be treated mechanically, but polyester and PA can only be treated chemically due to their high melting point. Therefore, the rope types comprising mixed polymers involving different recycling technologies need sorting, cleaning, and extensive pre-treatment, which can be demanding with respect to both time and money. The interactions with expert stakeholders highlighted the need for mixed materials in rope to attain the desired functionality. PP, PE, and a mixture of low-density polymers are used to obtain the floating properties, while PA ropes with metal cores are typically used for sinking properties. E.g., two varieties are found in Danline ropes, and the heavy or sinkable Danline are made with lead as a core material.

Table 4
Inventory of fisheries rope types based on the material composition.

Type of ropes in the fishing sector	Plastic polymers				Other material	Metal or alloys		
	Poly amide (PA)	Poly ethylene (PE)	Poly propylene (PP)	Poly ester		Lead	Steel	Copper
Dolly Rope		x			No			
Danline Rope		x	x		No			
Polyethylene Rope		x			No			
Nylon Rope	x				No			
Polyester Rope				x	No			
Silver Rope		x	x	x	No			
Ultra-High Molecular Weight Polyethylene Rope		x			No			
Danline with lead		x	x		Yes	x		
Polypropylene Rope			x		No			
Mixed Rope (Poligareta)	x	x		x	No			
Polirex Rope		x		x	No			
Seine Rope with Steel		x	x		Yes		x	
Terylene Rope with Lead				x	Yes	x		
DURA - Float	x		x		No			
Nylon rope with copper coating	x				Yes			x



3	4	5	6	7	8	9
Dolly rope	Nylon rope	Danline rope	Danline with lead	Ultra-High Molecular Weight Polyethylene rope	Silver rope	Seine rope with steel
Polyethylene rope	Polypropylene rope	Polyester rope		Nylon rope with copper coating	Mixed rope (Poligareta)	Terylene with lead rope
					Polirex rope	
					Dura-Float	

Fig. 5. Ranking of studied rope types based on the ease of recyclability.

Fig. 6. Mixed fractions of end-of-life ropes collected at the waste management companies.

Fig. 7. End-of-life ropes with a) steel wire and b) lead as a core.

The composition of similar types of ropes varies significantly depending on the producers. The exact composition of polymers and plastic-associated chemicals (PACs) in rope types remains unknown to the regional stakeholders, including the producers in Norway, as the raw materials used for the ropes are imported mainly from Asia and other regions (Deshpande et al., 2020b). The unfamiliarity with a material composition causes a lack of knowledge among stakeholders resulting in lower recycling rates and an inability to recycle ropes into high-quality recycled pellets with significant economic value. Therefore, the simplistic ranking provided here can form the first step to mark the ropes types and seregate them based on their recyclability for improved material recovery.

5.2. *Strategies for sustainable and circular management of ropes*

Since the inclusion of the CE directive in the EU, a strong focus has been placed on ensuring circular management of ropes and FG. Here we discuss some strategies that can aid the region's sustainable and circular management of ropes. In the EU's current directive on reducing the impact of certain plastic products on the environment, a particular focus was placed on waste from fisheries (fishing gear and ropes). The directive advises that the member states should monitor the waste quantities and develop actions to recycle, reduce or recover the plastics from these sectors.

Here, we present some relevant management actions toward meeting the goal of sustainable and circular economy-based management of ropes in Norway. Furthermore, we discuss the relevance of the findings from this study for the effective implementation of the presented strategies.

5.2.1. *Collection and transport of waste ropes*

The technology to recycle the ropes and recover material from the process is available but has a severe limitation concerning the type and quality of the EOL ropes. Polymers like PP, PE, HDPE, and LDPE can be recycled mechanically, while PA and polyester need chemical recycling (Gu et al., 2017; Uekert et al., 2023). Even ropes that are fit for recycling with today's technology are not all recycled. One of the reasons is the lack of efficient collection and waste management of ropes at EOL (Deshpande and Haskins, 2021), as the results in MFA also show significant losses in the ocean. Furthermore, the waste collected at the WMFs is sent to landfill and incineration as it seems to be a preferred option due to low processing and transport fees (Deshpande et al., 2020b).

Moreover, the results from MFA show that repairing is not practiced for ropes, even though it is a widely used alternative for FGs (Deshpande et al., 2020b). As discussed in the previous study by Deshpande and Haskins (2021), the key challenge lies in the overall lack of Port Reception Facilities (PRF) infrastructure across the Norwegian ports. The EU Directive 2000/59/EC dictates that all EU-EEA member states safeguard a PRF's availability and provide a waste management plan on all ports (EC, 2018a). PRFs are defined as 'any facility, which is fixed, floating or mobile and capable of receiving ship-generated waste or cargo residues' (EC, 2018c). According to the European Free Trade Association (EFTA) court's recent judgment, Norway has failed to fulfill the EU directive's obligations. Only one-third of Norway's registered ports contain a dedicated PRF or waste management plan. A lack of PRF can lead to an inappropriate collection of fisheries-related waste and may give rise to illegal dumping, burning, or stockpiling of waste in ports hindering the waste collection regime from recovering valuable material (Court, 2016).

Therefore, there is an imminent need to establish PRFs or other facilities to collect and transport the EOL ropes to the subsequent waste handling and management facilities in the region.

5.2.2. *Labeling and marking of ropes*

Effective collection and transport will only help prevent the illegal discharge of EOL ropes to the land and water. It will have minimal impact on improved recycling and resource recovery due to the complex rope design. The inventory of the ropes and recyclability ranking is considered helpful by the regional recyclers and waste managers (personal communication) to identify the ropes according to the materials and properties. However, identifying rope types in mixed waste fractions is difficult. Fig. 6 shows the mixed aggregate of EOL ropes on WMFs, which undergo a laborious manual segregation into recyclable fractions. As per the field visits to recycling facilities and stakeholder interaction, the EOL rope fractions are manually separated and sent to pre-treatment. Automation for sorting rope and FG waste fractions is not practiced in Norway due to a lack of capacity and economic burdens. The manual segregation is based on primary visual criteria, including clean and unclean ropes, color identifications, identification of the state of EOL rope (i.e., degraded or good condition), and potential metal coating or content in the ropes (Personal communication with recyclers). These criteria are applied to sort PE, PP, and HDPE ropes for mechanical recycling and PA for chemical recycling.

For improved circularity and value creation, we propose amendments to the FG marking tool proposed by the Food and Agriculture Organization (FAO). Macfadyen et al. (2009) recommend that gear marking technology improve the traceability of FGs and ropes that can be installed/incorporated into the gear during manufacturing and assembly operations. Gear marking also helps to identify the producer(s)/manufacturer(s) at the production/assembly stage and may facilitate the Extended Producer Responsibility (EPR) schemes discussed later. FAO's traditional gear marking scheme proposes several ways of marking the FG and parts to improve traceability and prevent illegal dumping (FAO, 2019). However, including other factors such as material/polymer composition and information on recyclability through the simplistic ranking system presented in this study may create vital insights for better EOL management of ropes or FGs. Including these criteria will guide fishers to dispose of the ropes through dedicated collection channels and further assist waste managers and recyclers in segregating the recyclable fractions efficiently.

5.2.3. Extended Producer Responsibility (EPR)

An EPR is a management principle with roots emerging from the polluter pays principle. Lindhqvist (1992) defines EPR as *"an environmental protection strategy to reach an environmental objective of a decreased total environmental impact from a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal of the product."* Norway has established schemes for EPR since the 1990s, several of which are relevant to plastics: discarded electrical and electronic products, scrapped vehicles, collection and recycling of discarded tires, and return systems for beverage containers and packaging waste (Environment, 2022). EPR is a widely used policy instrument to promote separate sorting, collection, and treatment of waste to prevent pollution and other environmental problems from waste. However, realizing EPR for FGs and ropes was deemed challenging due to the uncertainty of the term "producer" and the role of "responsibility" among the involved stakeholders. In the studied case of FGs and ropes, the "producers" are mere "suppliers" of ropes and customized FGs since most of the raw material is imported from outside Norway. The study highlighted areas where the EPR scheme should focus, including preventing illegal dumping and loss of ropes upon deployment by fishers, improving collections and sorting systems, and targeted recycling to recover the value of waste ropes highlighted through the MFA system. The interaction with stakeholders and ranking exercise further assisted in developing feasible mechanisms for managing ropes.

Table 5 provides the alternative EPR mechanisms that can be implemented across the life cycle phases of ropes for improved EOL management. In the production phase, the focus should be on developing ropes designed for recycling. Additionally, we propose that the rope supplier/producer may consider providing information on "material type/polymer composition" and "recyclability" for the rope type, similar to the existing labeling system practiced for food products or plastic bottles in Norway. For improved collection, harmonizing PRFs can increase the likeliness in a collection of ropes. Different ropes have different retail values, but it is relevant that they are segregated based on the quantities and environmental impacts (Nogueira et al., 2022). For example, Nylon ropes are abundant and have high economic value upon recycling, so they must be assigned a higher retrieval value than other gears.

Educating and working with fishers may help to effectively separate ropes, resulting in improved recycling and reduced discard and landfilling. Similar strategies are used by recycling companies in Taiwan to prevent landfilling (Su et al., 2023). Take-back or reward schemes are also considered adequate for the improved collection of EOL ropes.

At the EOL stage, chemical and mechanical recycling technologies are available to produce recycled polymers for reuse and repurposing. The personal interaction with the regional mechanical recyclers demonstrated some examples that are currently in practice within Norway, e.g., trolleys used at a supermarket or serving trays at a fast-food restaurant, aquaculture brackets and walkways made from recycled polymers from ropes and FGs (Fet and Deshpande, 2023; Havas et al., 2022). This kind of resource sharing among companies to improve environmental sustainability is known as industrial symbiosis (Neves et al., 2020). In Norway, an example is Nordic Comfort Products (NCP) which uses aquaculture waste on the coast of Helgeland, such as ropes, as raw material to create furniture, e.g., chairs (Hermann et al., 2022; NCP, 2022). This way, monetary and material resources are circulated within the country, benefiting the local economy and developing self-reliance.

The Norwegian Directorate of the Environment conducted a feasibility assessment of the EPR scheme in 2018 (SALT, 2018), highlighting the need for an in-depth understanding of the system life cycle quantities (flows and stocks) to aid in the selection of relevant mechanisms for the implementation of EPR. The EPR regulations are being drafted for fisheries and will be ready for implementation by 1st January 2025. Therefore, suggestions made in this study directly impact sustainable management and circular value creation for ropes, especially as it is the most complex waste fraction from fishing.

5.3. Limitations and future work

Notwithstanding their grounding in empirical data, it is imperative to acknowledge that the values generated by the MFA system do not align precisely with real-world conditions. The act of modeling necessitates the introduction of assumptions and estimations, which inherently introduce elements of uncertainty. Nevertheless, it is essential to recognize that these models can serve a valuable purpose in interpreting potential outcomes and variations, thus offering guidance to informed policy formulation (Deshpande and Tippett, 2023).

This study concentrated on a static MFA tailored to ropes procured from commercial fisheries. Notably, our analysis excluded ropes sourced from recreational fisheries, foreign fishing fleets, and ropes deployed in other marine applications as these entities may also obtain ropes from small-scale suppliers who could potentially engage in import activities and, hence, be challenging to track.

Additionally, ropes collected from ocean and land sources through

Table 5
Potential strategies and improvement mechanisms for ropes across the life cycle phases adapted and modified after (Deshpande, 2020).

Production	Facilitate research and innovation to realize eco-design or designing of ropes for recycle Improved collection through a take-back scheme Develop a "marking/labeling" system for ropes along with details on material composition and recyclability for improved traceability and EOL management
Use	Development of a best practice guide for users for improved handling, management, and disposal of ropes Awareness of sorting, disposal of ropes based on their recyclability potential Development of PRFs for better collection of EOL ropes
End-of-Life Phase	Capacity building for efficient recycling (both chemical and mechanical) Exploring opportunities for the market uptake of recycled polymers as a replacement for virgin plastic polymers Exploring pathways to reuse, repurpose, repair, and remanufacture material from EOL ropes

clean-up operations presented challenges regarding measurement units. These clean-up efforts often record the collected ropes fractions based on the OSPAR guidelines of size-based recordings (Wenneker and Oosterbaan, 2010). Therefore, conversion factors were used for MFA to obtain mass-based data from the size-based collections. Consequently, heightened uncertainty is associated with the data derived from oceanic and terrestrial sources. In instances where specific rope-related data was unavailable, assumptions were formulated, drawing from the MFA study of FG waste management in Norway by Deshpande et al. (2020a). These assumptions sought to account for the divergent handling of FGs at waste management facilities throughout their life cycle phases, which are considered relatable for ropes, as a majority of ropes are used as a part of FGs.

Notably, the quality of recycled plastic degrades over successive recycling cycles, necessitating the incorporation of virgin plastic (Fraser et al., 2023). Additional research efforts are imperative to realize genuine circularity for ropes, complemented by the design developments of ropes for improved and efficient recycling. The survey responses provided by stakeholders are characterized by substantial uncertainties, which may be attributed to potential gaps in knowledge about recycling mixed plastics or concerns regarding privacy. Furthermore, the ranking system developed in this manuscript provides the first rapid estimates on recyclability of ropes in current management scenario in Norway. The criteria used for ranking may vary and must be adjusted to include other socio-economic criteria while replicating the study in other fishing regions. The study underscores the significance of transparency and ongoing monitoring endeavors to track the volumes of ropes and their potential for recyclability. Precise and reliable data can facilitate the implementation of dynamic MFA models aimed at devising future strategies.

Additionally, given their substantial prevalence in marine applications, future research initiatives should also encompass ropes from the aquaculture and shipping sector. The comprehensive inventorying of ropes is essential in comprehending their material properties, reuse, repurpose and recyclability and potential research on material promoting design for circularity; however, data gaps persist, especially concerning the recycling processes specific to various rope types. This study solely considered polymer and polymer-metal ropes while omitting biodegradable and sensor-equipped intelligent ropes from the analysis, considering their current pilot-scale applications. However, future inventory efforts should encompass these types of ropes to enable sustainable management of novel rope materials and types.

6. Conclusion

In this study, we identify the problems and strategies related to the recyclability of ropes in Norway's fisheries sector. The complexity, design, and material variations in different rope types contribute to these issues. The exact material composition of ropes often remains unknown as the raw materials are primarily imported from other countries. Utilizing static MFA, we determined that approximately 383 tons of ropes leak into Norwegian waters annually due to fishing activities. This analysis aids in understanding areas for improvement throughout the rope's life cycle and the implementation of preventive and mitigative measures.

The Norwegian Fisheries Sector is dedicated to recovering significant quantities of fishing gear, including ropes, from the ocean which is then sent to recyclers. Therefore, a critical aspect of assessing rope recyclability is the classification of the 15 major rope types based on their material composition. Stakeholder consultations were conducted to rank the ropes, revealing barriers and opportunities for closing the loop on rope recycling in the region. The combination of ranking and MFA offers crucial scientific and technological insights to regulatory actors in Norway, enabling the formulation of policies to monitor and minimize rope leakage from the commercial fishing sector. These results can also facilitate informed discussions on implementing upcoming Extended Producer Responsibility (EPR) strategies for plastics in the fishing sector of Norway and the Food and Agriculture Organization's (FAO) Gear Marking guidelines.

Moreover, the documented yearly quantities of ropes gathered during the EOL phase, along with their recyclability attributes, constitute pivotal empirical substantiation for recyclers and waste management professionals endeavoring to realize circularity within the domain of rope materials in Norway. The research endeavor showcased herein possesses the potential for replication in nations characterized by a substantial fishing industry presence, thereby facilitating the paradigm shift toward sustainable and circular rope management practices. The sustainable utilization of ropes assumes paramount significance in the conservation and rehabilitation of the marine ecosystem, a pivotal factor in ensuring the viability of fisheries.

CRediT authorship contribution statement

Paritosh C Deshpande (PCD): Funding acquisition, project management, conceptualization, data refining and visualization, investigation, writing and revision, methodology.

Sidra Tul Muntaha (STM): Data collection, data visualization, investigation, methodology, writing original draft and revisions.

Ragnhild B Alnes (RGB): Data collection, methodology and investigation.

All authors approved the final submitted draft.

Funding

This research was conducted under the multi-stakeholder project: "SHIFT Plastics: Shifting to sustainable circular values chains for handling plastics in the fisheries and aquaculture sector," funded by the Norwegian Research Council (Project nr. 326857).

Declaration of competing interest

The authors 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.

Acknowledgements

This research was conducted under the multi-stakeholder project: "SHIFT Plastics: Shifting to sustainable circular values chains for handling plastics in the fisheries and aquaculture sector," funded by the Norwegian Research Council (Project nr. 326857). The authors kindly thank all the stakeholders actively participating in the data collection and validation step.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115798.

References

APEM, 2020. Understanding Commercial Fishing Gear Use and Disposal Needs in Wales.

Brunner, P.H., 2016. Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers. CRC Press.

Buhl-Mortensen, P., Buhl-Mortensen, L., 2018. Impacts of bottom trawling and litter on the seabed in Norwegian waters. Front. Mar. Sci. 5, 42.

Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN. EnviroInfo 440–447.

Court, E., 2016. EFTA Surveillance Authority v The Kingdom of Norway (Failure by an EFTA State to fulfill its obligations — Directive 2000/59/EC on port reception facilities for ship-generated waste and cargo residues). European Free Trade Association (EFTA). Case E-35/15 ed. Luxembourg: Official Journal of the European Union.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.

Deshpande, P.C., 2020. Systems Engineering for Sustainability in the Life Cycle Management of Commercial Fishing Gears. 2020:78 Dotoral Degree (Ph.D.) Thesis. Norwegian University of Science and Technology, Faculty of Economics and Management.

Deshpande, P.C., Haskins, C., 2021. Application of Systems Engineering and Sustainable Development Goals towards sustainable management of fishing gear resources in Norway. Sustainability 13, 4914.

Deshpande, P.C., Tippett, A.W., 2023. Application of material flow analysis: mapping plastics within the fishing sector in Norway. In: Fet, A.M. (Ed.), Business Transitions: A Path to Sustainability: The CapSEM Model. Springer International Publishing, Cham.

Deshpande, P.C., Brattebø, H., Fet, A.M., 2019. A method to extract fishers' knowledge (FK) to generate evidence for sustainable management of fishing gears. MethodsX 6, 1044–1053.

Deshpande, P.C., Philis, G., Brattebø, H., Fet, A.M., 2020a. Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. Resour. Conserv. Recycl. X 5, 100024.

Deshpande, P.C., Skaar, C., Brattebø, H., Fet, A.M., 2020b. Multi-criteria decision analysis (MCDA) method for assessing the sustainability of end-of-life alternatives for waste plastics: a case study of Norway. Sci. Total Environ. 719, 137353.

Duguy, R., Moriniere, P., Le Milinaire, C., 1998. Factors of mortality of marine turtles in the Bay of Biscay. Oceanol. Acta 21, 383–388.

EC, 2018a. DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Port Reception Facilities for the Delivery of Waste from Ships, Repealing Directive 2000/59/EC and Amending Directive 2009/16/EC and Directive 2010/65/EU. European Commission, Directorate-General for Mobility and Transport, Strasbourg.

EC, 2018b. A European Strategy for Plastics in a Circular Economy.

EC, 2018c. Proposal for a Directive of The European Parliament and of The Council on the reduction of the impact of certain plastic products on the environment. In: EUROPEAN COMMISSION, E (Brussels).

Edinger, E.N., Jompa, J., Limmon, G.V., Widjatmoko, W., Risk, M.J., 1998. Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. Mar. Pollut. Bull. 36, 617–630.

Environment, N. M. O. C. A. 2022. Norwegian Plastics Strategy. Environment, N. M. O. C. A. (Norway).

FAO (Ed.), 2013. Fishery and Aquaculture Country Profiles. Norway. 2011–2018, 2013 ed. FAO Fisheries and Aquaculture Department.

FAO, 2019. Voluntary Guidelines on the Marking of Fishing Gear. Food and Agricultural Organisation of the United Nations Rome, Italy.

FAO, 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action, FAO, Rome.

FAO, 2021. Assessment of agricultural plastics and their sustainability. In: A Call for Action. Rome. https://doi.org/10.4060/cb7856en.

Fet, A.M., Deshpande, P.C., 2023. Closing the loop: Industrial ecology, circular economy and material flow analysis. In: Fet, A.M. (Ed.), Business Transitions: A Path to Sustainability: The CapSEM Model. Springer International Publishing, Cham.

Fisheries, D.O., 2010. Description of Relevant Fishing Gear and Fishery Activities in the Norwegian Economic Zone. Directorate of Fisheries, Norway, Norway.

Fisheries, N.D.O., 2022. In: Fisheries, N.D.O. (Ed.), Economic and Biological Figures from Norwegian Fisheries 2022. Norway. Retrived on Sep. 2023. https://tableau.fiskeridir.no/t/Internet/views/Fiskefarty/Fiskeflten.

Fiskeridirektoratet, 2022. Tapte redskap. Retrieved 5 July 2022 from. https://portal.fiskeridir.no/portal/apps/webappviewer/index.html?id=9e35f133ef924d68bfa0455965230f5a.

Fraser, M., Haigh, L., Soria, A.C., 2023. The Circularity Gap Report 2023. https://circulareconomy.europa.eu/platform/en/knowledge/circularity-gap-report-norway.

Gall, S.C., Thompson, R.C., 2015. The impact of debris on marine life. Mar. Pollut. Bull. 92, 170–179.

GESAMP, 2021. Sea-based sources of marine litter. In: Gilardi, K. (Ed.), (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 108 (109 pp.).

Gilardi, K.V.K., Carlson-Bremer, D., June, J.A., Antonelis, K., Broadhurst, G., Cowan, T., 2010. Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. Mar. Pollut. Bull. 60, 376–382.

Gu, F., Guo, J., Zhang, W., Summers, P.A., Hall, P., 2017. From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Sci. Total Environ. 601-602, 1192–1207.

Havas, V., Falk-Andersson, J., Deshpande, P., 2022. Small circles: the role of physical distance in plastics recycling. Sci. Total Environ. 831, 154913.

Hermann, R.R., Pansera, M., Nogueira, L.A., Monteiro, M., 2022. Socio-technical imaginaries of a circular economy in governmental discourse and among science, technology, and innovation actors: a Norwegian case study. Technol. Forecast. Soc. Chang. 183, 121903.

Hong, S., Lee, J., Lim, S., 2017. Navigational threats by derelict fishing gear to navy ships in the Korean seas. Mar. Pollut. Bull. 119, 100–105.

Huntington, T., 2019. Marine Litter and Aquaculture Gear–white Paper. Report Produced by Poseidon Aquatic Resources Management Ltd for the Aquaculture Stewardship Council, 20.

Johnsen, H.R., Johannessen, E.R., Roland, A.O., Johannessen, F., 2020. Fishing for Litter som tiltak mot marin forsøpling i Norge – Årsrapport 2020 (1054). Retrieved 5 July 2022 from. https://salt.nu/assets/projects/SALT-1054-Fishingfor-Litter-som-tiltak-mot-marin-forsopling-i-Norge–Arsrapport-2020-1613653318.pdf.

Krauklis, A.E., Karl, C.W., Gagani, A.I., Jørgensen, J.K., 2021. Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. J. Compos. Sci. 5, 28.

Kubiczek, J., Derej, W., Hadasik, B., Matuszewska, A., 2023. Chemical recycling of plastic waste as means to implement the circular economy model in the European Union. J. Clean. Prod. 136951.

Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Marine Debris: Sources, Impacts, and Solutions, pp. 99–139.

Lawson, R., 2015. In: Affairs, T. N. M. O. F. (Ed.), Mini-facts About Norway. Statistics Norway's Information Centre, Oslo, Norway.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., Noble, K., Debeljak, P., Maral, H., Schoeneich-Argent, R., Brambini, R., Reisser, J., 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Sci. Rep. 8, 4666.

Lindhqvist, T., 1992. Extended Producer Responsibility as a Strategy to Promote Cleaner Products. Lund University, Department of Industrial Environmental Economics.

Macfadyen, G., Huntington, T., Cappell, R., 2009. Abandoned, lost or otherwise discarded fishing gear. In: UNEP Regional Seas Reports and Studies, No. 185. FAO Fisheries and Aquaculture Technical Paper, No. 523. Rome, UNEP/FAO.

NCP, 2022. Public resirkulert.

Neves, A., Godina, R., Azevedo, S.G., Matias, J.C., 2020. A comprehensive review of industrial symbiosis. J. Clean. Prod. 247, 119113.

Nogueira, L.A., Kringelum, L.B., Olsen, J., Jørgensen, F.A., Vangelsten, B.V., 2022. What would it take to establish a take-back scheme for fishing gear? Insights from a comparative analysis of fishing gear and beverage containers. J. Ind. Ecol. 26, 2020–2032.

O'Hanlon, N.J., Bond, A.L., Lavers, J.L., Masden, E.A., James, N.A., 2019. Monitoring nest incorporation of anthropogenic debris by Northern Gannets across their range. Environ. Pollut. 255, 113152.

Oxvig, U., Hansen, U.J., 2007. Fishing gears. In: Fisheries Circle. http://www.fisheriescircle.com/home/educationalmaterials/educationalmaterials/fishinggears.

Paul, H., Helmut, R., 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers, Washington, DC.

Phillips, C., 2017. Ghostly encounters: dealing with ghost gear in the Gulf of Carpentaria. Geoforum 78, 33–42.

Phillips, R.A., Ridley, C., Reid, K., Pugh, P.J.A., Tuck, G.N., Harrison, N., 2010. Ingestion of fishing gear and entanglements of seabirds: monitoring and implications for management. Biol. Conserv. 143, 501–512.

Rent, H.N., 2021. RYDDERAPPORTEN 2020. In: Dahl, M.S. (Ed.), Hold Norge Rent. Miljødirektoratet, Oslo.

Richardson, K., Gunn, R., Wilcox, C., Hardesty, B.D., 2018. Understanding causes of gear loss provides a sound basis for fisheries management. Mar. Policy. 96, 278–284.

Salt, M., 2018. In: Norway, T. E. D. O. (Ed.), Subsidy to Investigate Producer Responsibility for the Fisheries and Aquaculture Industry. The Environmental Directorate of Norway, Norway.

Smith, S.D.A., Gillies, C.L., Shortland-Jones, H., 2014. Patterns of marine debris distribution on the beaches of Rottnest Island, Western Australia. Mar. Pollut. Bull. 88, 188–193.

Stolte, A., Schneider, F., 2018. Recycling Options for Derelict Fishing Gear.

Su, C.-T., Schneider, F., Deshpande, P.C., Xiao, H.-Y., Su, T.-A., Yen, N., Lin, H.-T., 2023. Material flow analysis of commercial fishing gears in Taiwan. Mar. Pollut. Bull. 190, 114822.

Sundt, P., Briedis, R., Skogesal, O., Standal, E., Johnsen, H.R., Schulze, P.-E., 2018. Underlag for å utrede produsentansvarsordning for fiskeri og akvakulturnæringen. Miljødirektoratet, Hentet fra. https://tema.miljodirektoratet.no/no.

Uekert, T., Singh, A., Desveaux, J.S., Ghosh, T., Bhatt, A., Yadav, G., Afzal, S., Walzberg, J., Knauer, K.M., Nicholson, S.R., 2023. Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics. ACS Sustain. Chem. Eng. 11 (3), 965–978.

Wenneker, B., Oosterbaan, L., 2010. Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area. Edition 1.0.