Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

Sidra Tul Muntaha

Plastic Ropes in Marine Applications: Analysing Problems and Proposing Remedies

Master's thesis in Industrial Ecology
Supervisor: Paritosh Chakor Deshpande
Co-supervisor: Sigrun Jahren and Karl Klingsheim
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Abstract

Marine plastic pollution is a problem for both marine and terrestrial animals. Plastic polymers have entered the human food chain through micro and nano-plastic materials. Although globally, both land-based and marine-based sources contribute to the marine plastic pandemic, plastic waste from ropes dominates the marine waste fractions in the Nordic region. The case study depicting the fate, handling, and management practices of ropes in Norway has been chosen. This is important for Norway due to its long coastline and its economy being majorly dependent on fisheries and aquaculture activities.

The large volume of ropes used in fisheries and aquaculture are made from many different polymers and a composite of polymers and metals. The complex design, heterogeneous materials, and multi-actor involvement present significant challenges in closing the loop for ropes. Therefore, a large proportion of the ropes in Norway are eventually incinerated or exported for recycling abroad.

Static material flow analysis is performed to map the relevant stakeholders and volume flow along the lifecycle of ropes which indicates huge opportunities for material and monetary resources to stay within Norway. It was, therefore, relevant to study the material of ropes and their recyclability. With the aid of literature and interaction with the relevant stakeholders, a material inventory for ropes was created which is the holistic mapping of ropes based on their applications, properties, material types and ease of recycling.

Results show that the volume of ropes utilized in the aquaculture sector is considerably greater compared to the fishery. Ropes used in both sectors, fisheries and aquaculture, are mostly exported abroad, and only 7.5% are recycled in Norway. Inventory data demonstrates that 19 rope types have different material mixes and the recycling technology of most of these ropes is not known. Ropes were ranked according to the ease of recycling in Norway and this provides an overall directory for the recyclers in effective recycling as well as for producers to design to recycle at the end-of-life of the ropes. The research will also initiate a discussion by all the stakeholders, particularly on the need for industrial symbiosis, small circles, extended producer responsibility, labelling of ropes and eco-designing of ropes for improving their recyclability upon end-of-life. This will not only lead to ropes becoming circular but will also result in efficient use of resources, financial incentives, and employment generation. Overall, more responsibility is placed on producers and recyclers for closing the loop of ropes in Norway.

Keywords: Marine Plastic Pollution, Ropes, Material Flow Analysis, Recycling, Circular Economy

Preface

This thesis is submitted to the Norwegian University of Science and Technology, NTNU as part of the partial fulfilment of the requirements for the Master of Science (MSc) degree. The work was carried out in the spring of 2022 at the Department of Industrial Economics and Technology Management under the course code: TIØ4955 - Industrial Ecology, Master's Thesis.

The work has been supervised by Associate Professor Paritosh Chakor Deshpande of NTNU Department of Industrial Economics and Technology Management and co-supervised by Adjunct Professor Karl Klingsheim and Associate Professor Sigrun Jahren of NTNU Department of Energy and Process Engineering.

This thesis is contributing to "SHIFT-Plastics Project: Shifting to sustainable circular values chains for handling plastics in the fisheries and aquaculture sector" which is an Industry-Academia collaborative project funded by the Norwegian Research Council (Project nr. 326857).

Acknowledgement

I would like to express my foremost gratitude to my supervisor Paritosh Chakor Deshpande who has been an inspiration to me during my project work. This thesis would not have been possible without his support, motivation, and encouragement. Whenever I ran into confusion, I would contact him without hesitation. I am utmost grateful to him for his useful feedback and engagement throughout. Staying calm and moving forward with the process regardless of the circumstances is surely the skill that I learned from him.

I would also like to extend my thanks to my co-supervisors, Karl Klingsheim and Sigrun Jahren for always giving me a chance to speak out my ideas and discuss them. Their encouragement gave me the support to think out of the box.

Without stakeholders' participation and their productive input, this thesis would not have been possible. Therefore, I would like to acknowledge stakeholders in Norway from industry, academia, waste handling and management, and recyclers working in the fisheries and aquaculture sectors.

I am much obliged to the 7th International Marine Debris Conference (7IMDC) for accepting this thesis abstract for poster presentation at a conference in Seoul from 18-24th September 2022. Presenting at this conference is significant as like-minded people working towards the solution to marine plastic pollution are of utmost relevance to my ambitions in life. Moreover, I am grateful for TEKSET 2022 conference that took place on 4-5th May 2022 in Trondheim, where I had the chance to present my thesis work on a stand and interact with companies in aquaculture.

Special thanks to my friends, Sara Yasmin Khan, Rimsha Zafar, Vedant Ballal and Modi Elisa who were always there to extend their help. They made my stay in Trondheim fun and memorable. It is worth mentioning my friend from my home country, Zainab Farooq who proofread my thesis.

My family's love, efforts, and prayers helped me achieve my goals and ambitions in life. My parents bestowed trust and motivation in me to grow as an individual. My brother was always there to make me laugh with his lame jokes. Moreover, I am thankful to my best friend and husband, Hassan Mujtaba. He made me realise that in order to make a pathway to conquer the world, hard work is imperative. His love made me strong, and I can never thank him enough for everything he has done for me.

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List of Abbreviations (or Symbols)

EoL	End-of-Life
PP	Polypropylene
PE	Polyethylene
PA	Polyamide
MFA	Material Flow Analysis
NRC	Norwegian Research Council
EU	European Union
EEA	European Economic Area
ALDFG	Abandoned, Lost or otherwise Discarded Fishing Gear
UHMWPE	Ultra-High Molecular Weight Polyethylene
HDPE	High-Density Polyethylene
EPR	Extended Producer Responsibility
LCA	Life Cycle Assessment
HNR	Hold Norge Rent
FU	Functional Unit
MoP	Mass of Plastic
HMPE	High Modulus Polyethylene
HTPP	High Tenacity Polypropylene
LDPE	Low-Density Polyethylene
NCP	Nordic Comfort Products
SWOT	Strengths, Weaknesses, Opportunities, and Threats

1. Introduction

1.1. Background

The impacts of marine plastic pollution can be widely seen in marine ecosystems, habitats, and food webs. There is a concern that chemical pollutants in plastics have an impact on the earth's ecosystems as well. Therefore, it is considered a planetary boundary threat due to physical, chemical, and biological harm (Borrelle et al., 2020; Rochman, 2020; Villarrubia-Gómez, Cornell, & Fabres, 2018). Some of the biodiversity threats to the marine animals and seabirds from marine plastic pollution are entanglement that restricts movement, suffocation if mouth or nostrils get caught, choking as airway passage gets blocked, ingestion that reduces the size of the stomach size causing starvation, and poisoning from the toxins absorbed in the seawater (Sundt et al., 2018; Thushari & Senevirathna, 2020). Terrestrial animals that live on beaches and rely on seafood are also under similar threat as marine animals (Sundt et al., 2018). Plastic pollution in the ocean has turned into an epidemic due to microbial colonization by pathogens when plastic gets entangled in corals. As the coral reef is part of the food chain for humans, marine plastic pollution is not only a problem for marine and terrestrial animals but a potential risk to human health as well (Lamb et al., 2018).

Plastic is broken down into smaller particles especially when exposed to sunlight, wind and waves causing thermal and mechanical degradation (Kershaw, 2015). Plastic particles of sizes ranging from 100 nm to 5mm, known as microplastics, can be further broken into even smaller particles of size less than 100 nm, which are referred as nano-plastics. These fragments have a high surface area to volume ratio that makes them easier for transportation and therefore, these are at high risk of entering marine animals (Nguyen et al., 2019). The exposure of these microplastics and nano-plastics to the ecosystem affects various aquatic species (De Sá, Oliveira, Ribeiro, Rocha, & Futter, 2018) as they ingest these plastic particles (Nguyen et al., 2019). Over the last 50 years, microplastics are often observed and reported in the stomach and intestines of aquatic animals (Gouin, 2020). This has raised concerns regarding the risk of microplastic toxicity in the human food chain as it constitutes reliance on marine life as well (Egbeocha, Malek, Emenike, & Milow, 2018). The study by (Ragusa et al., 2021) has shown evidence of the presence of microplastics in the human placenta.

The plastic circular economy is not up to the mark and hence the plastic waste is still ending up in the oceans instead of the recycling plants (PlasticsEurope, 2022), majorly due to poor waste management systems (Geyer, Jambeck, & Law, 2017). According to some scientists, if plastics keep on ending up in the oceans in the business-as-usual scenario, then by 2050, there will be more plastic waste instead of fish in the world's oceans (Omstedt, 2020).

Globally, oceans are polluted by plastic through marine-based, and land-based sources (Thushari & Senevirathna, 2020). 28.1% of marine plastic pollution is reported to be from marine-based sources (Lebreton et al., 2018). However, the contribution of sources varies geographically, e.g., the Great Pacific Garbage Patch comprises 52% plastic waste from marine-based sources (Lebreton et al., 2018). Similarly, Norway has significant marine-based sources of plastic pollution (Abate et al., 2020). As mentioned by (Deshpande, Brattebø, & Fet, 2019), Norway has one of the largest coastlines in the world expanding its length to 25,000 km. The study further shows that Norway has significant fish stock, therefore, its economy is heavily dependent on activities based on fishery and aquaculture.

Ropes alone contribute to around 20.9% of marine plastic waste in Norway, according to (Sundt et al., 2018). Further analysis shows that a lot of beach cleaning reports in Norway and Fishing for Litter (pilot project) in 2016-2017 suggest that ropes are one of the major contributors to marine plastic pollution. The same analysis references a beach clean-up activity in 2017 at Lofoten, an island in Norway, which led to 68,200 items being registered, out of which 8,600 were ropes pieces and 3,000 were large ropes. Another example is the North Sea, where dolly rope fibres accounted for 10% of collected total plastic waste.

In Norway, the main cause of ropes ending up in the oceans is their poor management at End-of-Life (EoL)(Deshpande, Skaar, Brattebø, & Fet, 2020). There are several reasons for the mismanagement. One of the major reasons is that marine plastic waste end-up being landfilled (24%) and incinerated (21%) while the rest is mostly recycled abroad as there is a lack of recycling facilities within Norway (Deshpande, Philis, Brattebø, & Fet, 2020). Recycling ropes is difficult due to the heterogeneous and complex materials and design of ropes (Stolte & Schneider, 2018). Only thick and clean ropes made of polypropylene (PP) and polyethylene (PE) are recycled within Norway while other rope types are sent abroad for recycling or reuse (Sundt et al., 2018) with little knowledge of their actual outcome (Bishop, Styles, & Lens, 2020). This also causes Norway to miss out on the benefits reaped from recycling within the country (Deshpande, Philis, et al., 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). These varying material properties and meltability of polymers are necessary to be evaluated before recycling for uniform and homogenized recycled polymer e.g., polyamide (PA) also known as nylon, must be separated from PE and PP as its density and melting point is higher

(Stolte & Schneider, 2018). The ropes are not yet produced with the aim of "design for recycling", however, there are efforts for smart ropes that can be tracked but the knowledge on recycling of these ropes is currently insufficient (Sundt et al., 2018). If the material or design is unknown, then problems can arise during the recycling phase. Different materials in ropes need to be handled differently when pre-sorting for recycling as they can otherwise damage the machinery. For instance, metal in ropes needs to be extracted when pre-sorting for recycling as it can damage the shredder blades (Deshpande, Philis, et al., 2020; Stolte & Schneider, 2018).

In order to solve the global problem of marine plastic pollution, there is a need for the involvement of stakeholders along the whole value chain (Haward, 2018; Omstedt, 2020). As (OSPAR, 2019) mentioned that there is no such thing as a "one size fits all" solution, therefore, there is a need for a solution that can look into the whole value chain and point out the most vulnerable spots within the value chain to reach the most effective solution.

1.2. Research Objectives

Due to limited research on ropes in aquaculture and fisheries within Norway, ropes are quantified using a material flow analysis (MFA) technique. Further, a material/recycling inventory is created by holistic mapping of ropes based on their marine-based applications, material types and ease of recycling.

This thesis will aim in defining circularity strategies along ropes' lifecycle using a multi-stakeholder perspective. Therefore, it will 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 and aquaculture sector?
2. What are the current barriers and opportunities in closing the loop for ropes from the Norwegian fishing and aquaculture sector?

1.3. Problem Scope

According to a study (Stolte & Schneider, 2018), reusability of the ropes is possible if the material and its properties are known, therefore, the lifecycle, types, properties, applications, material contents and recyclability of ropes are studied in detail. Even though the thesis research scope boundary is set to be the case study of Norway, the methodology can be adopted for any other country with similar ecosystems.

After World War II, ropes were replaced by metal and synthetic fibres and are now mostly made with polymer or a mix of polymer and metal (Oxvig & Hansen, 2007). Thus, ropes of any other material are not studied. The applications of the ropes are many, but this thesis will specifically investigate marine-based applications from commercial fisheries and aquaculture as it is one of the major sources of marine pollution within Norway (Sundt et al., 2018). The different types of ropes in these applications vary according to the properties required. The rest of the marine-based applications are beyond the scope of the study as they contribute little to the marine plastic pollution problem.

There are different stakeholders involved in the lifecycle of ropes in the fisheries and aquaculture sectors. In this thesis, manufacturers and suppliers are considered the same who produce, import, and supply ropes within Norway. All types of ropes are treated together by waste management and are further segregated by recyclers. Ropes used in land-based activities are not included in this thesis as they are composed of different materials and applications. Ropes are often confused with terms such as cables, wires, chains, and nets. These terms are out of the scope of the thesis but are explained in **Appendix A** to improve the understanding of a reader. The scope of the thesis is described in **Figure 1**.

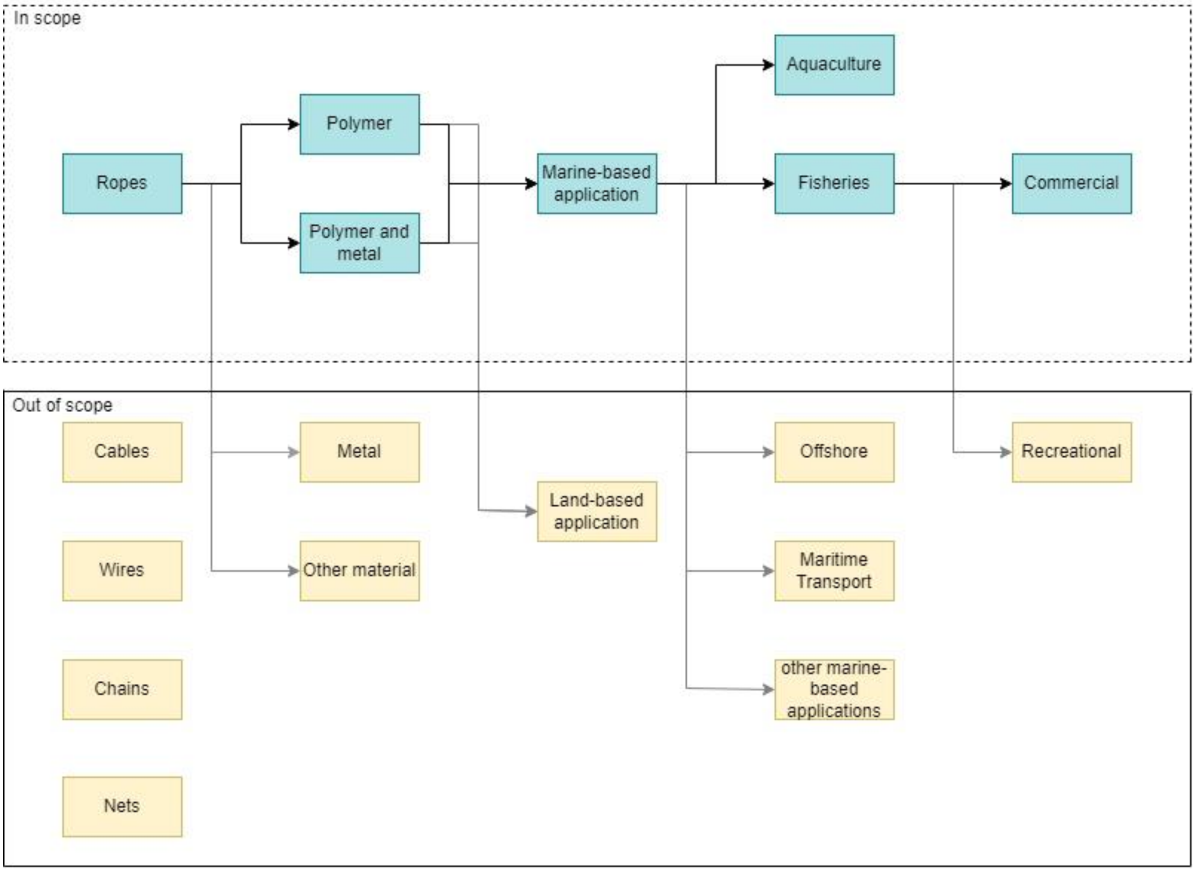

Figure 1. Problem scope flowchart.

1.4. Thesis Structure

The thesis is divided into 6 chapters as shown in **Figure 2**.

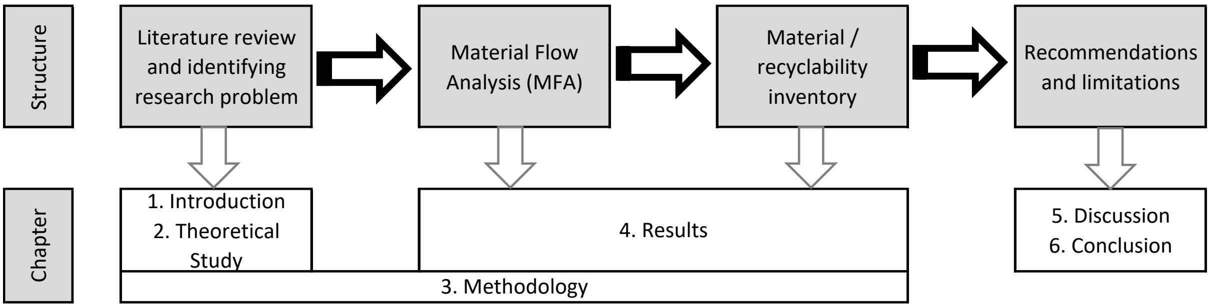

Figure 2. Thesis structure flow.

The first chapter of the thesis is an introduction to the research topic. It starts with discussing the background of the topic and then continues to explain the research objectives and problem scope.

The second chapter is the theoretical study of the ropes explaining its structure, applications, material, and challenges.

The third chapter is the methodology section which lets the reader know how the thesis research is carried out and what procedures were followed. There is an insight into the method adopted for carrying out a literature review, interviews and questionnaires, MFA and inventory of material and recyclability.

The fourth chapter is the results section where MFA is done for the aquaculture and fisheries sector to know the lifecycle and volume flow of ropes in Norway. Further, the materials/recyclability inventory of the different types of ropes used in Norway's aquaculture and fisheries sector is presented.

The fifth chapter is a discussion where results are elaborated. The issues relating to the circularity of ropes are also discussed to understand the solution for closing the loop in the fisheries and aquaculture sector. This further discusses the limitations of the research and recommendations for future research.

The last chapter is a conclusion that is the overall outcome of the research and a reflection from the author is given.

Lastly, the thesis ends with the reference lists followed by supplementary material in the appendix section.

2. Theoretical Study - Ropes

As discussed in the background, ropes are the major contributor to marine plastic pollution and are a difficult recyclable fraction. Therefore, this section is dedicated to knowing the rope itself. It will particularly investigate the theory of ropes from its structure, applications, material, and problems perspective.

2.1. Structure

Ropes structure in the literature is well defined by (Oxvig & Hansen, 2007). According to it, ropes are made of varying thickness and numbers of strands that are again made of varying thickness and number of yarns. Yarn is weaved together of fibres. Further, the study also explains the multiple ways ropes can be laid in terms of varying designs and measurements. The way the rope is laid depends on the hardness of the rope. The same study suggests that the softly laid rope is easy to splice and doesn't kink but hard-laid ropes are of high wear resistance.

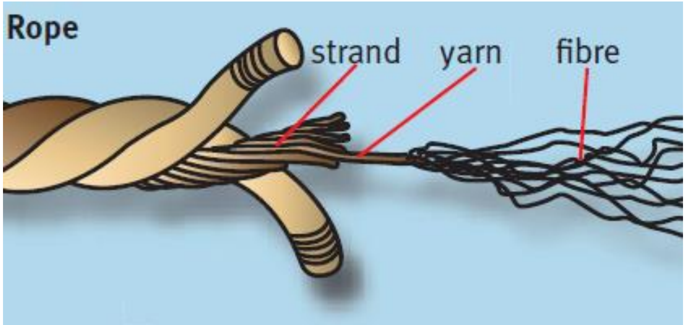

Figure 3. Structure of rope *(Oxvig & Hansen, 2007)*.

In addition, (Oxvig & Hansen, 2007) categorise ropes into two types that are either twisted or braided, as explained below:

In **twisted ropes**, there are twisting levels: beginning with fibres, yarns and then strands. The direction of twisting is important in deciding the desired property.

Figure 4. Twisted ropes ©Sidra Tul Muntaha 2022.

Braided ropes are structured in a way that is crisscrossed in a diagonal direction. The fibres may have been pre-twisted. These types of ropes are often used in the replacement of metal wires.

Figure 5. Braided ropes ©Sidra Tul Muntaha 2022.

2.2. Applications

Aquaculture is marine animal and plant farming (Tacon, 2020) and is mostly known as fish farming. Therefore, it is a method for breeding fish in water in a human-controlled environment (Goldburg & Naylor, 2005). It could be both land-based and sea-based, but the thesis will only cover aquaculture based in seawater. In Norway, salmon is the most cultivated fish in aquaculture (Bjelland et al., 2015). Most of the ropes in aquaculture are imported which forms the largest share, especially in the application of mooring (Sundt et al., 2018).

Fisheries in the sea can be divided into two categories: Recreational and commercial fishing. As only commercial fishing is within the scope of the study, information on recreational fishing for clarity between the two categories can be found in **Appendix B**.

Commercial fishing is done by registered fishers (Zimmermann, Kleiven, Ottesen, & Søvik, 2022). Norway is one of the leading industries in this sector too as it alone contributes to one-third of the total catch in the European Union (EU) and European Economic Area (EEA). One of the reasons is its long coastline and the other is modern vessels (Deshpande, Skaar, et al., 2020). According to (Deshpande, Philis, et al., 2020), 380 tons/year of plastics from fishing gear are lost in the ocean from commercial fishing activities in Norway. Ropes are a part of fishing gear that is the physical equipment used underwater for capturing marine animals (Deshpande, Philis, et al., 2020). Fishing gear can be categorized as one of the worst waste fractions (Wilcox, Mallos, Leonard, Rodriguez, & Hardesty, 2016) for marine animals since Abandoned, Lost or otherwise Discarded Fishing Gear (ALDFG), also known as "ghost fishing", can have long-term detrimental impacts on marine life (Macfadyen, Huntington, & Cappell, 2009).

Possible key applications of ropes in aquaculture and fisheries are mentioned below in **Table 1** and further details can be found in **Appendix C**.

Table 1. Possible key applications of ropes in aquaculture and fisheries sector.

Application sector	Possible key applications of ropes	Literature source
Aquaculture	Mooring, Hauling, Buoy line, Floating collar, Cage	(Drury & Crotty, 2022; Xu & Qin, 2020)
Fisheries	Gillnets, hook-and-line gear, trawling, seines, Anchoring	(Directorate of Fisheries, 2010)

The applications according to each rope type are studied while creating an inventory and are presented in the results section.

2.3. Material

The material of ropes is dependent on their applications. The details of the materials according to different types of ropes are missing in the literature and are therefore looked at in this thesis which can be found in the results section.

Majorly ropes are made of polymers or polymers with metals (Sundt et al., 2018). The most used polymers are PP, PE, PA, polyester, Ultra-High Molecular Weight Polyethylene (UHMWPE), High-Density Polyethylene (HDPE) (APEM, 2020; Sundt et al., 2018). Sometimes, these polymers have the addition of lead, steel and copper as metals (Sundt et al., 2018). The density of the material of the rope decides its application based on its floatability and sinking. PE, PP and HDPE float while metal and PA sink (APEM, 2020; Stolte & Schneider, 2018).

Different polymers have different recycling potentials therefore, their market value varies at the EoL. PA has much higher supply and demand due to higher market value because of its greater tensile force than PE and PP, though PE and PP are abundantly available in the market (Sundt et al., 2018). Like the properties of materials are an important factor in deciding the applications, it is also important in deciding the recyclability e.g., the melting point of PA and polyester is higher than PE and PP, thus recycling together as a mixture is not recommended (Stolte & Schneider, 2018).

Reuse is the most financially feasible option benefiting material reserves as well. Recycling is done mostly in Europe but the ropes for reuse are sent to Asia (Sundt et al., 2018).

2.4. Problems

At the EoL, existing practices to treat plastic waste are based on the approach of waste management hierarchy. In order of least preferred to most preferred, it is as follows:

1) Disposals such as landfilling and open burning without energy recovery
2) Recovery such as energy recovery in incineration
3) Recycling
4) Reuse
5) Waste prevention (Christensen, 2011).

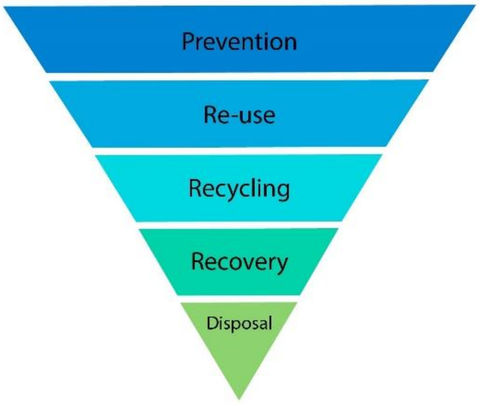

Figure 6. Waste management hierarchy (Adapted from (*Christensen, 2011*)).

Regardless of the waste hierarchy present, ropes are still ending up in the ocean causing marine plastic pollution. The problem is not only linked to the EoL stage but there are various problems at various stages in the lifecycle of ropes that lead it to leak into the marine environment. They are mentioned in **Table 2**:

Table 2. Problems across the lifecycle of ropes are identified in the literature.

Lifecycle Stages	Problems associated across the lifecycle	Literature Source
Production	1) Composite polymer materials 2) Economically cheaper to produce from raw materials 3) Imported ropes and raw material from Asia 4) Absence of Extended Producer Responsibility (EPR)	(OSPAR, 2019; Sundt et al., 2018)
In-use	1) Short-lived life span 2) Ghost fishing from ALDFG 3) Marine ecosystem impacted	(Deshpande & Haskins, 2021;

	4) Adhering to stringent quality requirements that are not met by recycled material	Sundt et al., 2018)
Waste Management	1) Lost or thrown in the ocean 2) Thrown away illegally or burned 3) No landfill ban on plastic waste in Norway 4) Exported abroad where they end up in landfills or dumped at sea 5) A lot of landfill sites near the entire coast 6) Grinding before incineration is necessary 7) Port facilities scarcity for collection 8) Guidelines and regulations missing for EoL waste collection and management 9) Volumes distributed along the long coast of Norway that are expensive to collect and treat	(Deshpande & Haskins, 2021; Deshpande, Philis, et al., 2020; Macfadyen et al., 2009; Sundt et al., 2018)
Recycling	1) Norwegian regulations on plastic sorting for aquaculture and fisheries are missing 2) Mixed waste is difficult for sorting 3) Manual disassembly before recycling 4) Ropes with metal are problematic 5) Infrastructure and technology missing 6) Lack of economical benefits 7) Unknown and mixed material composition 8) Volumes are distributed unequally among waste management companies	(Deshpande & Haskins, 2021; Deshpande, Philis, et al., 2020; Sundt et al., 2018)

3. Methodology

This section details the research methods applied. These methods were designed to support the Shift-Plastics (2021-2024) which is an NRC Funded project. It aims to create sustainable circular value chains for plastics in the fisheries and aquaculture sector in Norway by bringing innovation to the collection, pre-treatment, and recycling of plastics. The work of Shift-Plastics includes conducting laboratory tests, literature studies, MFA, Life Cycle Assessment (LCA), and economic cost analyses. This thesis focuses on ropes plastic waste in the fisheries and aquaculture sector and uses the research methods of literature review, interviews and questionnaires, MFA, and inventory formation to aid the work of Shift-Plastics. Details of the methodology applied are elaborated in **Figure 7**.

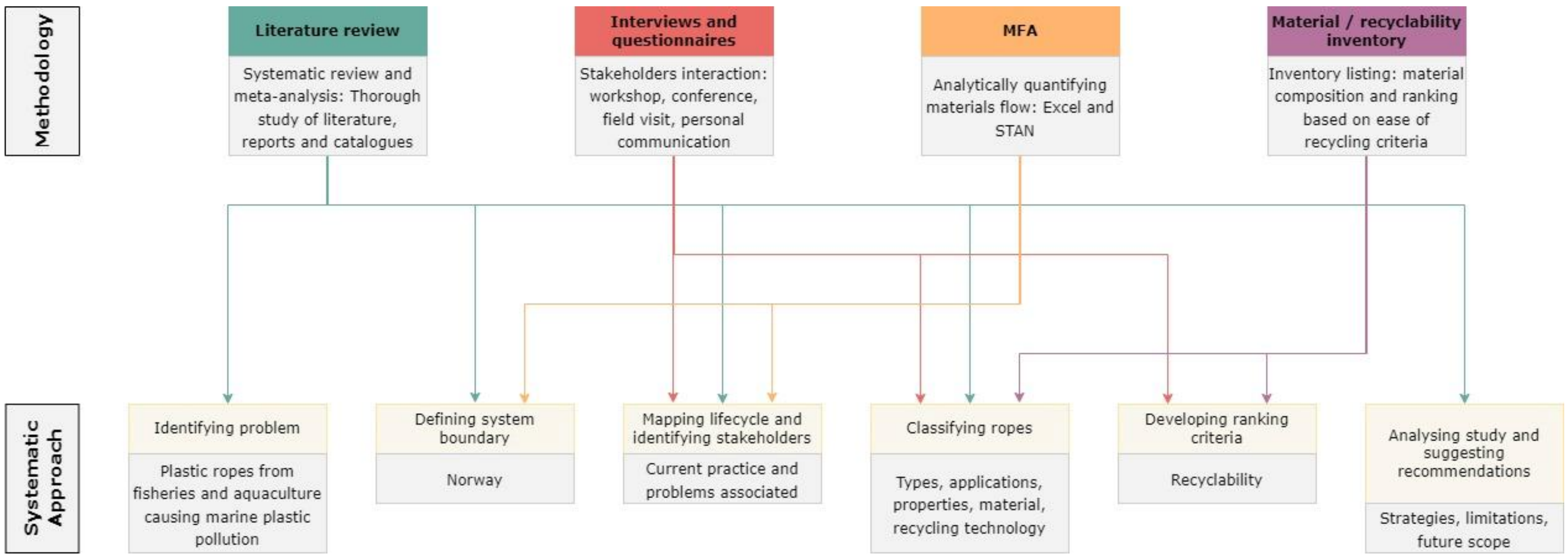

Figure 7. Thesis methodology flow.

3.1. Literature Review

A literature review involves a secondary analysis of knowledge and concepts that have already been published. The use of doing this is to demonstrate existing knowledge on a given topic and identify gaps and opportunities for further research (Jesson, Matheson, & Lacey, 2011). The literature review was performed using Google Scholar and Scopus as the main database platform for undertaking a literature review. The following keywords were used:

'Ropes in Norway', 'Ropes in aquaculture', 'Ropes in fisheries', 'Aquaculture and fisheries', 'Types of ropes', 'Circular economy and ropes', 'Material Flow Analysis', 'MFA of ropes'

However, after extensive research, it was realized that not much literature was publicly available on this topic and therefore, this thesis uses data from a variety of sources to paint a complete picture. These sources were usually reports of collaborative ventures between stakeholders or research by research institutes that are not published in journals. These unpublished reports were obtained from expert sources, mostly working in SINTEF.

As a next step, collection of the volume of ropes and details on transfer coefficients was also collected using the literature, particularly (Deshpande, Philis, et al., 2020), (Alnes, 2022) and (Sundt et al., 2018). Information on lost ropes retrieved from the ocean was collected from a web tool for logging data on clean-ups by the Norwegian Directorate of Fisheries (Fiskeridirektoratet, 2022) and data report from Fishing for Litter (Johnsen, Johannessen, Roland, & Johannessen, 2020) while the data collected from the beaches is obtained from Hold Norge Rent (HNR). Use of tool Rydde was made from www.ryddenorge.no which included details of litter collections classified under certain categories. This tool included details of all litter collected, even from organizations other than HNR i.e., Runde Miljøsenter, Lofoten Avfallsselskap, Clean-Up Lofoten and In The Same Boat (Johannessen, 2018).

Furthermore, data on specific rope types were studied from catalogues of ropes available on suppliers' websites. These suppliers included Mørenot AS, Selstad, Fiskevegn AS, Greenline Fishing Gear, Frøystad AS, Badinotti Peru, Nofi AS, Egersund Herøy AS and OK Marine AS. This helped to study rope types in Norway, but limited data was found on the material of ropes. Further research on the material was done by using the search engine Google.

3.2. Interviews and Questionnaires

At times, information from stakeholders was the only available source when no publicly disclosed information was found. Therefore, there were multiple interviews, conferences and workshops attended with relevant stakeholders to gather information. The details of the type of stakeholders contacted and the type of information obtained are detailed in **Table 3**.

Table 3. Type of data obtained from relevant stakeholders.

Stakeholders	Materials	Volume	Technology	Use phase	End-of-life phase	Recyclability
Producer/Supplier	✓	✓	✓			
Users (Aquaculture and fishers)			✓	✓		
Port and harbour administration		✓			✓	
Government					✓	
NGOs					✓	
Researchers and academia	✓					✓
Waste collection and management		✓			✓	✓
Recyclers	✓	✓	✓		✓	✓

The timeline at which interviews, conferences, workshops, and questionnaires are completed on google forms is indicated in **Table 4**.

Table 4. Timeline and purpose of the interaction with the stakeholders.

Date	Company/ Project	Stakeholders/ Position	Format	Location	Purpose
23-Mar-22	SINTEF	Research Scientist in the Climate and Sustainability Group	Interview	Online	Connections formed
29-Mar-22	Blue Circular Economy	Academia, research centres, industries, and municipalities	Hybrid Conference	Ålesund	Details on recent research on fishing gear pollution
1-Apr-22	Bellona.no	Senior advisor – Aquaculture	Interview	Online	Connections formation, refinement of questionnaires and literature sharing
8-Apr-22	SINTEF	Research scientist in Materials and Nanotechnology Senior Research Scientist in Fisheries and new Biomarine industry	Interview	Online	Expert opinion on material aspects of ropes and literature sharing

3-May-22	Shift-Plastics	Industry, academia, waste handling and management, and recyclers working in the fisheries and aquaculture sector	Workshop	Bodø	Connections formation and verbal answering of a questionnaire (**Appendix D**). Value chain challenges in aquaculture mapping including materials in use and establishing a model circular value chain
25-May-22	Selstad	Head of Sustainability	Interview	Online	Discussion on material composition and volume of ropes
		Research and Development Manager	Interview	Online	
23-Jun-22	Oceanize	Project Managers from the Communications Department, Value Chain Manager, and Field Workers	Field Visit	Ottersøya	Understanding of plant operations and problems dealing with ropes. Flowchart mapping on mechanical recycling within Norway (**Figure 8**) Filling of Questionnaires (**Appendix E**) and obtaining data on the volume of ropes recycled
5-Jul-22	Selstad	Head of Sustainability	Interview	Online	Discussion on the material composition of ropes and a questionnaire on volumes of ropes handled was sent (**Appendix F**)
14-Jul-22	SINTEF	Research scientist in Materials and Nanotechnology	Interview	Online	Expert opinion on the recyclability of ropes and literature sharing
11-Aug-22	Quantafuel ASA	Business Development Manager	Interview	Online	Discussion on recyclability within Norway

In addition to stakeholders' engagement, multiple meetings were held with the supervisor and co-supervisors in the formulation of this thesis work.

Moreover, mechanical recyclers from Trøndelag were involved in updating the mechanical recycling mapping flow happening in Norway as a pilot plant. This had been initially mapped by (Deshpande, Skaar, et al., 2020). The updated process flow of mechanical recycling in Norway is shown in **Figure 8**. The mechanical recycling in the pilot plant has two types of pallets, namely high-grade recycled pallets and low-grade recycled pallets as shown in **Figure 9**.

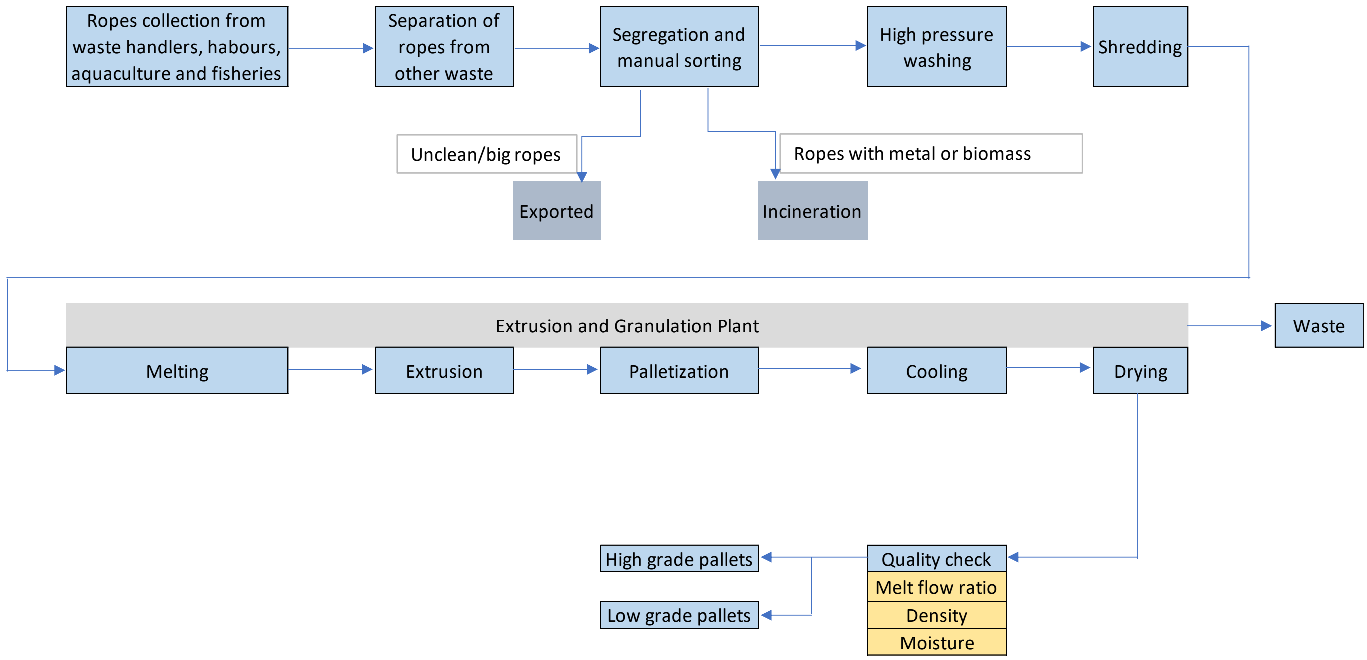

Figure 8. A typical process flow diagram for mechanical recycling of plastics in Norway.

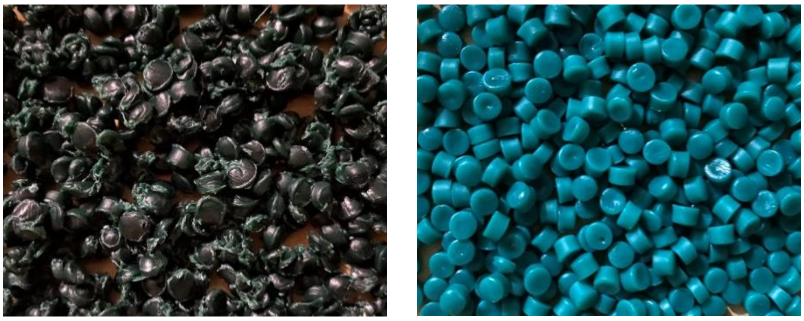

Figure 9. Low-grade recycled pallets on the left side and high-grade recycled pallets on the right side © Sidra Tul Muntaha 2022.

3.3. MFA

MFA is an evaluation of the changes in the flow and stocks of materials defined in space and time (Brunner & Rechberger, 2016). Materials can refer to both goods and substances. The system consists of both flows and processes (Cencic & Rechberger, 2008). 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 & Helmut, 2004). Diagrammatically, processes are depicted through black boxes which signifies that detailed information within the process is not taken into consideration, but inputs and outputs are indicated. Flows are present to act as connectors to processes. Flows that cross the system boundary are known as import or export flows. Names of flows are taken from the good that is transported through them (Cencic & Rechberger, 2008). Static MFA models show the current state of the systems at a specific time (Allesch & Brunner, 2017). MFA has multiple applications and is most useful in analysing resource efficiency, and resource and waste management that helps in policy formation (Brunner & Rechberger, 2016).

3.3.1. System Description

The Functional Unit (FU) of MFA is one tonne of plastic in ropes and the system boundary is Norway for the year 2020. The FU passes through the processes of fisheries/aquaculture activities, and waste management at EoL while some are lost in the ocean. Lost ropes in the ocean are retrieved from the oceans and the beaches through clean-ups. After collection of ropes from oceans and beach clean-up activities, these are sent to waste management facilities where these are segregated between recycling, landfilling and incineration fractions. The system is adapted from (Deshpande, Philis, et al., 2020) which is further extended to the recycling process within Norway based on communication with the regional mechanical recyclers from Trøndelag. In the category of recycling, these are recycled mechanically or are sent abroad. Moreover, talking to stakeholders, the repair part is removed as ropes are not majorly repaired. The following **Figure 10** shows the complete MFA system that was made using Microsoft Excel software. This material flow system is in general for fisheries and aquaculture. The only difference is that in aquaculture, there are no lost ropes in the ocean according to the expert opinion from the stakeholders. Thus, the ocean process and therefore, flow A1-2, A2-3a and A2-3b are absent.

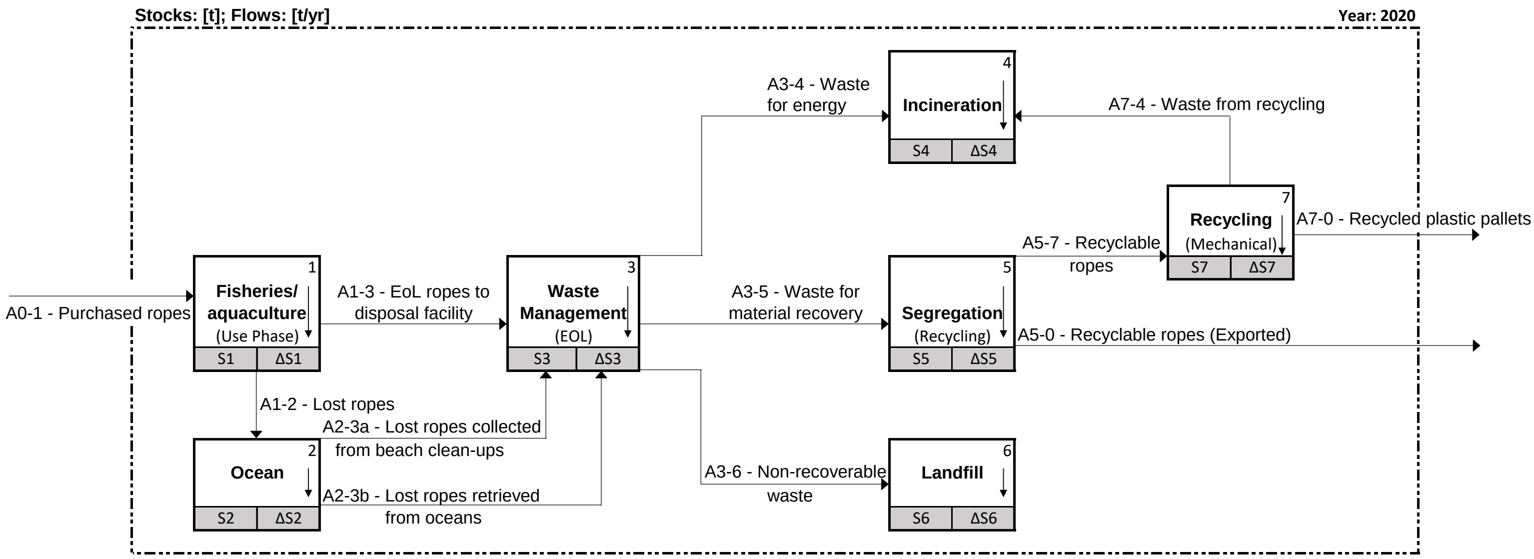

Figure 10. Blank MFA system.

3.3.2. Calculations and Uncertainty

There are 7 processes and 17 variables in the MFA system. This is assuming no stock and no stock change in process numbers: 3 (waste management), 5 (segregation), and 7 (recycling). For process number 4 (incineration) and 6 (landfill), stock change is considered because further flows are not taken into account as they are beyond the scope of our study. The calculations were performed on Microsoft Excel for each process through the equations mentioned below in **Table 5.**

Table 5. MFA calculation data of variables, data sources and flow equations.

Variable symbol	Variable name	Data source	Equation
$A_{0\text{-}1}$	Purchased ropes (t/yr)	(Alnes, 2022) and Rope Suppliers	$A_{01} = \sum \text{purchased ropes}$
$A_{1\text{-}2}$	Lost ropes (t/yr)	(Deshpande, Philis, et al., 2020)	$A_{12} = \sum C_{lost} \cdot (A_{01} + A_{01} \cdot C_{stock})$
$A_{1\text{-}3}$	EoL ropes to disposal facility (t/yr)	(Deshpande, Philis, et al., 2020)	$A_{13} = \sum C_{dispose} \cdot (A_{01} + A_{01} \cdot C_{stock})$
$A_{2\text{-}3a}$	Lost ropes collected from beach clean-ups (t/yr)	Data in units: Rydde/HNR Mass conversion factor: (Deshpande, Philis, et al., 2020)	$A_{23a} = \sum$Collected ropes at beach (unit) · MoP in ropes at beach (kg/unit)
$A_{2\text{-}3b}$	Lost ropes retrieved from oceans (t/yr)	Data in units: The Norwegian Directorate of Fishery (Johnsen et al., 2020) and Fishing for Litter (Fiskeridirektoratet, 2022) Mass conversion factor: (Deshpande, Philis, et al., 2020)	$A_{23b} = \sum$Retrieved ropes from ocean (unit) · MoP in ropes from ocean (kg/unit)
$A_{3\text{-}4}$	Waste for energy (t/yr)	(Alnes, 2022)	$A_{34} = \sum C_{incineration} \cdot (A_{13} + A_{23a} + A_{23b})$
$A_{3\text{-}5}$	Waste for material recovery (t/yr)	(Alnes, 2022)	$A_{35} = \sum C_{Segregation} \cdot (A_{13} + A_{23a} + A_{23b})$

A_{3-6}	Non-recoverable waste (t/yr)	(Alnes, 2022)	$A_{36} = \sum C_{Landfill} \cdot (A_{13} + A_{23a} + A_{23b})$
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/ aquaculture (t)	(Deshpande, Philis, et al., 2020)	$S1 + \Delta S1 = \sum C_{Stock} \cdot A_{01}$
$\Delta S2$	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	$\Delta S6 = A_{36}$

These calculations are in general for both the fisheries and aquaculture, though the aquaculture data is mostly retrieved from (Sundt et al., 2018). There are a lot of assumptions involved to refine the best data points that were used to adjust the values accordingly. Specific calculations, equations and data sources on aquaculture can be found in **Appendix G**.

MFA mass balance modelling has been done in STAN v.2.6.801 software which allows for catering to data uncertainties (Brunner & Rechberger, 2016). The STAN v.2.6.801 software is widely used in MFA and contains a graphic user interface. Data uncertainties are calculated using the Gaussian error propagation, assuming a normal distribution. Data reconciliation is another key feature of the system as all input values are constrained by the mass balance equation (Van Eygen, Feketitsch, Laner, Rechberger, & Fellner, 2017).

3.4. Inventory – Material and Recyclability

This thesis identifies the rope types being sold in Norway in the form of a listing inventory. Since brand names of the ropes were not always similar, therefore this study classifies rope types as per their material and application. This inventory further analyses the rope types based on strands being twisted or braided, applications within the fisheries and aquaculture sector, and their properties. This information was identified from the catalogues and Google searches. This was compiled in tabular format in terms of materials which was further discussed with the stakeholders and expert opinion was obtained. To further create a link between the material and recyclability, the type of recycling for each type was identified from the stakeholders and Google search.

Furthermore, using the material inventory along with the insights on the problems with the current recycling practice within Norway and the expert opinion from the stakeholders were very crucial factors in the ranking process. Therefore, after mapping the lifecycle, forming materials inventory and studying mechanical recycling in Norway, the ranking of each rope type was done as per their ease of recyclability. Ease of recycling is measured using the three ranking criteria methodology that is ranked from 1-3 as mentioned in **Table 6**. This shows the key for ranking criteria set, differentiating between polymer type, recycling technology and capacity in Norway. Individual rankings from Table 6 are summed up for the final rank in **Table 7**, with green being the easiest to recycle, yellow being the moderate level and red being the most difficult to recycle.

Table 6. Criteria for individual ranking.

Ranking Criteria	1	2	3
Polymer Type	Homogeneous polymer	Heterogeneous polymer	Polymer with metal
Recycling Technology	Mechanical / Chemical Recycling	Pre-processing Required	Unknown
Capacity in Norway	Available	Upcoming	Not available

Table 7. Key for calculating the sum ranked for the ease of recycling for each rope type.

	Polymer Type (A)	Recycling Technology (B)	Capacity in Norway (C)	Sum/Rank (A+B+C)		
Ranking	1-3	1-3	1-3	3-4	5-6	7-9

4. Results

4.1. MFA on Fisheries and Aquaculture

As mentioned, the availability of the data on ropes is scarce, including data on volumes. However, more data is available on fisheries as compared to aquaculture as per a study by (Deshpande, Philis, et al., 2020) on fishing gears, of which ropes are a part. This MFA is specifically on ropes and recycling within Norway is taken into consideration which has not been considered in the abovementioned study on fishing gears. MFA of fisheries with uncertainties is given in **Figure 11** and the input values in the tabular format can be found in **Appendix H**. 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 Figure 11, in 2020, 1614 ± 271 tons per year of ropes are imported within the fisheries sector. Among that, 2.76% is lost in the ocean while 18.8% is sent to waste management facilities directly after usage. Efforts are made to retrieve the waste from the ocean and land through clean-up activities. In total, approximately 59 ± 49 tons per year are retrieved and sent to a waste management facility. The waste gathered at waste management is segregated into three pathways with 48% for incineration, 45% for recycling and 7% for landfill. Amongst this, the ropes sent to an incineration plant mostly have biomass or metal rust attached to them that have inadequate technology for its cleanliness (Deshpande, Philis, et al., 2020). Out of 45% of ropes segregated for recycling, only 7.5% are recycled within Norway (Class 1) and the rest of the recyclable ropes that are either unclean, thick or nylon (Class 2 or 3), or has metal inside are sent abroad. Of the recycled ropes in Norway, 3% of the waste from the recycling plant is sent to an incineration plant.

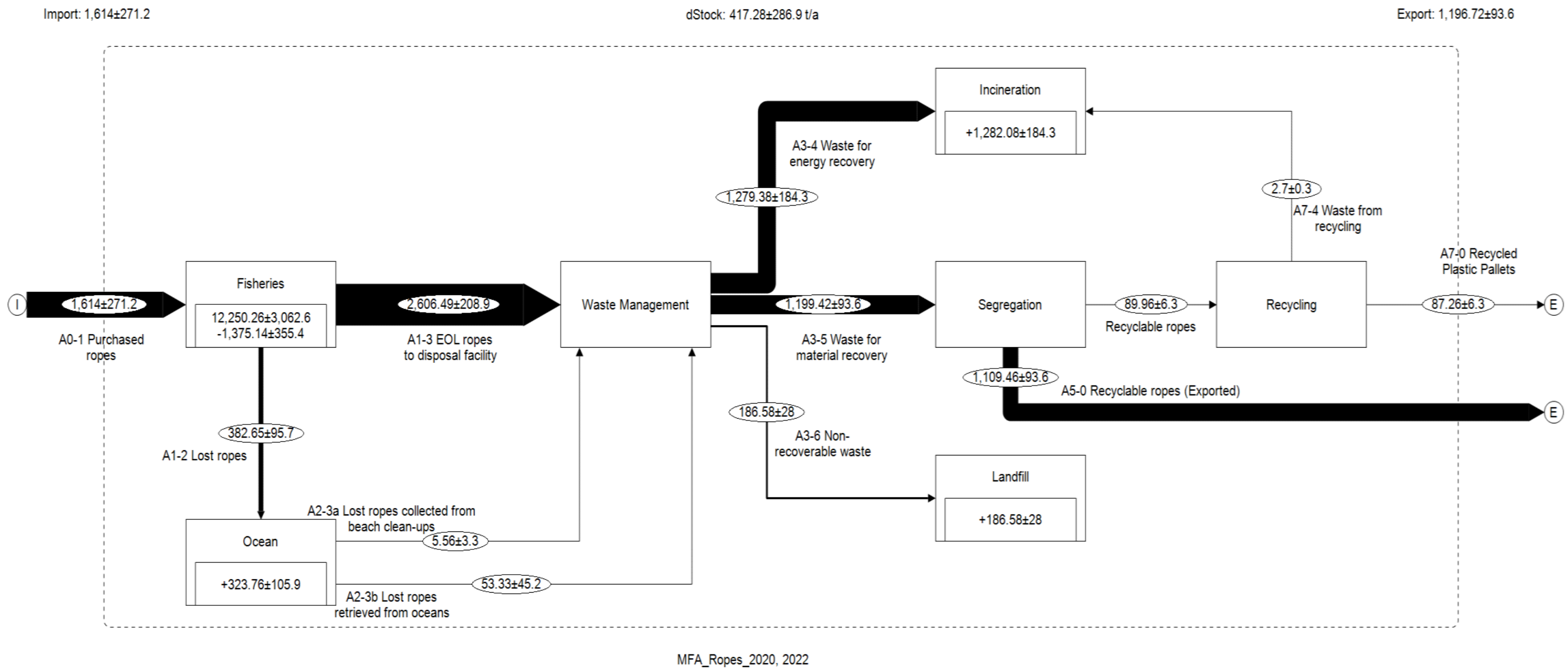

Figure 11. MFA of ropes on Norwegian fisheries in the year 2020.

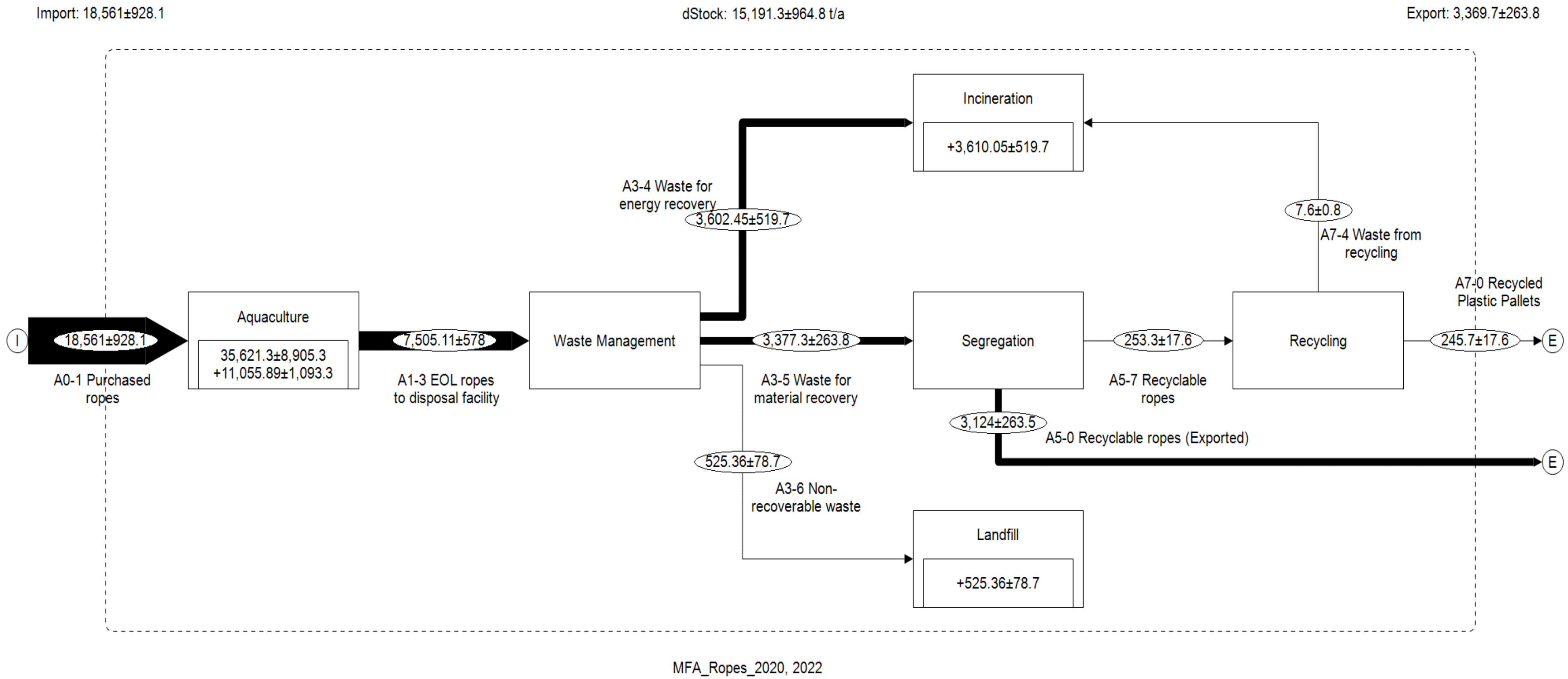

Figure 12. MFA of ropes on Norwegian aquaculture in the year 2020.

Similar to fisheries, MFA on aquaculture (**Figure 12**) was done through similar equations after the collection at the waste management facility. It was assumed from personal interaction with regional mechanical recyclers from Trøndelag that the ropes from fisheries and aquaculture are handled collectively by the waste management facility and the treatment plants, as ropes aren't segregated based on their industry once collected by waste managers.

As per the same interaction with the stakeholders, aquaculture facilities within Norway are significantly more than fisheries, as high as 90-95%. As per the calculated estimate for the year 2020, the purchased ropes are 18561 ± 928 tons/year which is 92% more than fisheries so it is within the range. Though the values are within the range, there are still uncertainties involved due to the lack of data available. In aquaculture, as there is no loss into the ocean, ropes are directly sent to the waste management facility after usage which is 7505 ± 577 tons per year. The stock turnover is low as compared to fisheries as ropes have a longer lifespan in aquaculture as per personal interaction with the stakeholders in the aquaculture industries.

4.2. Ropes inventory

19 rope types were identified that are sold in Norway within the fisheries and aquaculture sector. There is very little information available in the literature about the ropes and this is the first time that ropes are classified according to their types as per the best of the author's knowledge. The rope types identified are further studied based on the application and properties as mentioned in **Table 8**. There were some ropes whose properties or applications were not available to the public, therefore these are not mentioned in the inventory.

Table 8. Listing inventory on rope types, applications, and properties.

Rope	Rope Type	Industry	Applications	Properties
Dolly Rope	Twisted	Fishery	Trawls and netting	High wear and tear resistance, protective buffer for nets
Nylon Rope with Core	Braided	Fishery		Sink or floats
Danline Rope	Twisted, Braided, Braided and twisted	Fishery, Aquaculture	Mooring, Towing, Lifting	Floats, very good UV and chemical durability, high strength and wear

				resistance, melting point: 165°C
Polyethylene Rope	Twisted, Braided	Fishery	Fishing, Sailing	Low breaking strength, floats, high chemical and abrasion resistant
Nylon Rope	Twisted, Braided	Fishery	Mooring, Anchoring, Towing, Straps, Sailing, Self-tensioning winches, Shipping	Sink, UV-resistant, melting point: 250°C, very strong, elastic, high breaking load
Polyester Rope	Twisted	Fishery, Aquaculture	Fish farm cages	Sink, very good UV and wear resistant
Silver Rope	Twisted	Fishery	Longline and end rope, Yarn, Pots, Mooring of boats and piers	Sink, melting point 130-260°C, high tensile strength, abrasion, UV and chemical resistant
Scanflyt®	Braided	Fishery	Gillnet	Floats
Dyneema®	Braided	Fishery, Aquaculture	Sweeps, Mooring, Towing, Cage net framing, Sinker tube suspension, Winch, Seismic, Subsea installation, Anchor, Lifting slings, Grommets, Tankers, Cruise ships, Tugboats	Melting point: 145ºC, lightweight, highest strength to weight, low elongation, abrasion, fatigue, UV rays and chemical resistant
Danline with lead	Twisted, Braided and twisted	Fishery, Aquaculture	Fish farming (cages) and seine netting	Sink, high strength, good abrasion resistant
PP Rope	Twisted	Fishery, Aquaculture	Fishing gear, Mooring of gear and boat, Yarn mounting and pots	Float, low elongation, wear-resistant
HDPE Rope	Twisted	Aquaculture		Higher breaking strength, lightweight, chemically inert, abrasion resistant, better grip, minimal elongation, durable and UV stabilized, excellent shape retention
Poligareta Rope	Twisted	Fishery		Very resistant to abrasion or friction

Polirex Rope	Twisted	Fishery		
X2 Ultra Rope	Braided	Aquaculture	Mooring and Towing	Shock absorber, abrasion resistant, higher strength-to-weight ratio, chemically inert, excellent shape and original weight retention even after prolonged use
Seine Rope with Steel	Twisted	Fishery, Aquaculture	Bottom fishing, Seine fleet	Good UV resistant and wear property
Terylene with Lead Rope	Braided and twisted	Fishery		
DURA - Float	Twisted	Fishery	Shipping, Mooring, Winch	High breaking load, good elongation, float, UV stabilised, abrasion resistant
Nylon rope with copper coating	Twisted	Fishery	Limits biofouling	

Further, the inventory was extended to combine the rope types with their material and the type of recycling (**Table 9**). The material is divided into two main categories of plastic and metals. Rope types having certain material or recycling types are marked in green colour. If the material is a certain type or of a very specific property, then that is mentioned within the green cell. The abbreviations used in Table 9 can be found in the *list of abbreviations*.

Gathering data on particular rope types for the recycling process was difficult as ropes are segregated manually in Norway based on the level of cleanliness, thickness, colour, ropes containing chains, wires or other metals as per the information shared by mechanical recyclers from Trøndelag. The current practice of recycling lacks segregation based on the material of the rope. Thus, the unknown recycling process for rope types is left blank.

Table 9. Material and recyclability inventory of rope types in fisheries and aquaculture.

Rope	Material								
	Plastic					Metal			
	Yes/No	Polyamide	Polyethelene	Polyproplylene	Polyester	Yes/No /Maybe	Lead	Steel	Copper
Dolly Rope	Yes					No			
Nylon Rope with Core*	Yes					Maybe			
Danline Rope	Yes		HDPE			No			
Polyethylene Rope	Yes					No			
Nylon Rope	Yes					No			
Polyester Rope	Yes					No			
Silver Rope	Yes					No			
Scanflyt® **									
Dyneema®	Yes		UHDMWPE / HMPE			No			
Danline with lead	Yes					Yes			
PP Rope	Yes					No			
HDPE Rope	Yes		HDPE			No			
Poligareta Rope	Yes					No			
Polirex Rope	Yes					No			
X2 Ultra Rope	Yes					No			
Seine Rope with Steel	Yes					Yes		Galvanized wire	
Terylene with Lead Rope	Yes					Yes			
DURA - Float	Yes			HTPP - Core		No			
Nylon rope with copper coating	Yes					Yes			

* Core material varies according to the application required to sink or float.

** Scanflyt® material was not available.

Studying the properties and applications of the rope was useful in understanding why certain materials were used. Since dolly rope and polyethylene ropes have the same material i.e., PE, but different applications, therefore it is assumed that the exact material composition might be different due to its application. Moreover, as mentioned that the properties are an integral part of deciding the material, the property of the core in the nylon rope with core is a decisive factor to choose a material depending on the application. If the application requires it to sink, then the core is metal or polyester and if it is required to float then the core is made of PE or PP.

4.3. Ranking of ease of recyclability

The inventory was used to rank the 19 rope types on the scale of easiest to hardest to recycle within Norway (**Figure 13**). Nylon rope with core could be on the scale rate of 8 or 9 depending on the core. The detailed calculation of the ranking of each type of rope is given in **Appendix I**.

Easiest to recycle ⟷ Hardest to recycle

3	4	5	6	7	8	9
Dolly rope	PP rope	Danline rope	Dyneema rope	Silver rope	Nylon rope with core	Nylon rope with core
Polyethylene rope		Nylon rope		Poligareta rope	Danline with lead	Nylon rope with copper coating
HDPE rope		Polyester rope		Polirex rope	Seine rope with steel	
				X2 ultra rope	Terylene with lead rope	
				Dura-Float		

Figure 13. Ranking on the ease of recyclability of different rope types.

5. Discussion

5.1. Challenges to Circularity

5.1.1. Recyclability

Ropes are essential in the fisheries and aquaculture sector as a significant amount is used which is evident from MFA results. Therefore, ropes cannot be eliminated and need sustainable solutions. The solutions can only be designed if the characteristics of ropes are known. Unfortunately, ropes are used extensively without much knowledge about them.

Ropes have complex material mixes that compose of not only polymers but metals too sometimes.

19 rope types are distinguished that are composed of polymers namely, PA, PE, PP, and polyester. Out of these ropes identified, four to five ropes have metal either as core inside or coating outside. These ropes are the hardest to recycle on the ranking scale (8 or 9) of recycling ease. Separating metal is an extensive task and metallic rust on the rope makes the ropes difficult to recycle and they are usually sent to incineration plants after shredding.

Ropes on the ranking scale of 7 are all the ropes that have only polymers, but the challenge is that they are composed of mixes of low-density polymer, PP or PE and high-density polymer, PA or polyester. These mixes are difficult to recycle together as their recycling processes are different to treat. PE and PP can be treated mechanically but PA and polyester can only be treated chemically due to their high melting point. Therefore, when two different recycling process combinations are found in ropes then that requires pre-treatment which can be a highly extensive process sometimes.

It was found in the study that the combination of material mixes in ropes is required due to the applications requiring specific properties. One of the properties can be if it is required to float, PP or PE can be added to the rope but if it is required to sink, PA, polyester or metal is added. E.g., Danline rope floats as it is required for lifting but fish farming cages require heavyweight to make it stay underwater, so Lead is used in Danline rope. One more property could be to increase the abilities of abrasion resistance or strength that could be possible with a composite of polyester and PP (Sundt et al., 2018) e.g., X2 ultra ropes.

The composition varies a lot in composites that remain unknown to the stakeholders within Norway as ropes are imported either as ropes or raw material from Asia mostly. This unfamiliarity causes a lack of knowledge among stakeholders that then becomes a problem to recycle ropes. It is a huge challenge to then recycle these as high-quality recycled pallets in Norway since industrial-scale recycling plants are not available. Therefore, most of the ropes ends-up in incineration or are exported abroad.

Apart from composites, homogenous materials such as HMPE are increasingly being used in Dyneema ropes making them difficult to recycle. Dyneema rope is very stiff as steel (Otto, 2019) and is very hard to recycle. It can only be chemically recycled back to the feedstock as by far the only option available today or it can be shredded to reuse it as a reinforcement in a composite (Lemstra, 2022).

5.1.2. Waste Management

Even ropes that are fit for recycling with today's technology are not all recycled. One of the reasons is due to the lack of efficient collection and waste management of ropes at EoL (Deshpande & Haskins, 2021) as the results in MFA for fisheries also show significant losses in the ocean. Waste collected is sent to landfill and incineration as it seems to be an easy option due to no processing fees involved and the transportation cost is low as well because of near stations (Deshpande, Skaar, et al., 2020). Moreover, there is illegal dumping or burning that is not on record as the laws aren't strict for the EoL (EUDirective, 2018a).

The ropes that are mixed with other waste are difficult to segregate and require extensive cleaning before recycling (Deshpande & Haskins, 2021). The segregation for recycling is manually done consumes a lot of time and cleaning requires advanced technology that is yet missing in Norway, therefore, it ends up in an incineration plant.

5.2. Closing the loop

5.2.1. Industrial Symbiosis

Today's technology in Norway can recycle PP and PE to HDPE and Low-Density Polyethylene (LDPE) (Deshpande & Haskins, 2021). There were no ropes identified made of LDPE, thus it is impossible to make rope out of it. Furthermore, even HDPE recycled pallets lack the quality to reproduce into 100% new ropes. The pallets are usually replacing virgin plastic in products that do not require high strength. The personal interaction with the regional mechanical recyclers from Trøndelag showed some examples that are currently in practice within Norway e.g., trolleys used at a supermarket or serving trays at a fast-food restaurant.

Figure 14. Serving tray made from recycled PE/PP ropes © Sidra Tul Muntaha 2022.

There is an opportunity for different companies as well that don't require high strength. They can use recycled pallets as raw material in the production phase of another product that might seem like a waste to the recyclers. This kind of resource sharing among companies to enhance sustainability is known as industrial symbiosis (Neves, Godina, Azevedo, & Matias, 2020). Industrial symbiosis could at least give a second life to the ropes even if it is not the same product. In Norway, an example of it 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, Pansera, Nogueira, & Monteiro, 2022; NCP, 2022). In this way, monetary and material resources are circulated within the country, therefore benefiting the local economy and developing self-reliance.

5.2.2. Small Circles

(Havas, Falk-Andersson, & Deshpande, 2022) suggested the idea of small circles as "Reshaping the circularity strategies through containment of the geographical boundaries of end-of-life products to avoid financial, material and energy losses, and to ensure transparency and resilience in implementing strategies for the circular economy."

It can be implemented in this study as well to keep the material and economical resources from ropes in fisheries and aquaculture within Norway. Through the implementation, stakeholders can take the responsibility on various stages. The identification of material flows in the lifecycle of rope are identified in the thesis' results that help stakeholders estimate the amount of potential present to deal with ropes locally. Waste management can improve the waste collection and handling practices while recyclers can have the technology locally to efficiently segregate and clean to recycle on industrial level in Norway. Mechanical recycling can be improved to recycle ropes on an industrial scale and chemical recycling plants can be installed inside Norway to reduce export and have more insight over the ultimate fate of ropes after EoL. Although, initial investment can be high to introduce the technology, it will have long-term benefit, both economically and environmentally. It will reduce the reliance on export for recycling and keep the resources within Norway. This will lead to job creation, upskilling of current workforce and increased availability of resources.

It was identified that most of the ropes exported outside Norway were ropes made of Nylon as Norway doesn't have a chemical recycling facility. Nylon has much higher recycling value as it retains its original properties through many recycling cycles (Deshpande & Haskins, 2021), therefore, small circles even if implemented only for nylon ropes can considerably make a difference.

5.2.3. Rope Labelling

The inventory of the ropes does help recyclers to identify the ropes according to the materials and properties but the identification while doing manual segregation is difficult. Norway currently only has a manual segregation facility at recycling plants, though efforts are being made to differentiate ropes with chemical processes that can help in segregation. Currently, as the manual segregation is based on rough estimates, such as white coloured ropes are nylon ropes because usually, this is the case, this becomes a problem resulting in loss of a potential PE/PP rope in white that might have been recycled mechanically otherwise. Therefore, if ropes are labelled with the name of the rope, then that could help identify ropes. The identification will help in running the recycling plant smoothly without the wrong material of rope added by mistake. E.g., if nylon rope gets into a mechanical recycling plant accidentally then the plant stops and needs cleanliness before running again. Therefore, rope labelling enhances the recycling process and can potentially avoid enormous investments in material segregation through chemical means.

5.2.4. EPR

EPR will link producers to bear the cost at the EoL (Thushari & Senevirathna, 2020) of the rope with the aim of eco-designing ropes at the initial stage of the lifecycle and bearing the cost of EoL ropes being exported, so maximizing the lifetime of the ropes. Thus, EPR is beyond production, extending throughout its lifecycle to prevent waste which is the top preference in the waste hierarchy (Gharfalkar, Court, Campbell, Ali, & Hillier, 2015). This will also be improving the collection at the EoL and perhaps investments will be made in recycling within Norway.

5.2.5. Stakeholders' Responsibility

Stakeholders need to act throughout the lifecycle of the ropes. Therefore, the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is done based on social, environmental, and economic factors. This will pinpoint the actions and weaknesses so that stakeholders can identify the right actions. Moreover, it will start the conversation by the stakeholders to take action and gain the monetary value being lost today to other countries. It will ultimately bring all stakeholders together to take initiative and cooperate for the circularity of the ropes.

Table 10. SWOT analysis on stakeholders' responsibility under sustainability factors.

Sustainability Factors	Strengths/Opportunities	Weaknesses/Threats
Social	SHIFT Plastic project – intellectual resources sharing platform among stakeholders Voluntary beach clean-ups	Absence of visibility and communication Lack of sharing information for fear of competitors Lack of awareness
Environmental	Foster the use of secondary raw material Encourage eco-design	Unclear and low preference to environmental objective Missing transparency in data Landfill is an easy option Low recycling capacity
Economic	Large volume of resources available Funding support available e.g., Handelens Miljøfond Job opportunities Opportunity for innovation and business solutions	Huge technological and infrastructure investment required

Strategies for the stakeholders to take on the responsibility are as follows:

Producers/Suppliers: They will be more vigilant to know the ease of the materials' recycling, therefore avoiding the materials that have difficult recyclability in the production phase. Thus, eco-designing the ropes is in alliance with the aim of "design for recycling" (Sundt et al., 2018).

Waste collectors: Adopt the practice of separating the different types of ropes from other waste collected at the harbour or aquaculture facility to preserve intrinsic value for high-quality recyclability. Therefore, reducing the ropes that end up in an incineration plant.

Recyclers: Knowledge of the material component of ropes is essential in designing the recycling strategies for ropes. This analysis, therefore, helps recyclers in improving recycling efficiency and ensuring the uniform quality of recycled plastic. Moreover, the MFA results indicate a significant volume of ropes available that are economic incentives to recyclers.

Regulatory actors: It is essential to formulate strategies for everyone, thereby establishing various circular economy strategies in the region such as EPR or tax on landfills, etc. Moreover, there must be annual audits by companies and sharing of the data sources for transparency.

Researchers: The research still requires further study on the chemical composition of the rope types identified to further aid with the recyclability technology and process development. With more accurate data on ropes, MFA along with LCA can be performed to study the impacts on the environment and develop future strategies.

5.3. Limitations and Future Work

Static MFA of ropes is aimed to show potential interaction between processes and understand volume losses within the lifecycle of ropes, but the system is not depicting the reality. It has huge uncertainty as it includes a lot of estimates and assumptions as the exact volumes are unknown.

MFA for fisheries excluded recreational fishers that would also be potentially buying ropes from small-scale suppliers who might import their supplies. Ropes retrieved from ocean and land have different units that needed conversion and ropes retrieved from voluntary clean-ups that collect without measuring and recording aren’t included in the thesis, therefore, there is increased uncertainty on the data retrieved from ocean and land. Some of the assumptions are taken from the overall fishing gears for doing the fisheries MFA as particular data on ropes isn’t known. These assumptions are for fishing gears at the waste management facility to be handled differently at the EoL. As ropes are the most recycled fraction out of other fishing gears (Deshpande, Philis, et al., 2020), the recycling percentage should be higher than 45%. Moreover, in doing MFA for aquaculture, the data was much more scarce and the last figures from grey literature were for 2016 or 2017 that were estimated for 2020 assuming that there was a constant increase.

High uncertainties can be attributed to the response from the stakeholders in the survey as they can be speculated to share the exact volumes due to a lack of knowledge or privacy concerns that they were reluctant to share data initially. These uncertainties show that there is a need to keep an account of the volumes of ropes and be transparent about practices thus so that they can be monitored and held accountable. Moreover, more accurate data can help in modelling Dynamic MFA which will be important to create scenarios so that strategies can be made in advance for the future.

The inventory of ropes is extremely important to understand the ropes' recyclability but there is still some data missing from the inventory as it is not available at all, especially the recycling process for each type of rope is not known. Moreover, only ropes made of polymer and polymer with metal were studied. Efforts are going on to form biodegradable ropes and intelligent ropes with sensors that were not added to the study. It will be worthwhile to add them to the inventory along with completing the missing information.

Conclusion

In this thesis study, the problems and strategies associated with the recyclability of ropes in the fisheries and aquaculture sector of Norway are identified. Problems associated with the ropes are because of complexity, design and variation of materials used in different types of ropes. In most cases, the exact material and its composition in ropes remain unknown because ropes are largely imported in Norway. MFA conducted has shown the sheer volume of ropes at EoL that are ultimately incinerated or exported, which indicates a significant loss in the potential of recyclability of ropes within Norway i.e., the current status of managing ropes as per research question 1.

Furthermore, ease of recycling ranking of rope types was developed for producers and recyclers to focus on the material content of ropes which helped identify barriers and opportunities for closing the loop as per research question 2. In the production phase, ranking can help producers to understand the type of materials in ropes that are easy to recycle and thereby optimize the design and composition of ropes. At the EoL phase, this can help recyclers to identify the type of ropes in the value chain and consider ways in which different rope types can be recycled and segregated efficiently rather than relying on rough estimates for manual segregation at EoL.

The study conducted helps to formulate strategies for all stakeholders in the lifecycle of ropes within Norway. In terms of the responsibility of recycling, the onus is placed more on the producers and recyclers as they are integral for starting and closing the loop. It is also vital that further research and studies are carried out on the rope types of fisheries and aquaculture in Norway to aid recyclability technology and processes.

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Appendix A

Cable, wire, chain, and net

Ropes are often confused with terms such as cables, wires, chains, and nets. These terms are defined below from the (Oxvig & Hansen, 2007) study.

Cable:

If three 3–strand ropes are twisted together, then it is called cable which is normally left-laid.

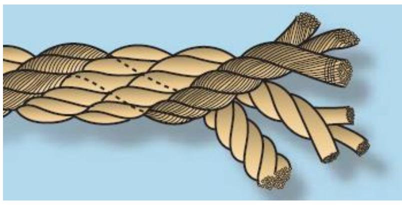

Figure A1. Cable *(Oxvig & Hansen, 2007)*.

Wire:

A wire is made up of metal, mainly iron or steel. Even after galvanization processes, they become corrosive. Wires can have complex structures with a varying number of strands. However, in fishing, mostly 6-strand wires are used. The thickness of strands in each wire can vary. Though there can be a combination of metal wire and polymer fibres, this combination is considered to be under the rope category and is in the scope of this thesis.

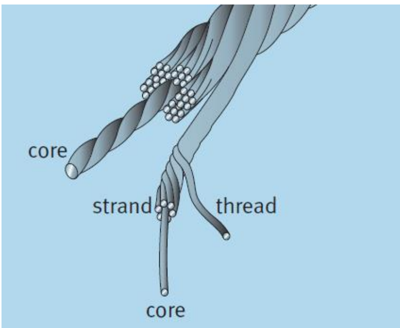

Figure A2. Wire *(Oxvig & Hansen, 2007)*.

Chain:

Shipbuilding steel is used to make chains. They vary in strength according to their application. There are two types of chains. The first is a chain without studs that are used for unloading systems and the second is a chain with studs that are used for anchoring. Chains with studs are stronger and kinks are not created. Chains are rigid and have no stretchability, unlike nets, ropes, and wires.

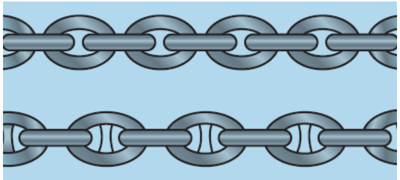

Figure A3. Top chain is without studs and below chain is with studs *(Oxvig & Hansen, 2007)*.

Net:

Nets are primarily used to catch fish. They are made by meshing technique where multiple knots are weaved in each row. However, now knotless nets are available as well. There are three types of it: twisted type, braided type, and crochet type. This technology is relatively new and expensive. Nets have ropes to hold the mesh, but these ropes are not considered in the thesis research.

Figure A4. Net with knots *(Oxvig & Hansen, 2007)*.

Appendix B

Recreational Fishing

Recreational fishing or non-commercial fishing is open-access fishing (Zimmermann et al., 2022). In Norway, it is a common activity among its people as part of the culture (Liu, Bailey, & Davidsen, 2019). As it doesn't require a licence, recreational fishing is becoming popular among tourists as well. Recreational fishing in Norway has the highest participation in Europe (Vølstad et al., 2020). The highest frequency is based on its location near the coast and the fact that the consumption rate of fish is high (Sundt et al., 2018).

Appendix C

Applications in aquaculture and fisheries

The detail of the applications of **aquaculture** from (Xu & Qin, 2020) are as follows:

Mooring:

In aquaculture structures, mooring systems include catenary, taut leg, single point and spread line configurations. Mooring grid systems are built in a way to decrease aquaculture cage disturbance from water waves and currents.

Floating collar:

Wide or narrow floating cage collars are normally seen, with the wide collar normally used in large cages. HDPE or steel is usually used as a material for collars, classified as either rigid or flexible. Floating collars strengthen the cage in the water, sustain the volume of a cage and provide buoyancy.

Cage:

Cages can be categorised as fixed, floating, submersible and submerged. Except for fixed cages, cages can be rigid or flexible. In the case of fixed cages, these are cheaper but can only be used in shallow water.

The detail of the applications of **fisheries** from (Directorate of Fisheries, 2010) are as follows:

Gillnet:

A gillnet is a net suspended in the water attached to floaters. It is used by most Norwegian fishing fleets and vessels to catch commonly cod, saithe, ling and monkfish, and redfish.

Hook-and-line gear:

Hook-and-line gear can be divided into two main categories as they are used by multiple fishing gears. Two categories are longlines and trolling lines.

Trawling:

Trawling is a new method that started around 100 years back. A trawl is a fishing net that tows the seabed water. It is attached to a vessel forming a tunnel shape that traps the fish. The type of fish collection varies according to the trawl shape, size, seabed condition, and vessel's engine power e.g., the lowest speed is required for smaller shrimps while the highest speed is required for whitefish and pelagic trawlers.

Seines:

The Seine fishing method is similar to trawling that can be divided into 2 types: Danish and Scottish seine. In Norway, usually, Scottish seines are used. The length of seine lines depends on the depth and conditions of the seabed.

Appendix D

Shift Plastics Workshop Questionnaire

8/23/22, 4:00 PM Questionnaire

Questionnaire

This questionnaire is made to support Master's thesis work "Plastic ropes in marine applications; Analysing problems and proposing remedies" which looks specifically at the ropes material aspects and its uses with relation to circularity. The questionnaire is anonymous and is entirely for the purpose of this thesis work.

* Required

1. Which industry does your company belong to? (Choose all relevant options) *

   Check all that apply.

   - [ ] Fisheries
   - [ ] Maritime transport / Offshore
   - [ ] Aquaculture

2. Mostly ropes are made of what kind of material? *

   Mark only one oval.

   - ( ) 100% plastic
   - ( ) 80% plastic 20% metal
   - ( ) 60% plastic 20% metal 20% other material
   - ( ) 60% plastic 40% metal
   - ( ) Other: ______________

3. What are the uses of the different types of ropes?

   ____

   ____

   ____

   ____

   ____

https://docs.google.com/forms/d/1_Nu6S7pszuwlOaGRALY9qirvaGpdF5wl7St7KAkFnu0/edit 1/3

Figure D1. Questionnaire used in Shift Plastic Workshop.

4. What is the specific reason for using the above-mentioned ropes? (Choose all relevant options) *

Check all that apply.

- [ ] Economically viable
- [ ] Durability
- [ ] Only option available
- [ ] High strength
- [ ] Other: ______________________

5. What is the average guaranteed durability of the ropes used by your company? (If known, you can provide the lifetime of each type of rope) *

Mark only one oval.

- ( ) Less than 1 year
- ( ) 1-3 years
- ( ) 3-10 years
- ( ) 10+ years

6. Do you know where the ropes are sourced from? (Choose all relevant options) *

Check all that apply.

- [ ] India
- [ ] Malaysia
- [ ] Thailand
- [ ] Bangladesh
- [ ] Other: ______________________

7. What makes ropes difficult to recycle? (Choose all relevant options) *

Check all that apply.

- [ ] Heterogenous materials
- [ ] Lack of knowledge
- [ ] Lack of infrastructure
- [ ] Additives inclusion in plastics
- [ ] Other: ______________________

8. Would you like to connect with me for further discussion on the topic or interested in knowing the results of the project? Feel free to share your contact information:

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Appendix E

Questionnaire to Oceanize

8/23/22, 4:22 PM Questionnaire on Plastic ropes in marine applications; Analysing problems and proposing remedies

Questionnaire on Plastic ropes in marine applications; Analysing problems and proposing remedies

This questionnaire is made to support Master's thesis work "Plastic ropes in marine applications; Analysing problems and proposing remedies" which looks specifically at the ropes material aspects and its uses with relation to circularity. The main theme of this questionnaire is to look at the ease of recycling of ropes that can help link different materials or types of ropes to close the loop. The questionnaire is anonymous and is entirely for the purpose of this thesis work.

1. Are ropes recycled with other fishing gears?

   Mark only one oval.

   ( ) Yes

   ( ) No

2. How are ropes collected, separated, and treated?

3. How are ropes handled in the recycling process?

https://docs.google.com/forms/d/1iERx9kaXCPiNFPkt-SckJZBG4ANcczzeAUsq9_wY33U/edit 1/4

Figure E1. Questionnaire sent to Oceanize after the field visit.

4. Which ropes are difficult to recycle? Rate the difficulty of each rope from low, medium, hard to impossible

Mark only one oval per row.

	Low	Medium	Hard	Impossible
Braided ropes	⬭	⬭	⬭	⬭
Ropes with metal	⬭	⬭	⬭	⬭
Twisted ropes	⬭	⬭	⬭	⬭
Ropes with single material	⬭	⬭	⬭	⬭
Ropes with chains	⬭	⬭	⬭	⬭
Ropes with wires	⬭	⬭	⬭	⬭

5. What are the major challenges in recycling ropes?

____

____

____

____

____

6. Where are ropes collected at the end-of-life? Select as many as applicable.

Check all that apply.

- [ ] Companies
- [ ] Harbours
- [ ] Fishers
- [ ] Waste Management facility
- [ ] Other: ______________________

7. How much ropes are handled every year in tonnes? Amongst this, how much is from fisheries, aquaculture and offshore, respectively?

8. What is the market share of recycling ropes within Norway?

9. Are additives added in the process of recycling? Why?

10. How much waste is produced while recycling ropes?

11. Does ropes come under hard plastic category that can be recycled? If yes, how is it possible?

12. Any suggestions on how to handle ropes that can't be recycled?

Appendix F

Questionnaire to Selstad

8/29/22, 5:03 PM Questionnaire on Plastic ropes in marine applications; Analysing problems and proposing remedies

Questionnaire on Plastic ropes in marine applications; Analysing problems and proposing remedies

This questionnaire is made to support Master's thesis work "Plastic ropes in marine applications; Analysing problems and proposing remedies" which looks specifically at the materials used to make ropes and its uses with relation to circularity. The main theme of this questionnaire is to look at the material composition and types of ropes that can then link with the ease of recycling of ropes to close the loop. The questionnaire is anonymous and is entirely for the purpose of this thesis work.

1. How many rope types are produced in Selstad?

   ____

2. What kind of material is usually used to make ropes?

   Check all that apply.

   - [ ] 100% plastic
   - [ ] 80% plastic 20% metal
   - [ ] 60% plastic 20% metal 20% other material
   - [ ] 60% plastic 40% metal
   - [ ] Other: ________________________

3. What are the major reasons for using specified ropes?

   Check all that apply.

   - [ ] Economically viable
   - [ ] Durability
   - [ ] Only option available
   - [ ] High strength
   - [ ] Other: ________________________

https://docs.google.com/forms/d/1j__VY4XK0BRWeTtwHmq2grQGD8MmF7QtSweHfrdH8oA/edit 1/3

Figure F1. Questionnaire sent to Selstad via email correspondence.

4. What is the average guaranteed durability of the ropes used by your company?

Mark only one oval.

- Less than 1 year
- 1-3 years
- 3-10 years
- 10+ years

5. Ropes that aren't produced in Selstad, where are those ropes sourced from?

Check all that apply.

- [ ] India
- [ ] Malaysia
- [ ] Thailand
- [ ] Bangladesh
- [ ] Other: ______________________

6. What is the quantity of ropes produced by Selstad every year in tonnes? Amongst this, how much is for fisheries, aquaculture and offshore, respectively?

7. What is the quantity of ropes imported by Selstad every year in tonnes? Amongst this, how much is for fisheries, aquaculture and offshore, respectively?

8. What is the Sestad market share of producing ropes within Norway?

9. What is the Selstad market share of importing ropes within Norway?

10. How much waste is produced in the production of ropes?

11. Any suggestions on how production of ropes can be improved to be 100% recycled?

Appendix G

MFA on Aquaculture

Methodology for aquaculture purchased ropes and disposed of ropes to waste management facility in the year 2020:

Available data in 2016 was on total purchased ropes for fisheries and aquaculture, purchased ropes for fisheries and EoL ropes to a disposal facility.

A_{0-1} = total purchased ropes for fisheries and aquaculture minus purchased ropes for fisheries

As the system is being calculated for the year 2020, revised values of A_{0-1} and A_{1-3} had to be calculated for future years. For A_{0-1}, it was assumed that the ratio of purchased ropes for aquaculture to purchased ropes for fisheries stays constant and for A_{1-3}, it was assumed that the ratio of purchased ropes for aquaculture to EOL ropes to disposal facility stays constant.

Moreover, stock turnover for the aquaculture (use-phase) process was calculated as EoL ropes to disposal facility/stock in 2017 which was then used to calculate the stock in 2020. The formula used is:

$$Stock\ Turnover = \frac{Stock\ consumed}{Stock}$$

Table G1. MFA calculation data for aquaculture.

				Aquaculture		
Variable symbol	**Variable name**	**Data source**	**Equation**	**Ropes MoP**	**Coefficient**	**Uncertinity (%)**
A_{0-1}	Purchased ropes (t/yr)	Sundt, Briedis et al. 2018 and Alnes 2022	$A_{01} = \Sigma$purchased ropes	18561		5
A_{1-3}	EoL ropes to disposal facility (t/yr)	Sundt, Briedis et al. 2018	$A_{13} = \Sigma$Disposed ropes	7505.1		25
A_{3-4}	Waste for energy (t/yr)	Alnes 2022	$A_{34} = \Sigma C_{incineration} \cdot (A_{13})$	3602.45	0.48	15
A_{3-5}	Waste for material recovery (t/yr)	Alnes 2022	$A_{35} = \Sigma C_{Segregation} \cdot (A_{13})$	3377	0.45	15
A_{3-6}	Non-recoverable waste (t/yr)	Alnes 2022	$A_{36} = \Sigma C_{Landfill} \cdot (A_{13})$	525.36	0.07	15
A_{5-7}	Recyclable ropes (t/yr)	Recyclers survey	$A_{57} = \Sigma C_{Recycle} \cdot A_{35}$	253.3	0.075	10
A_{5-0}	Recyclable ropes (Exported) (t/yr)	Mass Balance	$A_{50} = A_{35} - A_{57}$	3124	0.925	10
A_{7-4}	Waste from recycling (t/yr)	Recyclers survey	$A_{74} = \Sigma C_{waste} \cdot A_{57}$	7.6	0.03	10
A_{7-0}	Recyclable plastic pallets (t/yr)	Mass Balance	$A_{70} = A_{57} - A_{74}$	245.7		10
$S1 + \Delta S1$	Stock and stock change of total ropes owned by aquaculture (t)	Sundt, Briedis et al. 2018	$S1 + \Delta S1 = \Sigma A_{01} / C_{Stock}$	35621.3	0.21	25
$\Delta S4$	Stock change of ropes in the incineration plant (t)	Mass Balance	$\Delta S4 = A_{34} + A_{74}$	3610.05		
$\Delta S6$	Stock change of ropes in the landfill (t)	Mass Balance	$\Delta S6 = A_{36}$	525.36		

Appendix H

MFA on Fisheries

Table H1. MFA calculation data for fisheries.

Variable symbol	Variable name	Data source	Equation	Fisheries Ropes MoP	Coefficient	Uncertinity (%)
$A_{0\text{-}1}$	Purchased ropes (t/yr)	Alnes 2022 and Rope Suppliers	A_{01} = ∑purchased ropes	1614		17
$A_{1\text{-}2}$	Lost ropes (t/yr)	Deshpande, Philis et al. 2020	$A_{12} = \sum C_{lost} \cdot (A_{01} + A_{01} \cdot C_{stock})$	382.65	0.0276	25
$A_{1\text{-}3}$	EoL ropes to disposal facility (t/yr)	Deshpande, Philis et al. 2020	$A_{13} = \sum C_{dispose} \cdot (A_{01} + A_{01} \cdot C_{stock})$	2606.48	0.188	25
$A_{2\text{-}3a}$	Lost ropes collected from beach clean-ups (t/yr)	Data in units: Rydde/HNR Mass conversion factor: Deshpande, Philis et al. 2020	A_{23a} = ∑Collected ropes at beach (unit) · MoP in ropes at beach (kg/unit)	5.56		59
$A_{2\text{-}3b}$	Lost ropes retrieved from oceans (t/yr)	Data in units: The Norwegian Directorate of Fishery and Fishing for Litter Mass conversion factor: Deshpande, Philis et al. 2020	A23b = ∑Retrieved ropes from ocean (unit) · MoP in ropes from ocean (kg/unit)	53.33		85
$A_{3\text{-}4}$	Waste for energy (t/yr)	Alnes 2022	$A_{34} = \sum C_{incineration} \cdot (A_{13} + A_{23a} + A_{23b})$	1279.38	0.48	15
$A_{3\text{-}5}$	Waste for material recovery (t/yr)	Alnes 2022	$A_{35} = \sum C_{Segregation} \cdot (A_{13} + A_{23a} + A_{23b})$	1199.42	0.45	15
$A_{3\text{-}6}$	Non-recoverable waste (t/yr)	Alnes 2022	$A_{36} = \sum C_{Landfill} \cdot (A_{13} + A_{23a} + A_{23b})$	186.58	0.07	15
$A_{5\text{-}7}$	Recyclable ropes (t/yr)	Recyclers survey	$A_{57} = \sum C_{Recycle} \cdot A_{35}$	89.96	0.075	10
$A_{5\text{-}0}$	Recyclable ropes (Exported) (t/yr)	Mass Balance	$A_{50} = A_{35} - A_{57}$	1109.46	0.925	10
$A_{7\text{-}4}$	Waste from recycling (t/yr)	Recyclers survey	$A_{74} = \sum C_{waste} \cdot A_{57}$	2.7	0.03	10
$A_{7\text{-}0}$	Recyclable plastic pallets (t/yr)	Mass Balance	$A_{70} = A_{57} - A_{74}$	87.26		10
S1 + ΔS1	Stock and stock change of total ropes owned by fisheries (t)	Deshpande, Philis et al. 2020	$S1 + \Delta S1 = \sum C_{Stock} \cdot A_{01}$	12250.26	7.59	25
ΔS2	Stock change of ropes in the ocean (t)	Mass Balance	$\Delta S2 = A_{12} - A_{23a} - A_{23b} - A_{23c}$	323.76		
ΔS4	Stock change of ropes in the incineration plant (t)	Mass Balance	$\Delta S4 = A_{34} + A_{74}$	1282.08		
ΔS6	Stock change of ropes in the landfill (t)	Mass Balance	$\Delta S6 = A_{36}$	186.58		

Appendix I

Ropes’ Recyclability Ranking

Table I1. Individual ranking summed to form the final rank for the ease of recyclability of ropes.

Rank	Uniform Polymer Type	Recycling Technology	Capacity in Norway	Rank
Dolly Rope	1	1	1	3
Nylon Rope with Core*	2/3	3	3	8/9
Danline Rope	2	1	2	5
Polyethylene Rope	1	1	1	3
Nylon Rope	1	1	3	5
Polyester Rope	1	1	3	5
Silver Rope	2	2	3	7
Scanflyt® **				
Dyneema®	1	2	3	6
Danline with lead	3	2	3	8
PP Rope	1	1	2	4
HDPE Rope	1	1	1	3
Poligareta Rope	2	2	3	7
Polirex Rope	2	2	3	7
X2 Ultra Rope	2	2	3	7
Seine Rope with Steel	3	2	3	8
Terylene with Lead Rope	3	2	3	8
DURA - Float	2	2	3	7
Nylon rope with copper coating	3	3	3	9

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