Article

Application of Systems Engineering and Sustainable Development Goals towards Sustainable Management of Fishing Gear Resources in Norway

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Abstract: Commercial fishing is a critical economic sector for Norway, yet deficiency of scientific information, regulatory instruments, inadequate implementation, and lack of management infrastructure are among the significant causes of mismanagement of fishing gear (FG) resources. Mismanagement of FGs results in leakage of plastics through abandoned, lost, or discarded fishing gears (ALDFG), which is the most threatening litter fraction for marine wildlife. In EU-EEA states, the management of ALDFG is prioritized through a dedicated circular economy (CE) action plan. Historically, systems engineering (SE) methods are successfully applied for resource management studies. This study adopts and applies the SPADE method to evaluate sustainable management for the system of FG resources in Norway. SPADE comprises five problem-solving activities covering stakeholders, problem formulation, analysis, decision-making, and continuous evaluation. Each activity is accomplished by data collected through stakeholder interviews and literature analysis to establish an initial structure of problems and associated management strategies across FG's life cycle phases. The application of SPADE spanned across four years (2017–2020) and resulted in scientific outcomes aimed at the common goal of improving the system of FG resources in Norway within the framework of sustainable development goals and CE. SPADE's practice to integrate stakeholders at each step and provision for continual systems evaluation proved effective in building a holistic understanding of the complex system.

Keywords: systems engineering; SDGs; circular economy; recycling; waste management; ALDFG; fishing gear; plastic pollution; marine pollution; resource management

1. Introduction

Policies and programs for sustainable development (SD) have undergone significant shifts in focus since the introduction of the SD concept at the first global conference on the environment in Stockholm in 1972 [1]. With prospects of a rising global population, accelerating development, increased resource use, and the associated environmental impacts, the definition of sustainability has broadened from mere concern about pollution and biodiversity to the promotion of resource management [2].

The science of resource management involves generating a systemic understanding of the processes that lead to improvements in, or deterioration of, natural or anthropogenic resources. Management of resources is relatively more straightforward, especially when the resources and use of the resources by users can be monitored, and the information can be verified and understood in a non-complex way [3]. In resource management terminology, 'information' refers to the fundamental knowledge about stocks, flows, and processes within the resource system as well as about the human-environment interactions affecting the system [4]. Highly aggregated information may ignore or average out local data essential to identifying future problems and developing sustainable solutions [3].

Historically, local and regional governments are deemed responsible for managing resources through political instruments, and resource users are assumed incapable of reversing the deterioration of natural resources [5]. However, Johannes [6] provided a strong argument advocating the necessity to study the resource itself and the local ways, traditions, and knowledge associated with its use. As all humanly used resources are embedded in complex, social-ecological systems (SES) [7], one needs to incorporate ecological and sociotechnical knowledge of stakeholders or 'resource users' in describing the resource system.

In this paper, a system of "Fishing Gear (FG) Resources" is studied for developing sustainable strategies in the life cycle management of FG for the commercial fishing sector of Norway. A systems engineering (SE) based method, SPADE, is adapted and modified to analyze FG resources in Norway. The challenges and need for coining sustainable management of FG resources are elaborated as a background in Section 2. Section 3 provides a brief account of the SPADE method's activity steps as they were applied in the study. An application of the SPADE method to explore the strategies for sustainable life cycle management in commercial FG system in Norway is elaborated in Section 4. The Sustainable Development Goals (SDGs) and EU's Circular Economy (CE) strategies are used as a backbone in designing the improvement strategies for FG. Finally, the framework and application are discussed in Section 5. The adapted SPADE model aims to assist decision-makers and system stakeholders in comprehending otherwise complex and multi-dimensional FG management themes, sustainability and circular economy.

2. Background of the Fishing Sector in Norway

Norway is a Northern European country surrounded by water to the south (Skagerrak), the west (the North Sea and the Norwegian Sea), the north and northeast (the Barents Sea). With a resource-rich coastline of more than 25,000 km, Norway is the European leader in the commercial fishery and aquaculture sector [8]. Historically, commercial fishing has played a significant socioeconomic role, nationally and regionally, providing a foundation for settlement and employment along the Norwegian coast [9]. The commercial fishery sector includes all registered fishing companies in Norway that conduct fishing operations for economic benefits. The fishing sector is segmented into the coastal and ocean fishing fleet. A fishing fleet is an aggregate of commercial fishing vessels engaged in a particular type of fishing with selected FG. The coastal fishing fleet comprises smaller vessels operated by one to five crew and sizes range from 10–20 m [10]. the ocean fleet is known for its deep-water and sophisticated fishing practices, where fishing vessels are generally more than 28 m in size, and crew members vary from 20 persons or more [10,11].

In 2016–2017, 5946 vessels were registered in Norway, out of which approximately 93% are coastal vessels, and the rest belong to ocean fishing fleets [11]. The economically essential and primarily captured species include herring, cod, capelin, mackerel, saithe, blue whiting, and haddock. Additionally, fish species such as prawns, Greenland halibut and ling are caught in smaller quantities, but they have a high commercial value. Figure 1 shows the diversification of the fishing fleet concerning the number of vessels and type of FG they use. Although leisure fishers and foreign vessels also fish in Norwegian waters through quota agreements, only fishing activity through Norway's commercial fishing fleet was considered for assessment in this study.
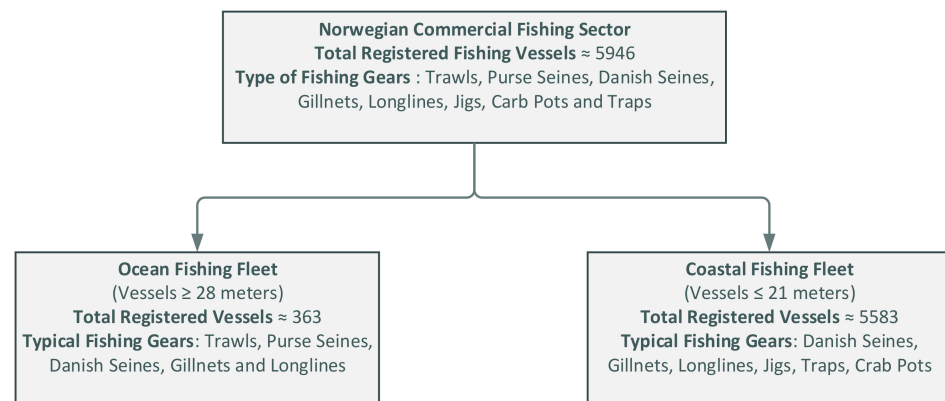
Figure 1. Structure of the commercial fishing fleet of Norway 2016–2017 [*modified after* 10].

The commercial FG resources are selected as a system in this study. FG are defined using an expansive definition proposed by FAO. According to FAO, FG are defined as "any physical device or part thereof or combination of items that may be placed on or in the water or on the seabed with the intended purpose of capturing or controlling for subsequent capture or harvesting, marine or freshwater organisms whether or not it is used in association with a vessel" [12]. Six major FG types, namely trawls, purse seines, Danish seines, gillnets, longlines, traps/pots and their associated ropes, are considered for this study. Polyethylene (PE), polypropylene (PP) and nylon (PA) are the primary building blocks of any FG [13]. Throughout the text, the term "plastics" includes PE, PP and PA. Although the FG unit contains other materials such as metals, lead, polyvinyl chloride (PVC) and wires, plastics constitute around 60% to 90% of any gear type [14]. Therefore, plastic polymers from FG are treated as resources in developing management strategies throughout this study.

Among the total plastic waste entering the oceans, *Abandoned, Lost or Discarded Fishing Gears* (ALDFG) are considered a particularly troublesome waste contribution that may continue to t trap, entangle and potentially kill marine life after all control of that gear is lost, which is defined as "ghost fishing" [15,16]. The amount, distribution and effects of ALDFG have risen substantially over past decades with the rapid expansion of fishing activity and fishing grounds and the transition to synthetic, more durable, and more buoyant materials used for some or all FG types [17,18]. In addition to the threat to marine ecology, the loss of fish stocks due to ghost fishing [19] and the additional cost of valuable resources on ALDFG also constitute significant economic setbacks [20].

The risk of ALDFG accumulation is relevant for countries characterized by a long and productive coastline. The geographic location and a strong dependence on fishing activity make Norway among the most vulnerable countries in the EU-EEA region to the detrimental effects of ALDFG pollution. Although ALDFG is the most dangerous fraction of marine litter, little or no information is available on the regional flows, sources and plastics from the fishing sector [14]. Consequently, there is a pressing need to build a holistic and systemic understanding of the fate, transport, sources, sinks and end-of-life (EOL) management alternatives of the fishing sector's regional plastic flow.

This paper aims to fill the knowledge gap by applying the SPADE method that facilitates the problem-driven, stepwise research to comprehend the sustainability dimensions for FG resource management in Norway. The adaption and application of SPADE are elaborated in Section 3.

3. Materials and Methods

Systems engineering is a discipline applied to structuring complex research problems where decision making is involved. The system of FG resource management presents a multifaceted, complex problem. Studying the entire system demanded detailed research

spanning four years (2017–2020). The research is designed according to the SPADE framework of SE and elaborated here.

Systems Engineering (SE)

SE methods are characterized by their ability to structure and scope complex research problems [21]. The SE process involves a series of steps accomplished in a logical sequence to consider a holistic view of the total system, its life cycle and other interrelated life cycles (e.g., material, cash flow) [22]. SE was invaluable to help design and maintain the scope and boundaries of the research. Four critical characteristics of SE support a holistic understanding of a given problem.

i.   A top-down approach where the system as a whole can be viewed.
ii.   A life-cycle orientation where all phases of the system are addressed.
iii.   A thorough identification of system requirements.
iv.   An interdisciplinary collaborative approach to ensure that objectives are met in an effective manner.

Principles of SE were used in developing methods aimed at resolving the complex problems related to resource management and sustainability. FG resources' system is characterized by the unavailability of scientific information and the need to rely on stakeholders' knowledge as a major and, at times, only available source for developing an in-depth understanding of the system and interacting elements [23]. Consequently, an essential SE method, SPADE, proposed by [24], is used to structure the problem. SPADE is characterized by its ability to keep stakeholders at the forefront in defining the problems and identifying potential system improvements [24].

The first activity (S) involves defining system stakeholders and their needs. In the second, (P) the problems associated with the system under study are scoped and identified. The identified problems are analyzed using applied research methods in (A). After analyzing system performance, the decision-making (D) activity aims to identify solutions/alternatives to improve system performance. Finally, in (E), continuous evaluation and monitoring of suggested performance strategies are conducted for continual improvement of system performance. The SPADE model has been applied effectively in solving complex problems involving transdisciplinary research methods on decision making for sustainability in ship acquisition [25], creating an eco-industrial network [26] and solving design problems for offshore fish cages [27].

Figure 2 illustrates the adaption of the SPADE model to structure the research steps for the system of FG resources in Norway. The research spanned four years and included two research studies, hereafter referred to as study-1 [14] and study-2 [28], directly adhering to the SPADE model's activities presented as a stepwise progression. Both qualitative and quantitative research methods are applied to address the specific questions related to the case study of Norway's commercial fishing sector. Here, the SPADE framework and the rationale behind method selection for each step are elaborated. The research reported in this paper builds on two studies [14,28] that contribute to Problem definition (P), Analysis (A), Decision making (D) and Evaluation (E) parts of the SPADE model and shows how it can be used to structure long-term and multifaceted research.
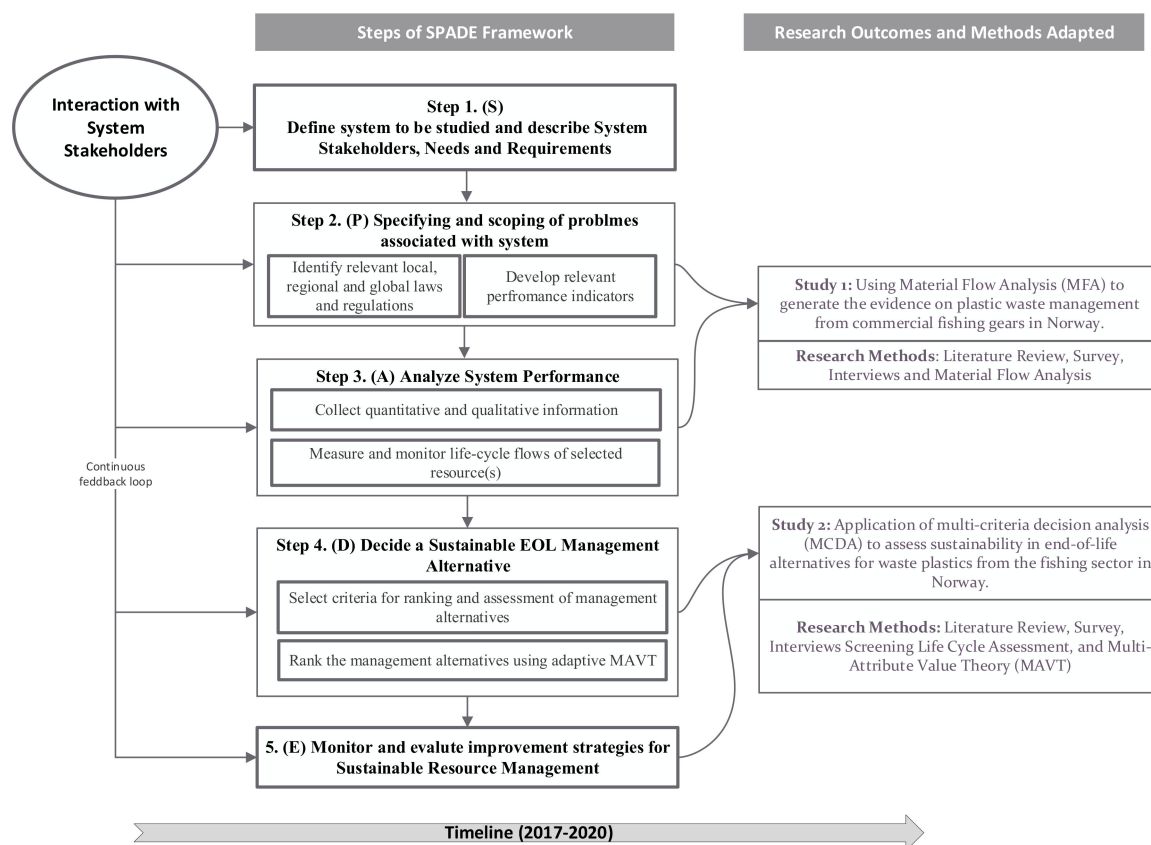
Figure 2. Research methods adapted in following SPADE framework for the management of FG resources.

The results of the literature review were used primarily to define the system and to map system stakeholders (step-1). The literature review and stakeholder interactions then were used to classify relevant life cycle processes of commercial FG and define associated problems across the life cycle phases (step-2). The industrial ecology (IE) tool, material flow analysis (MFA), is applied in study-1 to analyze system performance (step-3) by mapping and quantifying plastics' flows throughout the FG life cycle. In the absence of information to conduct MFA, questionnaires, semi-structured interviews and stakeholder surveys were used to collect the information necessary to validate the MFA model. Further, in study-2, a multi-attribute value theory (MAVT) method was adapted to determine sustainable management strategies for FG resources (step-4). The essential information for MAVT model inputs was obtained through site visits of waste management and recycling facilities and relevant expert stakeholders' questionnaires. The data collections routines and analysis of MAVT are elaborated in the study [28].

Finally, in the last step (step-5), literature review, expert opinion and insights gained through field visits were used to recommend strategies for continuous evaluation of the circular economy's targets for the FG resource management in Norway.

4. Results

SPADE is used here to organize the results regarding the system of commercial FGs in Norway.

4.1. System Stakeholders (S)

The first step taken is an identification of system stakeholders and their needs. There are wide ranges of groups that may be considered stakeholders in managing FG resources. Users and other stakeholders are individuals or groups of individuals who use the resource system in diverse ways for sustenance, recreation or commercial purpose [7]. The classification and mapping of stakeholders have been carried out in several ways based on the

applicability and relevance to the problem. Here stakeholders are classified based on their relation to phases of the FG system life cycle. Purchase, use and end-of-life are the three main life cycle phases of FG. Stakeholders directly involved in one or more life cycle phase, their relationships and roles are presented in Table 1.

Table 1. List of stakeholders and their relevance to the life cycle stages of the FG system.

Stakeholders'	Pre-Use (Purchase)	Use-Phase	EOL Phase	Other	Category
Directorate of Fishery			X		Regulatory
Directorate of Environment			X		Regulatory, Environmental
Ports and harbours		X	X	X	Regulatory
Fishers and fishermen associations	X	X	X	X	Economic
Fishing Gear Producers/Suppliers	X				Economic
Relevant NGO's	X		X	X	Social, Environmental
Research & consultancy companies and Academia			X	X	Social, Environmental
Waste management companies			X		Economic, Environmental
Waste collection and recycling companies			X	X	Economic, Environmental

4.2. Problem Definition (P)

Problem formulation is among the most critical tasks for any research project. An in-depth understanding of the problem statement helps build a comprehensive analytical framework for the system under consideration. Figure 3 depicts the significant problems associated with the life cycle stages of FG resources. The problem identification was made by interacting with the indicated system stakeholder group(s). During the study period (2017–2020), a semi-structured questionnaire, interviews and a literature review were used to extract necessary information from relevant actors (FG producers, fishers, waste managers, beach clean-up volunteers, Directorate of fisheries, NGOs working on FG pollution, recyclers and landfill operators). Information was collected to build holistic problem definition for the study. The questions asked for each stakeholder groups across the life cycle of FG are presented in Supplementary Information Material (SI).
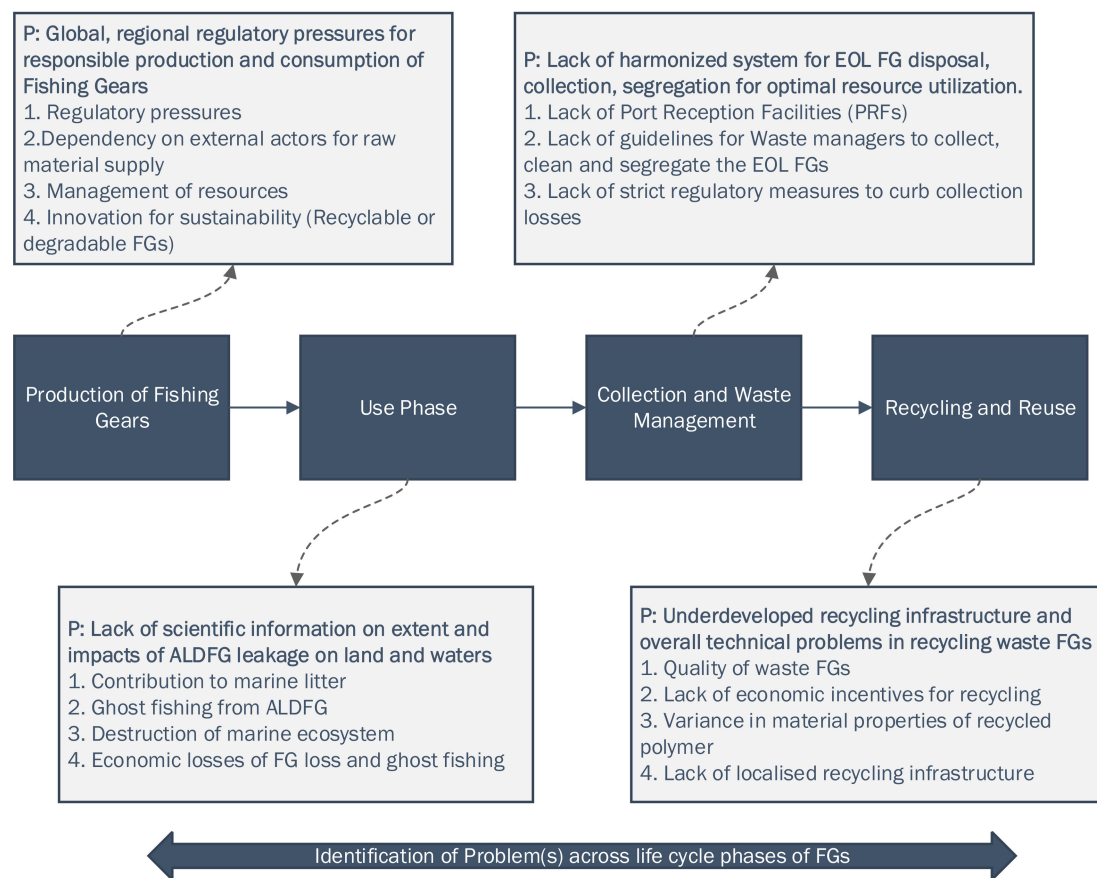
Figure 3. Problems associated across the system life cycle phases of fishing gear resources.

4.2.1. Problems across Production Phase

The design and production of FG vary considerably depending on the fishing community, type of target fish species, fishing grounds, size of the fishing vessel and local fishing regulations. Typically, FG are predominantly made of plastic polymers (PE, PP and PA) and other materials, such as metals, lead, polyvinyl chloride (PVC) and wires, only constitute around 10–30% of any FG type [14]. Intricate gear design, inability to track or trace FG once they get lost in the operation phase, and the dominance of durable plastic polymers resulting in ghost fishing are among the significant concerns associated with the current FG design. The use of three polymers and metal wires make it one of the most challenging products from which to recover material upon the end of useful product life. Additionally, the FG producers in Norway import most plastic polymers from Asian countries, causing dependencies on external actors [16]. Such dependency on external actors and the absence of in-house capacity to source raw materials had emerged as critical challenges for business firms during the current pandemic (COVID-19) times when import-export was significantly impacted. Consequently, developing local eco-industrial networks and improving self-reliance by recycling/reusing waste material could be explored as a long-term and sustainable alternative.

Furthermore, a rise in marine plastic pollution depletes fish stocks due to ghost fishing from ALDFG. These pressures on the marine ecosystem pose additional regulatory pressures on FG producers to innovate and develop biodegradable or recyclable designs for commercial FG. Hence, material resources and recovery underpin the fundamental problems identified by the regional FG producers in this study.

4.2.2. Problems across Use Phase

In the use-phase, fishers deploy FG in the ocean to catch a target species. Deployed FG, or their parts, may get lost during operation due to various reasons listed by Macfadyen [16]. FG have been lost, abandoned, or otherwise discarded in all seas and oceans since fishing began [13]. Moreover, in coastal countries like Norway and Iceland where fishing is among the primary economic contributors, impacts from ALDFG are detrimental [23]. Several studies document the damaging impacts of ALDFG on fish stocks and potentially harmful impacts on endangered species and benthic environments [16]. Apart from ghost fishing, ALDFG also increases ecological and economic threats, including navigational hazards and associated safety issues [29].

Commercial fishing is regulated in Norway through national, international and regional instruments. The Supplementary Information Material (SI) provides a brief overview of available policy instruments regulating the capture fishery practices. Norway's Marine Resources Act (6 July 2008) [30] is the primary fisheries legislation in Norway. This legislation prohibits the dumping of FG, moorings and other objects in the sea that may injure marine organisms, impede harvesting or damage gear. The act also mandates fishing vessels that lose FG to remove the object from the sea. If this is not possible, this loss must be reported to authorities. These lost-gear reports help the coast guard effectively plan the annual clean-up campaigns.

Although ALDFG is the most dangerous fraction of marine litter [13], little or no information is available on the regional flows, sources, and plastics' fate from the fishing sector. Jambeck [31] identifies this knowledge deficiency about plastic flows from fishing activities. Lack of scientific evidence resulted in strong dependence on precautionary principles or conservative methods to manage FG resources in coastal countries. Consequently, the problem associated with the use phase implies a need to build a holistic and systemic understanding of fate, transport, sources, sinks of ALDFG in land and waters.

4.2.3. Problems across End-of-Life Phase

At the end of gears useful life, fishers dispose of FG in the waste management facilities (WMF) as mandated in the Norwegian Pollution Control Act of 1981. The Pollution Control Act is modified to enforce the Port Reception Facility (PRF) directive by the EU. The Norwegian act states that littering is prohibited, which applies both on land and at sea [32]. Sound waste management is of crucial importance in preventing and reducing marine litter. Under the act, municipalities are responsible for collecting and treating household waste, while business and industry are responsible for properly handling and treating their waste.

The Norwegian Directorate of Environment and the Norwegian Directorate of Fisheries conduct programs to collect ALDFG from the ocean to minimize threats of ALDFG to the marine ecosystem. Similarly, ALDFG from shores are collected through annual beach clean-up operations in Norway. Waste FG collected through ocean and beach clean-up activities are deposited to the nearest WMF. Additionally, the waste generated through FG repair facilities end up in the WMF. At the WMF, this waste is segregated into fractions suitable for recycling, fractions for landfilling and fractions for incineration and then transported to respective facilities [14].

Semi-structured interviews during the site visits of waste management companies and waste recyclers in Norway for study-1 highlighted the problems in collections of EOL FG. The key challenge lies in the overall lack of PRF infrastructure across the Norwegian ports. The EU Directive 2000/59/EC dictates all EU-EEA member states to safeguard a PRF's availability and provide a waste management plan on all ports. PRFs are defined as *'any facility, which is fixed, floating or mobile and capable of receiving ship-generated waste or cargo residues'* [33]. According to the European Free Trade Association (EFTA) court's recent judgment, Norway has failed to fulfil the EU directive's obligations. Only one-third of the total registered ports in Norway contain a dedicated PRF or waste management plan. Lack of PRF can lead to an inappropriate collection of FG related waste, and may give rise to

illegal dumping, burning or stockpiling of waste on ports hindering the waste collection regime from recovering valuable material [34].

4.2.4. Problems in Closing the Loop for FGs

Capacity building and technical support are critical to extracting value from waste based on CE principles. Currently, there exist numerous challenges in closing the loop for plastics from waste FG. The EOL collection, segregation, capacity, and availability of recyclers are among the critical concerns in realizing the economic benefits of material recovery. Hence, to establish opportunities for regional recycling or circular business models, it is imperative to know the quantity of waste plastic available for recycling from the fishing sector. Furthermore, while pursuing the goals of a circular economy, it is essential to assess the sustainability of the proposed EOL management strategies.

Considering all the collected information in the first two steps of the SPADE method, the following fundamental problems are defined in the second step of the SPADE framework that are subsequently answered in the last three steps SPADE method.

- What information is essential to aid system performance analysis and improvement? (answered in study-1)
- How much plastic is available at waste management facilities from the fishing sector in Norway? (answered in study-1)
- Which methods are available to assess sustainability in implementing circular economy strategies in managing FG resources? (answered in study-2 and partially in the current study)
- What measures are needed to ensure continual and sustainable improvement in system performance? (current study)

Additionally, the problem associated with plastic's value chain includes the absence of industrial recycling infrastructure. Lack of recycling facilities resulted in transboundary export of recyclable materials out of Norway, thereby missing an opportunity to recover material locally. If not handled responsibly, the exported waste may result in landfills or contribute to the pollution of marine or riverine ecosystems through leakages. Plastics polymer PE from waste FG can be processed through mechanical recycling to yield HDPE (high-density polyethylene) and LDPE (low-density polyethylene), which can be used further to replace virgin polymers in the products made by injection molding technology [35,36]. The PAs from waste FG retain their properties post-recycling, making them an economically attractive byproduct of recycling.

Therefore, the SPADE method's analysis must be articulated to understand opportunities and barriers in realizing sustainable closed-loop strategies for FG within Norway.

4.3. Analysis (A)

The analysis was conducted mainly through the IE-based MFA method and presented in study-1 [14]. The data and findings from study-1 are used here to define the analysis, and the lessons learnt from MFA are deliberated further. In analyzing the system's performance, it was essential to understand the physical flows and stock of mass of plastics (MoP) from the FG system in Norway.

Accordingly, in study-1 [14], a static MFA model was developed from 2016 to 2017 and accounting of MoP through purchase, use and post-use processes of FG life cycle were mapped. In MFA, static models provide insight into systems at a specific time, allowing holistic assessment of their current state [37]. Based on data from gear producers, fishers, collectors and recycling and waste management companies, an MFA model was established to quantify the annual stocks and flows of plastic polymers from six commonly used FG for commercial fishing by the Norwegian fishing fleet. The summarized results reported that the average MoP in the form of newly purchased FGs is estimated to be 2626 ± 143 tons per year.

Additionally, 1755 ± 681 tons of MoP are purchased as FG parts for replacement during significant repairs. Fishers reported the associated risk of damaging FG and losing

part of or the entire gear upon deployment in the ocean. Such FG and/or parts leaked into the marine environment as deployment loss are estimated to be 400 tons per year. The beach and ocean clean-up efforts at the national scale contribute to removing/recovering cumulatively 100 tons/year of MoP from lost FG. Finally, if not lost during operation or repaired, fishers must dispose of FG at their end-of-life. The MFA estimates that annually around 4000 tons of MoP are collected at Norwegian WMFs for EOL treatment from the commercial fishing sector, and more than 50% of the collected waste fraction is sent out of Norway for further processing and recycling.

Building upon the problem definition stage, analysis uncovered the loopholes in the system of FG resources in Norway. Results suggest that although there are ample policy instruments available in regulating the fishing sector, leakage of plastics to the marine ecosystem, and an underdeveloped infrastructure to collect, handle and treat waste are causing system malfunction. Finally, the analysis can be used to develop additional insights through processing the data gathered from the system stakeholders and to design a strategy to ensure sustainable management of plastics from FG.

4.4. Decide (D)

Until the end of 2017, industrial-scale recycling of waste plastic was unavailable in Norway [28]. Consequently, the entire fraction of recyclable material was sent out of Norway for mechanical recycling of PP, PE and PA from EOL FG. However, industrial-scale recycling for obsolete plastics from the fishing and aquaculture sector began in Norway in the latter half of 2017. Although recycling began in Norway, a still significant fraction of waste is sent abroad for further processing and recycling. Therefore, decisions must be taken to assess the sustainable EOL management alternative for FG resources, ensuring optimum material or energy recovery. These decisions are studied and presented in Study-2 [28], and the findings are summarized here.

In study-2, to assess the sustainable EOL management alternative for FG resources, four scenarios were selected: landfilling, incinerating, recycling (inland) and recycling (export). Sustainable management is defined as "The ability of EOL management alternatives to manage 4000 tons of waste FG annually through maximizing environmental and economic and social benefits while minimizing the negative effects" [28].

Based on the qualitative and quantitative data from relevant system stakeholders, MAVT was adapted to rank the EOL alternatives based on their ability to manage 4000 tons of waste plastics from FG in Norway within the defined sustainability criteria. The application of multi-criteria decision analysis (MCDA) to address the decision-making problem is presented in the study [28]. Sustainable Development Goals (SDGs) and targets are considered helpful in assessing the three dimensions (environmental, economic and social) of sustainable development proposed by [38]. SDGs are preferred as they address some of the systemic barriers to sustainable development (SD) and contain better coverage of and balance between the three dimensions of SD and their institutional/governance aspects [39]. The assessment criteria are chosen to reduce the uncertainty, increase the understanding of the FG system, and measure the EOL alternatives' performance against a defined goal.

Figure 4 presents the value tree developed for the decision analysis problem in study-2. The top of the value tree diagram presents the decision problem, which was assessed to attain sustainable strategies for FG management as per the definition. SDGs are used to define the assessment criteria under environmental, economic and social objectives, and the four alternatives are evaluated. The first target under SDG 14 is to prevent and significantly reduce marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution, by 2025. Under OSPAR convention's *Marine Litter Regional Action Plan 2014-2021*, Norway has adopted the goal of reducing litter inputs that have negative impacts on coastal waters, the sea surface, the water column or the seabed. Accordingly, the environmental criteria are chosen to minimize the risk of marine pollution and climate change.
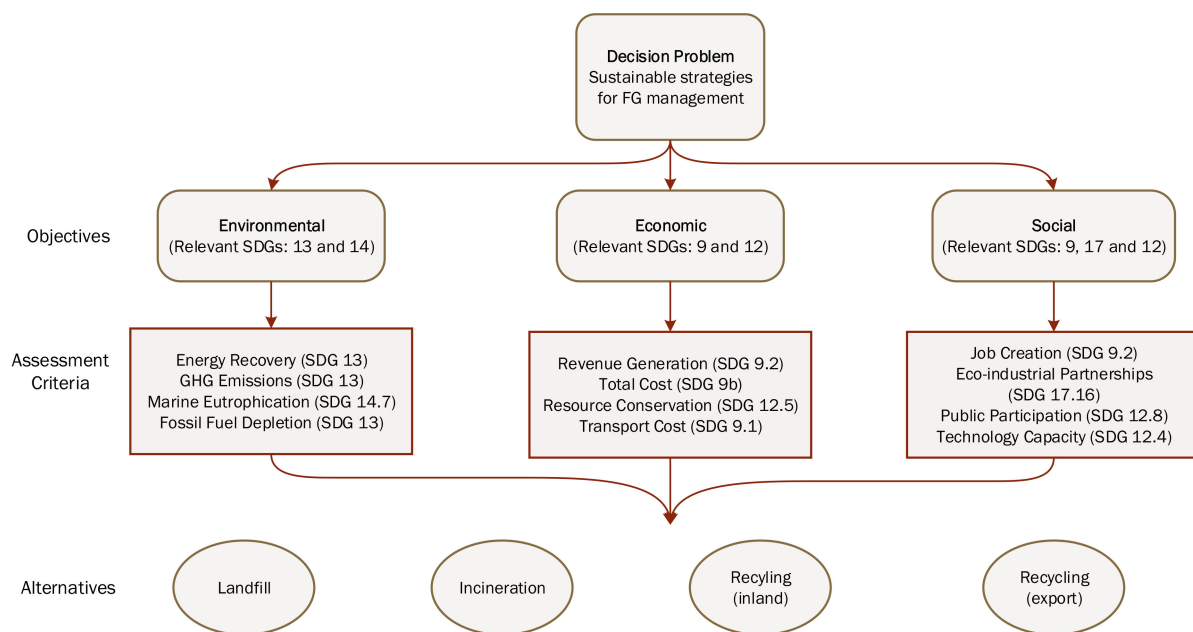
Figure 4. MCDA model for proposed alternative evaluation in selecting sustainable EOL management alternatives for FG and ropes.

The analysis was performed using DECERNS (Decision Evaluation in ComplEx Risk Network Systems) software [40]. The three core criteria, environmental, economic and social, and associated sub-criteria, are chosen through expert judgment. Additionally, the performance of each of the four alternatives against the selected sub-criteria was calculated using data from site visits and personal interviews of waste managers, recyclers. The rationale behind the selection of environmental, economic and social assessment criteria, and their relation to SDGs, data collection and analysis, are detailed in study-2 [28].

The adaptions in MAVT were made for addressing the research questions to facilitate the participatory process and gain flexibility in processing the available information. In a typical MAVT study, stakeholder opinion, qualitative and quantitative information is processed to find the "best" or "most-suitable" solution [41]. Hence MAVT was chosen to incorporate qualitative and quantitative information obtained from the expert stakeholders.

The results of MAVT decision-making analysis are detailed in study-2, which strongly suggest the importance of the location for recycling waste. The recycling operations shows the potentially maximum positive effects on the environment and society with additional economic benefits from resource conservation and energy recovery. In contrast, the overall sustainability scores were lowest for exporting recyclable FG waste material out of the country [28].

These decisions helped to determine the sustainable alternative for managing plastic resources from commercial FG in Norway. Adaption and application of MAVT provided flexibility in using available information in the assessment. Stakeholders are the key source of inputs throughout this research. In the MAVT study, 31 expert stakeholders participated, consisting of regional waste managers, recyclers, collectors, NGOs, academic experts and regulatory agencies. Involving these actors within the MAVT framework enhanced deliberated discussions on several aspects of EOL management that helped build a holistic understanding of EOL strategies during the decision-making process. Building on Analysis and Decision-making, the SPADE method's evaluation activity aims to encourage a continual evaluation of employing sustainable alternatives.

4.5. Continuous Evaluation (E)

Evaluation as an explicit activity of the SPADE method offers the opportunity to reflect on the progress of the research and the findings. The data collection steps applied for the previous studies yielded information for a comprehensive understanding of the system life

cycle for commercial FG. The literature review on existing policy instruments (presented in SI) and the current status of system performance studied through the earlier steps were used to derive the elaborate evaluation strategies for improvements in system performance.

In improving system performance, sustainability and resource conservation following the circular economy principles are prioritized. CE is primarily at the forefront in Norway as the first analysis of the Circularity Gap Report Norway 2020 reveals that 97.6% of materials consumed each year in Norway never return to the Norwegian economy [42]. At only 2.4% circular rate, Norway has enormous potential and urgent need to explore various strategies to improve circularity within the region. CE is a priority of the European Green Deal through the *Circular Economy Action Plan* adopted in March 2020. Since the EU is among Norway's key trading partner, adopting CE principles is strategically important for Norway.

Additionally, CE strategies provide a new incentive by promoting local eco-industrial networks, creating new jobs and improving national self-reliance by recycling/reusing waste material. Therefore, the continuous evaluation of problems identified across system life cycle phases of commercial FG is an essential component to ensure follow-up of CE and SDG targets.

Based on information obtained from literature, site visits and interaction with system stakeholders for the data collection phase of earlier studies, a continuous evaluation strategy is proposed for enabling principles of CE and sustainability within the life cycle of commercial FG. Figure 5 presents a brief overview of evaluation strategies across the system life cycle of FG resources.
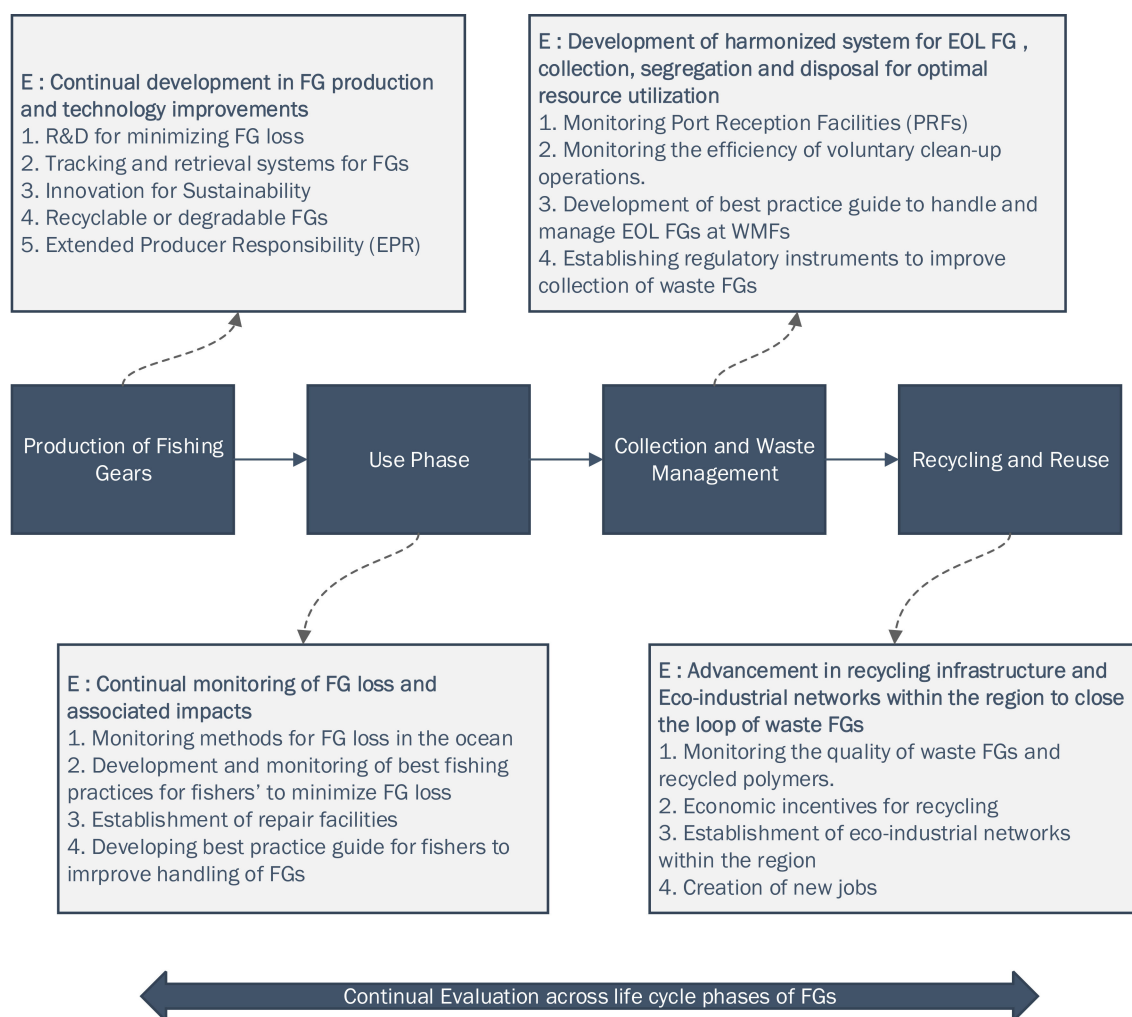

Figure 5. Continuous evaluation strategies suggested across the system life cycle phases of fishing gear resources.

4.5.1. Production Phase

Continuous evaluation is one way to improve the FG production material and technology. The research on alternative raw materials for FGs must be emphasized. The principles of eco-design, design for recycling and design for sustainability may contribute to create FG from material that allows efficient and profitable recovery upon end-of-life without hampering the product's effectiveness. In its current strategy, the EU invites innovation and business solutions across the member states to facilitate the transition towards a circular economy with a particular focus on marine plastic waste from FG [35]. Accordingly, the strategies such as gear marking, recycle friendly gear design and biodegradable FG should be explored further and monitored continuously to ensure the sustainability of improvement strategies.

Extended producer responsibility (EPR) is considered an efficient strategy to hold the manufacturer/producer responsible for the end-of-life treatment of their products, including FG. In effect, this removes the inconvenience and cost factors associated with waste management from the fishers. By linking the producer to the product's EOL stage, the scheme can also indirectly encourage more life cycle focused product design [43]. These schemes can also help trigger infrastructure development to support the EOL collection process. In Norway, the Ministry of Climate and Environment has announced its goal to introduce a producer responsibility scheme for fishing and discarding marine equipment from the aquaculture industry [44]. Together with EPR, gear marking or gear identification is identified as an essential strategy for responsible fishing and for controlling the ALDFG problem. The Fisheries Department of the FAO published systematic guidelines encouraging member states to incorporate gear marking policies. According to these guidelines, gear marking aids in understanding the location, scale and nature of FG in the water [12].

Careful introduction and incorporation of these strategies may improve the state of circularity in the system of FG resources. However, continuous monitoring is essential, as advised by SPADE, to ensure successful implementation and performance improvement.

4.5.2. Use Phase

The science of resource management involves generating a systemic understanding of the processes that lead to improvements in or deterioration of natural or anthropogenic resources. For the system of FG resources, management strategies are based mainly on highly segregated, generally outdated, non-uniform and unscientific estimates on FG life cycle phases resulting in an overall absence of system information. Therefore, to evaluate the system performance, continuous monitoring of flows and stocks of plastics throughout the life cycle phases of FG is essential. In order to establish scientifically sound mapping and monitoring systems for macro and microplastics in the marine environment, internationally agreed definitions, standardized quantitative methods and regionally suitable indicators are needed. Several European states are taking coordinated action to develop a common standard for analyzing and mapping microplastics and investigating the impacts of microplastics on the marine environment and seafood. These monitoring strategies need continual evaluation to understand better the fate and transport of plastics in the environment.

Additionally, ghost fishing's environmental, economic and social impacts must be studied and communicated to the system stakeholders. Fishers and other resource users are the critical stakeholders in the use phase of FG. Consequently, fishers' knowledge of fishing grounds and responsible gear use must be documented to develop best practice guides for young fishers to minimize FG loss or prolong the operational life span of FG. The performance of selected improvement strategies and collected information through monitoring must be evaluated continually to ensure the FG system's betterment.

4.5.3. End-of-Life Collection

The analysis (study-1) proved that in Norway, the logistics transporting EOL FG to respective recycling industries are immature or nonexistent [28]. On the contrary, findings

from study-1 show the dominance of transboundary export of EOL FG from Norway, facilitated by the availability of organized actors collecting, segregating and transporting recyclable fractions of plastic FGs out of Norway for further treatment. Therefore, a continuous evaluation is needed towards harmonizing and regulating the network of actors responsible for EOL handling and management of waste FG. Additionally, monitoring the status of PRF is vital to improving the collection of waste gears. The recent judgment by the EFTA court highlighted Norway's apparent failure in fulfilling the obligations of establishing PRF across all the ports [34]. The gigantic coastline and numerous ports put an enormous burden on regulatory actors in managing the landing sites. Harmonized collection of waste FG is imperative for improving the material recovery in Norway, therefore, updating the PRF infrastructure is an urgent need for avoiding material loss.

Apart from the lack of collection facilities, material loss occurs within the WMF as well. The collected waste FG are often laden with dirt, rotten biomass and needs pre-treatment (segregation, cleaning, cutting) before proceeding further with material recovery. Intricate gear designs and presence of metal parts makes cutting and segregating recyclable plastic even more difficult. However, personal communication with a regional waste manager revealed that biomass laden waste is often subjected to incineration or landfills and completely bypasses any opportunity for material recovery. Minor changes in the waste handling practices at WMF and developing best-practice guides for handling the FG related waste could improve the recycling of FG in Norway.

4.5.4. Closing the Loop of Waste from the Fishing Sector

Previous research shows that commercial fishing practices generate an estimated 4000 tons of waste plastics from EOL FG collected at WMF in Norway. In addition to the commercial fishery, leisure fishing, fish farming, and inland fishing generate similar plastic composite material accessible for recycling. In addition, mechanical and chemical recycling technologies are available to recover material from waste FG. Mechanical recycling of waste FG generates HDPE and LDPE polymers that can be used as a raw material in the plastic products manufactured through injection molding technology. Pilot tests are underway to assess the feasibility of replacing virgin plastic polymers with recycled plastic pellets of HDPE and LDPE in the production of brackets and walkways for the aquaculture sector [45].

Positive results from the pilot test could boost the opportunity for realizing circular business models in Norway. Such product-to-product recycling may also reduce the dependence of plastic industries on foreign actors responsible for the supply of virgin polymers. Regional recovery of plastic polymers may provide flexibility in the supply chain, and additional positive social impetus by creating new jobs. In addition, Vildåsen [45] lists cost-cutting and reduced environmental impacts as other factors motivating regional plastic industries to aim for circular strategies.

The semi-structured interviews with regional recyclers pin-pointed the ambiguity in Norway's waste regulation in Chapter 9 [46], which states that *"All waste must be treated before landfilling, and landfilling is allowed if the processing and treatment of waste fraction are socio-economically non-viable."* According to the regional recyclers, the latter half of the statement results in landfilling as a preferred alternative over recycling because the lack of segregation and transport facilities for EOL FG makes it economically burdensome to recycle.

The availability of waste material as a resource for the technology to recycle plastic contents of FG indicated the opportunity to realize the circularity for the FG in Norway. However, establishing an eco-industrial network between the fishing and plastic industries demands assurance of quality and quantity of the eventual recycled polymers. Changes in policy drivers for waste management are necessary to promote material recovery over landfilling. Stakeholder awareness and involvement are vital in raising the demand for environmentally friendly products. Stabilizing all the factors may influence the market

acceptance of products with recycled polymers and may result in elevated demands for such products.

Finally, a constant dialogue with system stakeholders, regulatory support through visionary policy instruments, research to advance technological feasibility and reduce operational challenges of FG recycling are among the areas that need continual evaluation to realize the sustainable management of FG resources in the Norwegian context.

5. Reflection and Conclusions

5.1. Reflections on SPADE Method

In this paper, we have explored an application of a SE framework, SPADE, to a case of the Norwegian commercial fishery sector, intending to develop strategies for the sustainable handling and life cycle management of FG resources. The science of resource management demands a transdisciplinary approach for studying complex socioecological systems. Consequently, a systems approach provides holistic coverage as it replaces the notion of resources as discrete entities in isolation from the rest of the ecosystem and social system. Here, the SPADE methodology was adapted to facilitate the problem-driven, interdisciplinary research to comprehend the sustainability dimensions in managing a system of FG resources in Norway.

The case study of FG resources is unique. There is an overall lack of scientific information to steer the meaningful policy or technological inputs for managing the potential plastic resources from FG. Qualitative research methods such as structured, semi-structured interviews, questionnaires and focus group workshops were used throughout the study period (2017–2020) to involve stakeholders. Involving stakeholders so early in the study helped build a dialogue with the actors, which eventually led to capturing several unnoticed or undocumented aspects of FG resources in Norway.

Although resource users develop a comprehensive knowledge of the resources they use/consume and associated environments, this knowledge is rarely collected systematically and therefore cannot be used scientifically. SPADE's application provided a scientific template to collect such knowledge in highly structured formats, resulting in the collection of large amounts of information on the FG resources and identification of associated problems. The data captured in the earliest phases also helped define the management problems for FG across their life cycle processes.

The continual interactions with several stakeholder groups further helped gain quantitative information on stocks and plastics flows from commercial FG in Norway. The mass of plastic flows across the system life cycle of FG provided a critical science and technology contribution for the Environmental Directorate and the Fishery Directorate of Norway, supporting the formulation of policies to monitor and abate the plastic pollution from the commercial fishing sector. Additionally, the reported annual quantities of plastic waste collected in the end-of-life stage are considered vital evidence for regional recyclers and waste managers looking for reasons for closing the material loop from FG resources in Norway. Simultaneously, the MAVT study results highlighted the improvement potential in realizing sustainable management's overall goal derived from the global framework of CE and SDGs.

Continual involvement of stakeholders' opinions in all the stages also allowed researchers (authors) to build a solid practical knowledge base for suggesting management strategies. Although proposed outcomes are limited to the case of Norway's commercial fishing sector, the knowledge can be adapted and exchanged with similar ecosystems elsewhere.

In retrospect, SPADE's structured simplicity and flexibility became increasingly valuable in selecting research methods to achieve a common goal. Nonetheless, it took four years (2017–2020) to address and apply the entire SPADE methodology, providing holistic coverage of all the life cycle processes of FG resources and enabling associated learning. Additionally, SPADE's logical and iterative workflow allowed the co-existence of qualita-

tive and quantitative research methods throughout the four-years without hindering the achievement of the study's overall goal.

5.2. Integrating Sustainable Development Goals

In this study, the UN's Sustainable Development Goals and the EU's Circular Economy framework were used to define and outline the potential for improvement in the management of FG resources in Norway. Given the all-inclusive scope of the SDGs, inputs from science are deemed significant for policymakers to assess the economic, social and environmental implications of their strategies in an integrated way over the long term. Here, adaptations in the SPADE method were made to facilitate synergy between the SDGs and policymakers. The synergy is illustrated by identifying relevant SDGs, targets and further developing a set of assessment criteria to monitor and ensure sustainable management of FG resources. In study-2, the sustainable decision making at the fourth step was achieved through linking the assessment criteria to SDGs in the MAVT method. Application of relevant SDGs and targets aided in producing a focused, measurable and all-encompassing coverage of sustainability's triple-bottom-line aspects.

Additionally, the SDGs ensured better communication and understanding of the criteria, as stakeholders were familiar with the goals. Unlike the SDGs predecessor, the Millennium Development Goals (MDG), the SDGs explicitly focus on businesses to apply their creativity and innovation to solve sustainable development challenges. The elaborated targets and set of indicators to assess the growth of selected SDGs were proven helpful in devising strategies in line with global sustainability priorities.

5.3. Limitations and Application

The SPADE method proposed in this paper helped translate and operationalize the SDGs in managing FG resources in the fishing sector; however, this is not necessarily the only approach applicable for other sectors. Selections of relevant SDGs, targets and following assessment criteria are essentially subjective and might vary while reproducing the research elsewhere. Moreover, the current study's scope focuses on the recovery and management of plastics from fishing gears, excluding other marine litter sources, while developing a set of improvement strategies. Additional analysis and deliberations with experts in marine ecology must be organized to create sustainable management of other marine litter sources in Norway and the planet. Furthermore, the case study only illustrates possible connections between SDGs, targets, indicators and improvement strategies. System improvement is a continuous process that involves the active participation of a range of stakeholders. It also demands a strong political will to transfer scientific findings into policy instruments followed by constant monitoring of implemented strategies. The cyclic and iterative steps needed for continual system improvement are a vital part of SPADE, yet, maintaining and monitoring the iterative progress, in reality, may be challenging.

Lastly, the stepwise SE framework presented here advocates the need to incorporate stakeholders across all the life cycle stages of a resource to ensure the sustainable management of anthropogenic resources under consideration. The adapted SPADE method is transferable, especially in the cases of data-less or data-limited resource management. Nevertheless, it is essential to apply it in another context with local adaptations to validate its robustness. As more evidence is required to create informed strategies for managing FG across all the fishing nations, the proposed SPADE model is currently being applied by the author(s) to understand plastic pollution across European waters.

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