SUSTAINABLE APPROACHES TO FISHING GEAR DEBRIS IN EUROPE: EFFECTIVE MANAGEMENT, REDUCTION AND RECYCLING STRATEGIES

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Preface

Due to its widespread and pervasive nature marine litter has become a global problem. It doesn't respect national boundaries while affecting coastlines, seas, and oceans across the world. The interconnectedness of marine ecosystems allows litter to travel vast distances, carried by ocean currents and winds, resulting in the accumulation of debris in remote and diverse marine environments. Marine litter originates from a variety of human activities such as shipping, fishing, tourism, and inadequate waste management practices.

To preserve the health of our oceans and the diverse marine life within them The necessity of fighting marine litter is of highest importance. Marine litter poses a significant threat to ecosystems, marine animals, and coastal communities. With this, it disrupts food chains, damages habitats, and harms marine species through ingestion and entanglement. As a consequence, the economic and cultural interests of coastal communities are affected. Therefore, concerted efforts to reduce, prevent, and clean up marine litter are crucial to safeguarding the marine environment and ensuring its sustainability for future generations.

Addressing marine litter requires international cooperation, coordinated action, and the implementation of effective policies and practices at a global level. The "Grant Programme Against Marine Litter" by the German Ministry of Environment, Nuclear Safety, and Consumer Protection aims to support projects that focus on reducing and preventing marine litter. The program intends to fund initiatives that address the root causes of marine litter, implement innovative solutions for waste prevention and management, and raise awareness about the issue. It also seeks to encourage stakeholder participation and international cooperation to tackle marine litter comprehensively.

The REVFIN project – as part of the aforementioned grant programme - focuses on the reduction of marine litter from abandoned, lost or discharged fishnets in Vietnamese coastal waters. The project promotes the development of capacities in higher education for the analysis of product life cycles, the definition of recycling routes and the creation of new value chains. By doing so it intends to increase the ability of higher education institutions to offer degree programmes connected this field of expertise. This seems to be necessary since environmental problems are rather complex and future generations of scientists and employees in enterprises need to draw on synergies from interdisciplinary collaboration and networking.

To initiate the development in economy and to anchor the mind frame in society, the project wants to support and advise the political partner and sector employers so that they can work towards the implementation of framework conditions for recycling of fishing net and gear opening a door for circular economy.

A circular economy is important for reducing marine litter because it focuses on minimizing waste and reusing resources. By transitioning from a linear "take-make-dispose" model to a circular approach that promotes recycling, reusing, and reducing waste, the amount of litter entering the marine environment can be significantly decreased. A circular economy also encourages the design of products and packaging that are more durable, easily recyclable, and less likely to become marine litter. Overall, by prioritizing sustainable resource use and waste management, a circular economy plays a vital role in preventing the generation of marine litter and mitigating its harmful impact on the marine environment.

As pointed out before, concerted efforts are necessary to reduce, prevent, and clean up marine litter. They are also crucial to safeguarding the marine environment and ensuring its sustainability for future generations. Concerted efforts clearly imply that solutions to the problem of marine litter, which have evolved in Western Europe in the last decades, cannot be easily implemented in Vietnam because the two regions have different environmental, cultural and economic contexts. The infrastructure, waste management systems, consumer behavior and legal frameworks vary significantly between regions. Therefore, adapting solutions to the specific context in Vietnam requires taking into account local conditions in order to develop effective measures. This could include adapting technologies, engaging local communities and collaborating with government agencies and stakeholders to create sustainable and realistic solutions to the problem of marine litter in Vietnam. Nevertheless, existing solutions always make a good focus to develop own approaches to a demanding problem.

European marine litter solutions can show best practices in waste management and recycling, the introduction of waste separation and collection infrastructure, and the implementation of regulations to reduce single-use plastics. They can inspire Vietnamese stakeholders to develop effective cooperation mechanisms between government, business and civil society. But most of all, it is important to adapt these findings to the local context and tailor them to the specific needs and challenges in Vietnam.

Keeping this in mind, this work wants to serve as a starting point for the development and adaptation of strategies for the reduction, management, and recycling of fishing gear debris in

Vietnam. The combination of the European perspective to a global problem with the specific objectives of the REVFIN project will give Vietnamese stakeholders a solid foundation for making wise decisions for their county, marine ecosystems and the future.

Figure 1: Fishermen preparing fishing nets in Vietnam

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Abbreviation

GWP	Global Warming Potential
EOL	End-of-Life-Strategy
EPR	Extended Producer Responsibility
HDPE	High-Density-Polyethylen
IUCN	International Union for Conservation
LCA	Life cycle assessment
NGO	Non-government organisation
PA	Polyamide
PE	Polyethylene
PET	polyethylene terephthalate
PS	polystyrene
PES	Polyester
PP	Polypropylene
PU	Polyurethane
PVA	Polyvinyl acetate
PVC	Polyvinyl chloride
UHMWPE	Ultra-high molecular weight polyethylene

1. Introduction

The alarming increase in plastic pollution poses serious threats to the ocean, an essential oxygen producer and CO2 sink. Approximately 10 million tons of plastic enter the ocean annually, with fishing gear debris accounting for the majority at around 640,000 tons [1]. This not only directly impacts the ecological balance but also carries significant socio-economic consequences [2]. Ecological consequences range from ghost fishing to the release of pollutants that create "dead zones" in the ocean. On a socio-economic level, gear debris hampers navigation and puts local economies under pressure. The additional challenges posed by overfishing, declining fish stocks, and climate change exacerbate the existing problem [3].

Given the escalating extent of marine pollution, increased public awareness and the implementation of concrete measures are urgently needed. A promising approach to mitigate this burden lies in the establishment of various measures in fisheries and the recycling of fishing gear debris. This approach not only promises to reduce pollution but also to efficiently utilize resources and minimize negative impacts on the marine ecosystem. To support the recycling of fishing gear debris, the development of strategies is crucial. Due to the complex structure of fisheries, various elements must harmonize to ensure effective recycling. Simultaneously, research explores the potential products that recycled fishing gear debris can be transformed into, promoting their versatile use and maximizing the sustainability of the process.

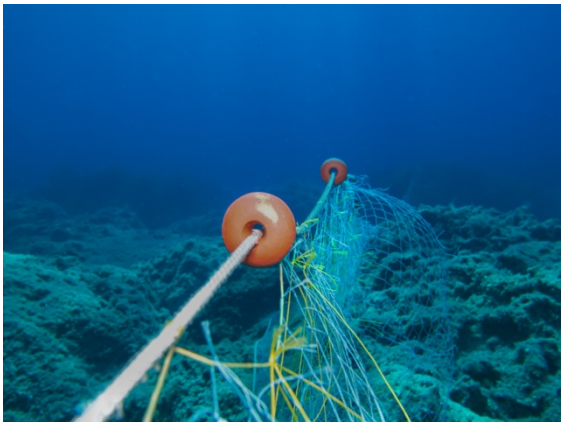

Figure 2: Discard Fishing net in the ocean

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2. Causes of fishing gear debris

To effectively address the issue of fishing gear debris, it is crucial to identify the underlying causes. A profound understanding of these causes forms the basis for developing preventive solutions and measures to minimize fishing gear debris. Additionally, this facilitates the implementation of efficient collection and recycling procedures. Factors contributing to the generation of fishing gear debris include:

- Extreme weather conditions
- Mechanical failures
- Human error and insufficient environmental awareness
- Collisions with other vessels or objects
- Vandalism or sabotage
- Economic factors

Extreme Weather Conditions, such as storms and rough seas, stand out as a primary cause for the loss of fishing gear in both commercial and recreational fishing. Intense winds and high waves can lead to the failure of anchorages or mechanical components, while unpredictable waves can damage or tear apart the fishing gear. Salvage attempts are often hazardous. To address these challenges, the fishing industry invests in weather monitoring and more resilient fishing gear. Additionally, currents can carry fishing gear into deeper waters, especially when surface floats submerge beneath the water surface. This emphasizes the need for strategies that enhance the durability and adaptability of fishing gear to withstand the unpredictable forces of nature [4].

Mechanical failure poses a significant risk to the loss of fishing gear in the ocean. The causes are diverse, ranging from manufacturing defects and improper maintenance to normal wear and tear. Modern fishing gear comprises numerous components, and the failure of even a small element can have serious consequences for the entire operation. A common example is the failure of anchorages, which can be compromised by material fatigue or corrosion, causing the net to lose its connection to the anchor. Another issue is the failure of winding mechanisms responsible for deploying and retrieving fishing gear. The breakdown of these mechanisms results in the inability to retrieve the fishing gear [5]. Moreover, fishing gear deployed on the seafloor is increasingly susceptible to wear and tear, also contributing to the loss of equipment [6].

Human error and insufficient environmental awareness, coupled with improper handling of fishing gear and unfamiliarity with fishing areas, heighten the risk of fishing gear debris. Issues with recovery, uncoordinated teamwork, and technical difficulties pose additional threats. The lack of awareness in dealing with fishing gear debris is both a significant cause and a crucial factor in the generation of such debris. Addressing these human-related factors is paramount in developing effective strategies to mitigate the impact of fishing gear debris on the marine environment. Increased education and training in proper handling procedures, coupled with heightened environmental consciousness, can play a pivotal role in reducing the occurrence of fishing gear debris [7].

Collisions with other vessels or underwater obstacles pose a substantial danger to active fishing gear, both in heavily trafficked sea routes and near harbours. Such collisions can result in severe damage or even the destruction of the equipment. Obstacles like sunken ships or rock formations increase the risk of nets, longlines, or traps being damaged or entangled. Extracting the gear from such situations is often challenging, especially when the obstacle is large or firmly anchored. Navigational awareness and the implementation of precautionary measures are crucial in minimizing the occurrence of these collisions and preserving the integrity of active fishing gear [8].

Vandalism or sabotage of fishing gear is a serious and sometimes overlooked problem in the fishing industry. In some cases, fishing gear is intentionally damaged or dislodged due to human interference. This can occur for economic reasons, conflicts between different interest groups, or as a result of legal and political considerations. Addressing this issue requires heightened security measures, stakeholder collaboration, and legal frameworks to deter and penalize such destructive activities. Recognizing and mitigating the risks associated with vandalism or sabotage is essential to maintaining the sustainability of fishing operations and reducing the environmental impact of lost or damaged gear [9].

Economic considerations often influence the decision to retrieve or abandon damaged fishing gear. High repair and retrieval costs compared to the actual value of the equipment may lead to abandonment. It is also economically sensible not to upgrade older equipment but to replace it with more cost-effective alternatives. Retrieval costs in hard-to-reach areas, taking into account fuel consumption, labour efforts, and potential loss of catch, may make abandoning the gear appear as a more cost-efficient option. Balancing economic factors with environmental sustainability is a complex challenge in the fishing industry, requiring careful evaluation and the development of strategies that align with both financial and ecological goals [10].

Regulatory uncertainties can contribute to the unintentional loss of fishing gear. Absence or unclear formulations in regulations can lead to misunderstandings in their application, facilitating equipment loss. Contradictory regulations between different authorities or levels complicate the proper deployment of fishing gear. Even clear regulations may lose their effectiveness due to inadequate enforcement or monitoring. Addressing regulatory ambiguities is crucial for fostering responsible fishing practices, reducing gear loss, and ensuring compliance with established guidelines. Clear communication and coordination among regulatory bodies are essential to minimize confusion and enhance the effectiveness of fishing gear regulations [11].

In summary, it can be observed that fishing gear debris can be caused by various factors such as extreme weather conditions, mechanical failures, collisions, vandalism, economic considerations, and regulations.

These findings underscore the necessity of preventive measures to reduce the generation of fishing gear debris and promote sustainability in the fishing industry. Collaboration among fishermen,

industry stakeholders, regulatory authorities, and research is crucial to minimize environmental impacts and enhance resource efficiency. This requires a holistic approach encompassing technological innovations, improved regulations, and education to effectively address the challenges associated with fishing gear debris.

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3. Consequences of fishing gear debris

The generation of fishing gear debris has not only ecological but also socio-economic consequences due to its underlying causes. In the ecological context, which describes the relationships and interactions of living organisms with their environment and the impact on ecosystems and biodiversity, the following consequences can be observed: Lost or abandoned fishing gear can lead to ghost fishing, capturing and killing marine animals such as marine mammals, fish, and birds. This can seriously decimate populations and disrupt the balance of marine ecosystems. Furthermore, the decomposition of fishing gear debris in the sea can release pollutants, leading to algae blooms and oxygen-depleted conditions, creating "dead zones" where marine organisms cannot survive. The decomposition can also act as a carrier of pollutants in various habitats and food chains, impacting the entire ecosystem [12].

In addition to the ecological impacts, fishing gear debris also poses significant socio-economic challenges. These challenges relate to the interface between social and economic aspects and their effects on the well-being and quality of life of people in a society. One example is the threat to maritime navigation. Lost fishing gear can impede navigation, posing a serious hazard to maritime traffic. Furthermore, fishing gear debris drifting onto beaches can affect tourism and impose costs on the local economy for its removal [13].

The issue of fishing gear debris is further compounded by factors such as overfishing, depletion of fish stocks, and climate change, which continue to escalate the pressure on marine ecosystems [14].

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4. Fishing gear debris and their material properties

To advance initiatives for measures and recycling processes for fishing gear debris, a comprehensive understanding of the properties of fishing gear is crucial. Only through in-depth knowledge of their materials and functions can targeted, sustainable recycling solutions be developed that consider ecological and economic aspects while minimizing environmental impacts. The term "fishing gear debris" refers to fishing gear left, lost, or otherwise discarded by fishermen in the sea. There are various types of fishing gear, such as nets, lines, hooks, baskets, and floating devices like buoys, as depicted in Figure 1

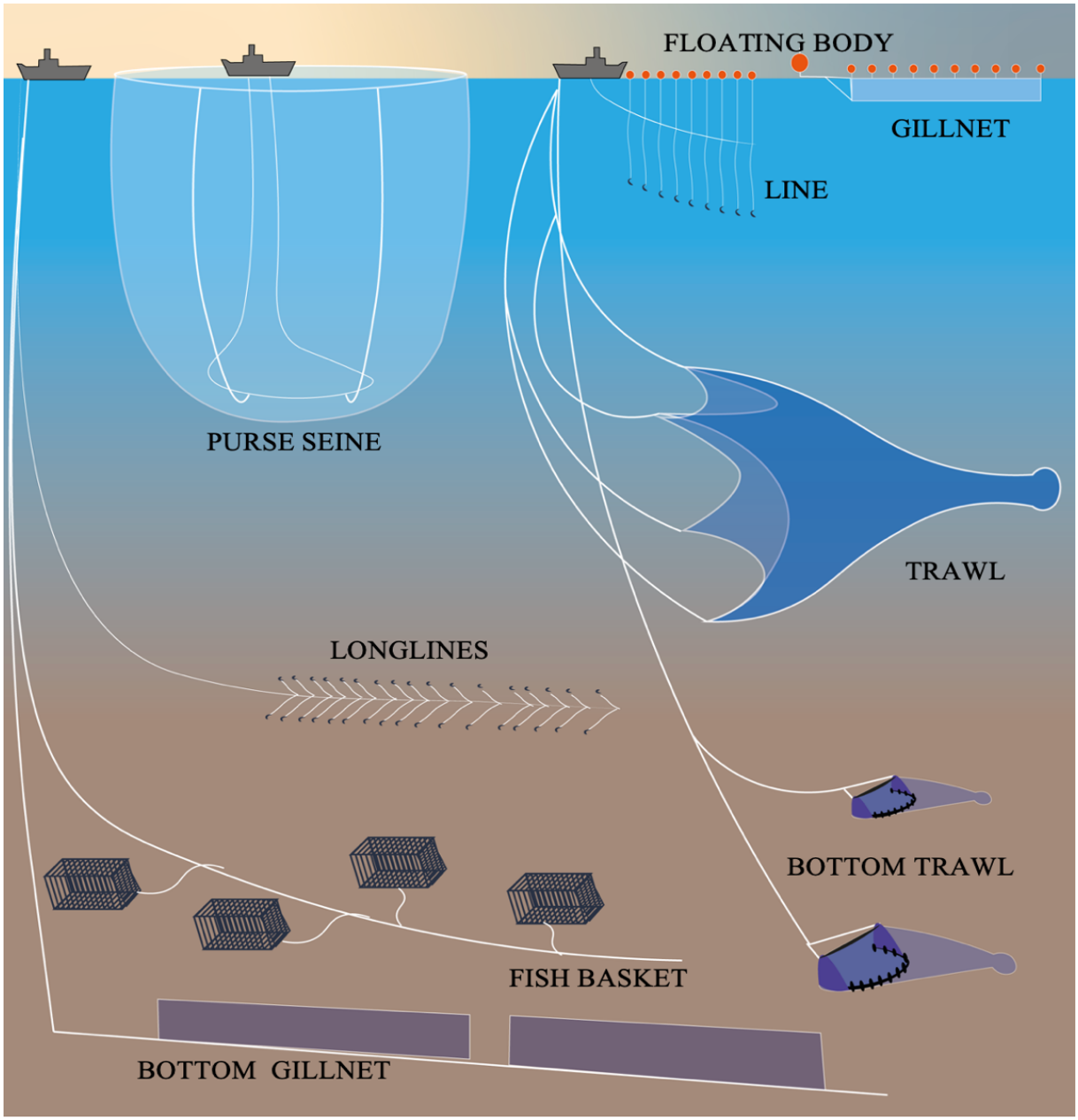

Fig 3: Examples of fishing gear at different water depths

These fishing gears can be broadly categorized into two main groups: textile and non-textile materials. Non-textile materials include sinkers, hooks, traps, pots, dredge frames, grids, and yarn reinforcements, primarily composed of metal and lead [15]. Lead is often used to weight gillnets and is considered hazardous debris due to its toxic properties [16]. Also falling under the non-textile category are floating devices, buoys, and rubber discs, mainly made of polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), and polyurethane (PU) [17]. The most commonly used fishing gears, especially fishnets made of textile materials, can consist of two types of fibres divided into two main groups: natural fibres and synthetic fibres. Historically, fishnets were predominantly made from natural fibres such as cotton and sisal. However, in modern times, synthetic fibres like polyamide (PA), polyethylene (PE), and polypropylene (PP) dominate their application [18]. The shift to synthetic fibres occurred due to their advantageous properties for fisheries, including high tensile strength, consistent material properties, abrasion resistance, low maintenance costs, and long lifespan, especially underwater. In contrast, natural fibres tend to absorb moisture and swell when in contact with water, affecting their handling. For fishing gear such as setting nets, purse seines, cast nets and drift nets Polyamides (PA), in the form of nylon profiles, are used due to their advantageous properties such as elasticity, high abrasion resistance, and temperature resistance. However, the high moisture absorption, limited dimensional stability, and the need for UV stabilization are drawbacks. Nylon loses strength under moist conditions. Polyolefins like polypropylene (PP) and polyethylene (PE) are commonly used in fisheries due to their high strength and durability, with nets often coated with UV stabilizers. Especially, polyethylene is used in trawl nets. In addition to the conventional PE variant, there are modified PE forms such as ultra-high-molecular-weight polyethylene (UHMWPE) and Dyneema, known for their excellent mechanical properties, UV and abrasion resistance. Dyneema stands out for its high strength-to-weight ratio and is used in trawl nets and aquaculture. UHMWPE is preferred for ropes and cage nets. Trawl nets made of high-density polyethylene (HDPE) also exhibit excellent knot strength and dimensional stability. Polypropylene is favoured for gillnets. Other polymers like polyvinyl chloride and polyvinyl alcohol are used for specific net types such as set nets and purse seines [19]. An overview of the association of materials with their respective properties and the various types of fishing gear is listed in Table 1.

Table 1: Assignment of Materials to Various Fishing Gear with Material Properties (THOMAS, 2017).

Fishing gear	**Material**	**Property**
Sinker; Hook; Fall; Weirs; Dredge frames; Grid; Gillnet	Steel	hard
	Aluminium	hard; tenacious; high strength
	Lead	soft; tenacious; poisonous
Set gillnet; purse seine net Setting nets;	PA	soft; lightweight; elastic; resilient; stretchable, high abrasion; high breaking strength; temperature-resistant; high moisture absorption; weather-resistant; unstable to UV rays; decreasing tensile strength with moisture absorption; resistant to chemicals
Floats; trawls; ropes; deep-sea set net; cage, hooks	PE	No moisture absorption; high tensile strength; high breaking strength; alkali-resistant; weather-resistant; stretchable; chemical-resistant; lightweight; low resistance to UV rays
Trawl nets; Knotless HDPE net	HDPE	Alkali-resistant; high rigidity; water-repellent
Floats; sinking lines	PET	high resistance; low sliding friction; high rigidity; high strength low water absorption
Floating body	PS	low water absorption; buoyant; medium hardness; medium strength;
Gillnets; ropes; floats	PP	Resistant to UV rays; no moisture absorption; high tensile strength; high breaking strength; low weather resistance; low elongation; resistant to chemicals; low water absorption
Float; Insulation; Buoy	PE, PET, PS, PU	alkali-resistant
Set nets; lifting nets	PVC	alkali-resistant
Purse seine	PVA	Long service life; low elongation; alkali-resistant
Cage; tubes	PVC	Low water absorption
Purse seines; trawls;	Dyneema	Very good resistance to UV rays; high abrasion resistance
Ropes; trawls; purse seines; longlines; cage nets	UHMWPE	high breaking strength; lightweight; high strength

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5. Pre-treatment and recycling processes for fishing gear debris

This section provides a comprehensive insight into the processes of recycling fishing gear debris. It not only presents specific recycling methods but also sheds light on crucial pre-treatment steps. Furthermore, the recyclability of fishing gear debris is discussed, and a glance at the challenges faced by recycling processes, along with their pre-treatment phases, is provided. This overview allows for a holistic understanding of the complexity and possibilities of recycling in the context of fishing gear debris. Finally, proven best practices for the successful implementation of recycling processes for fishing gear debris will be introduced later in this section.

5.1. Pre-treatment for fishing gear debris

The recycling of fishing gear debris involves a multifaceted process that encompasses both pre-treatment and the actual recycling procedures. Various methods, such as sorting, shredding, density separation, cleaning, and drying, are employed in pre-treatment [20].

The initial step of targeted sorting, whether through manual methods or mechanical processes, facilitates the efficient separation of different materials, including nets made of various plastics and metals. This sorting plays a crucial role not only in enhancing the purity of the end product but also in improving material quality [21].

After sorting, discarded fishing gear undergoes a shredding process. Mechanical methods break down the components, facilitating handling and transportation, and laying the foundation for subsequent processing and recycling. Industrial single-shaft shredders, such as the Vecoplan VZ200, can reduce plastic debris to a size of 20-30 mm in multiple stages. Following the shredding process, manual or ferromagnetic removal of metal, especially large metal parts from fishing nets, occurs with the aim of achieving a separation efficiency of 100% for steel. The challenge lies in removing lead, which is incorporated into some nets. While complete separation is not feasible due to the structure of the nets, the dissimilar density of lead and plastic fibres can be exploited for contactless separation. The shredded fractions undergo a two-stage density separation process. In the first stage, separation of lead and mineral fractions occurs using saltwater, achieving separation efficiencies of 90% for minerals and 100% for lead. In the second stage, plain water is used to separate the less dense polymers from the nylon fractions, with a success rate of 100% based on industry experiments [22].

In the subsequent cleaning step, undesirable impurities such as salt and mud are removed to enhance the quality of the recycled material. Cleaning methods vary depending on the type of marine debris [21]. A modelled cleaning process utilizes water, friction, and radial forces to eliminate impurities from the plastic. After the initial wash, water is filtered and reintroduced into the process. This results in a plastic loss of 15% and complete cleaning of minerals. Finally, the cleaned fishing gear

debris undergoes drying to eliminate residual water and enhance the material's quality for recycling. Paddle dryers with a heating medium through hollow blades are particularly efficient and suitable for polyamide and polypropylene [22]. For instance, a recommended drying time is 8 hours at 80 °C in a vacuum oven for polyamide [23].

Table 2 summarizes these pre-treatment steps with corresponding methods and objectives.

Table 2: Overview of the current pre-treatment phases for the recycling of fishing gear debris with the associated methods and objectives

Pre-treatment phases	**Method**	**Goal**
Sort	• Manual • Automatic	• Separation of different types of material
Chop	• Mechanical	• Reduction of size
Removal of metal	• Wire cutters • Ferromagnetic force	• Removal of metal objects
	• Manual • Density separation	• Separation of lead
Density separation	• Salt Water, Normal Water	• Separation of minerals and lead • Separation of nylon from other polymers
Clean	• Different Techniques	• removal of salt, Sludge and other contaminants
Wash	• Water, friction, radial forces	• Removal of minerals from polymer fraction
Dry	• Vacuum Oven • Paddle dryer	• Drying of the cleaned material

5.2. Recycling processes of fishing gear debris

After successful pre-treatment, fishing gear debris is prepared for the respective recycling process based on its type and condition. Mechanical, chemical, and thermal processes are applied, incorporating specific technologies and methods tailored to the characteristics and composition of the material. Figure 2 provides an overview of the pre-treatment process and the associated recycling process for plastic and metal.

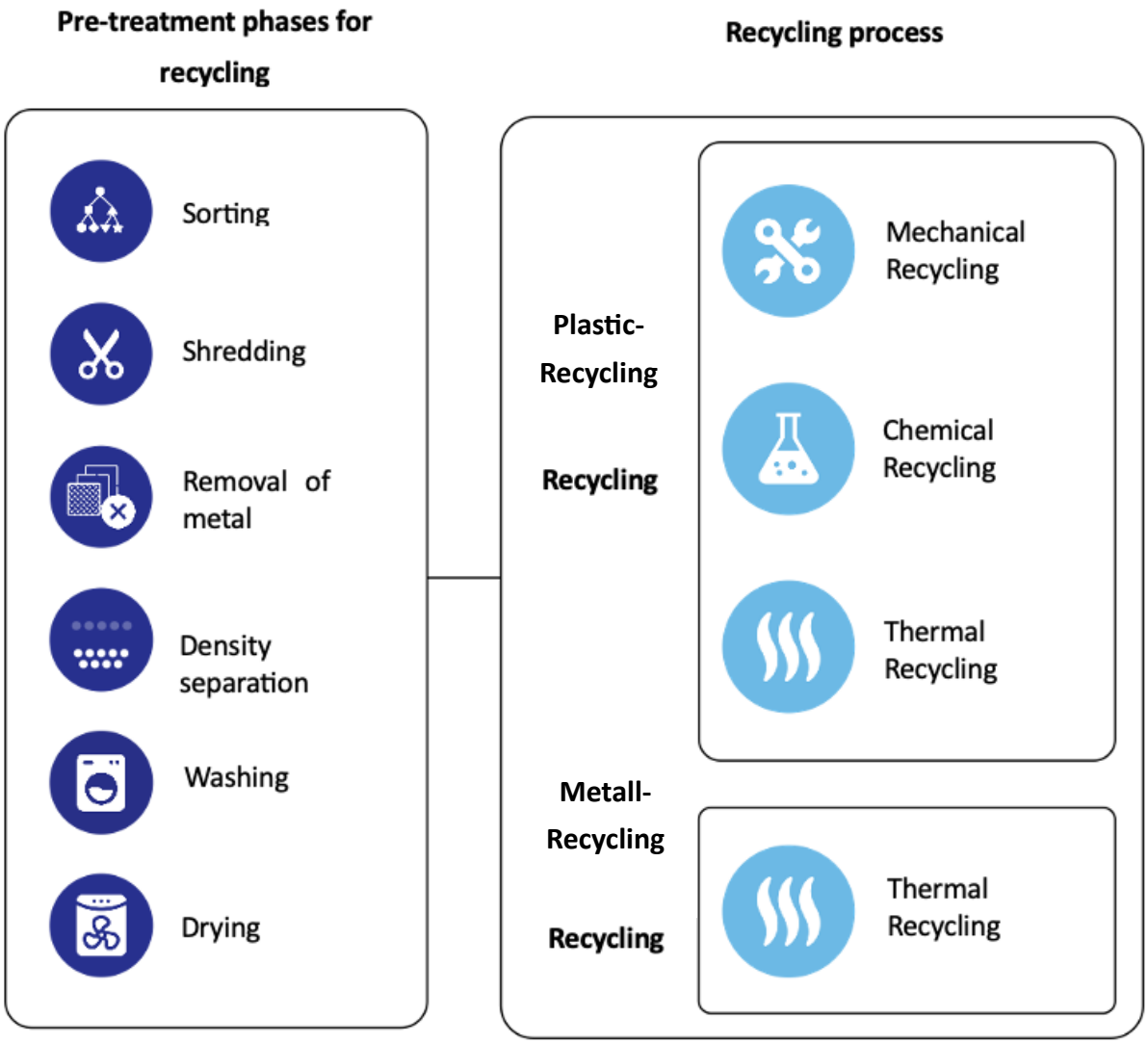

Fig. 4: Overview of the pre-treatment phases for recycling and recycling processes for plastic and metal

After the pre-treatment of fishing gear debris, various recycling methods are available, including mechanical, chemical, and thermal processes that address the polymeric fractions.

Mechanical recycling of plastics is particularly suitable for thermoplastic polymers such as polyamide, polyethylene, polypropylene, polyester, or polystyrene. These can be directly converted into raw materials or material components after pre-treatment by melting, granulating and injection moulding processes [24]. An example from Korea demonstrates a method for volume reduction in the recycling of polystyrene buoys, where thermal extrusion facilities for polystyrene buoys are operational in Korean communities [20].

In the chemical recycling of plastics, especially fishing gear debris made of polyamide, solvolysis or depolymerization processes follow pre-treatment. In this method, macromolecules are broken down into their basic monomers by adding chemical solutions [25]. The resulting product can be recycled as a raw material for producing new polyamide yarns. Furthermore, thermal recycling of plastics is divided into raw material recycling

and energy recovery. In raw material recycling, macromolecules are transformed into basic molecules, and unlike mechanical and chemical recycling methods, mixed and impure polymer fractions can be used. Thermal processes such as pyrolysis, thermolysis, hydration, and steam reforming allow the conversion of plastic debris into base monomers as fuel for engines. However, this is not suitable for the production of new plastic polymers or as recyclate. Thermal recovery or incineration with energy recovery uses the energy stored in plastic debris to replace fossil fuels in power plants or production facilities. Harmful substances are either thermally destroyed or separated during exhaust gas cleaning [24]. Regarding metals, especially lead, recycling technologies are technically demanding. After pre-treatment, metals must undergo special recycling processes, often pyrometallurgical methods. In lead recycling, it is melted in blast or rotary furnaces and separated from impurities like slag. Refining is another step to remove unwanted elements and add desired elements to optimize lead for specific applications [26]. Steel and aluminium can also be thermally recycled, with aluminium melted in a high-temperature furnace and steel processed in an electric arc furnace. After melting, metals can be cast into various forms or processed into new products [27]. The identification of various recycling methods for fishing gear debris demonstrates different approaches for the recovery of polymeric and metallic fractions. Mechanical and chemical recycling require effective pre-treatment. In contrast, thermal processes do not require pre-treatment and offer the possibility of using mixed plastic fractions. This diversity underscores the efficiency of available recycling methods for fishing gear debris. Table 3 provides an overview of the different recycling methods, their characteristics, and applications.

Table 3: Current recycling methods with their processes and treatments for fishing gear debris.

Recycling process	**Procedures and treatments**	**Applications**
Mechanical recycling for plastics	• Pre-treatment • Melting • Extrusion	• Thermoplastic polymers: PA, PE, PP, PES
Chemical recycling for plastics	• Pre-treatment • Solvolysis	• PA • Production of plastic raw materials
Thermal recycling for plastics	• Pyrolysis • Thermolysis	• Fuel production • Energy recovery
Thermal utilization for metals	• Pyrometallurgical process • Refining	• Lead
	• Blast furnace temperatur • Ferining	• Aluminium
	• Electric arc furnace • Refining	• Steel

5.3. Challenges in the recycling of fishing gear debris

After identifying the possibilities for recycling fishing gear debris, it is crucial to understand the associated challenges. This enables the development of effective solutions for implementing fishing gear debris recycling in the fisheries sector, considering technical, economic, organizational, and political challenges.

Technical challenges in recycling fishing gear debris are diverse and complex. A key issue is the lack of standardized facilities, hindering efficient and consistent recycling processes [24]. This lack, particularly prevalent in regions like Norway, hampers the import and export of recycling materials, thereby affecting the overall efficiency of the process [28]. In the pre-processing stage, during the shredding phase, specialized technologies are required for fibre shredding due to increased wear and clogging in the machines. So far, only a few companies, including Plastix, Aquafil, and Antex, have developed specialized processes [29].

Additional challenges arise in the sorting phase, especially with mixed materials like fishing nets made of nylon and polyester or polymers with copper or lead, which need both mechanical and chemical recycling. These materials are often intertwined, making separation and recovery more difficult. Due to the lack of established lead removal technology, manual measures are required to minimize lead contamination. The complex task of removing metals such as lead from fishing gear can also contribute to machine wear. Metal parts in ropes and fishing gear also affect shredding and increase the maintenance needs of recycling facilities [24].

Additional challenges arise from contaminations such as biofouling with decomposing biomass and fish oil, especially in the pre-processing phase. The lack of technologies to address these impurities can impact the recycling process and lead to machine damage [28]. When using antifouling coatings, recycling issues may also arise as they could potentially influence the quality of the granulate [*29*].

The density-based separation of fibres can also be problematic, especially when the fibres are entangled. It is crucial that these entangled fibres can be loosened, presenting a significant challenge, particularly for mechanical recycling [24].

After examining the technical challenges in the recycling process, it is now crucial to shed light on the economic aspects related to fishing gear debris recycling. Economic factors play a significant role in the feasibility and efficiency of recycling processes, significantly influencing the sustainability of the entire process. Several costs contribute to the overall expenses. It starts with establishing systems for efficient collection of fishing gear at various locations, especially in ports. Additionally, the retrieval of sunken or lost fishing gear from the water requires specialized equipment and expertise. After collection and retrieval, the material needs to be transported to recycling facilities, posing additional logistical challenges and associated costs. Finally, a careful pre-processing of the fishing gear into its various

components is required before the actual recycling process, consuming more time, space, and resources. This includes sorting or cleaning costs. These additional steps make the recycling process more expensive and less attractive to investors and businesses. Moreover, recycling fishing gear proves to be economically less lucrative compared to producing new material, with recycling costs often exceeding potential returns [*29*]. To economically drive the recycling of fishing gear debris, there is a lack of sufficient commercial incentives and resources to make gear recycling more appealing. The industry faces the dilemma of making high initial investments without a guarantee of adequate returns [30].

The economic aspects not only raise questions about profitability but also influence the organizational challenges associated with fishing gear debris recycling. Organizational issues encompass various aspects, ranging from coordinating stakeholders to efficiently managing specific steps in the fishing gear debris recycling process.

A recurring problem in the fishing industry is the lack of awareness among fishermen regarding the importance and methods of proper disposal and recycling of fishing gear debris. Often, there is a lack of clear information, leading to improper disposal practices. Additionally, fishing gear is frequently not marked, making their location and identification challenging and significantly reducing collection efficiency. Another obstacle lies in the lack of infrastructure in many ports, where suitable facilities for accepting discarded fishing gear are often unavailable. This poses a significant problem for fishermen who wish to dispose of their equipment properly. Especially in regions without adequate facilities for collection and sorting, fishermen face the dilemma of how to handle their gear correctly. On a practical level, there is not only a lack of problems but also a lack of a central coordination point and clear responsibilities among the involved stakeholders, leading to inefficiencies and overlaps in efforts. It becomes evident that the lack of communication between different stakeholders is another existing issue, often resulting in information gaps and misunderstandings due to inadequate communication systems [29]. Another obstacle is the absence of a clear model for collaboration among stakeholders, hindering the establishment and operation of disposal and recycling solutions [28].

The political challenges in the recycling process of fishing gear should not be underestimated. They reflect the complexity of developing effective regulations and frameworks while balancing environmental protection and the interests of various stakeholders. Particularly noteworthy are regulatory gaps, often inadequate legislation, and challenges in implementing international agreements. A critical point is the current lack of political frameworks for dealing with fishing gear debris. This regulatory gap not only hinders the implementation of structured and systematic management of such debris but also prevents the establishment of environmentally friendly and efficient practices. Another issue concerns the transportation of fishing gear debris.

Without clear regulations and permits, this area is legally uncertain, leading to delays, additional costs, and environmental risks. Therefore, it is essential to create clear regulations and approval processes to make transportation safer and more effective. In parallel, support for collection points is crucial for the proper disposal and recycling of fishing gear debris. However, there is often a lack of financial, technical, or personnel resources, hindering the motivation to establish additional collection points. Authorities must recognize their role and act accordingly [31].

In general, it is essential to consider that potential issues and challenges related to fishing gear debris are exacerbated by geographical and oceanographic variations, as well as differences in fishing practices among various countries [32]. The recycling of fishing gear debris faces diverse challenges in technology, economics, organization, and politics. The lack of standardized facilities and expertise hampers technical efficiency. The separation of different materials and contaminants proves to be challenging. Economically, various factors increase costs, while incentives for the economic attractiveness of recycling are lacking. Organizational challenges manifest in cooperation, coordination, and awareness. Additionally, there is a lack of political commitment to establish an adequate legal framework for recycling. Table 4 provides an overview of these aspects.

Table 4: Problems and challenges in the recycling of fishing gear debris

Aspect	**Problems and Challenges**
Technical	• Lack of standardized recycling facilities • Difficulty in separating and processing fishing gear made from different materials • Wear and clogging issues in fibre recycling • Challenges in density separation • Contamination from biofouling and metals such as lead
Economic	• High costs associated with port facilities • High costs for the retrieval and collection of fishing gear debris • High costs in pre-treatment processes • Low profitability • Lack of commercial incentives
Organizational	• Lack of awareness among fishermen • Insufficient harbour reception facilities • Lack of coordination and unclear responsibilities • Challenges in information transfer • Lack of cooperation
Political	• Absence of frameworks and regulations • Political challenges

5.4. Recycling potentials of fishing gear debris

A comprehensive understanding of the recycling possibilities of fishing gear debris is crucial to develop effective solutions and facilitate the creation of closed material loops. In general, most polymers are recyclable; however, they exhibit differences in recycling rates due to their material properties, degradability in the marine environment, and the quality of resulting recycled products. PA (polyamide) can be mechanically and chemically recycled after pre-treatment. The quality of products from recycled PA and HDPE (high-density polyethylene) deviates less from virgin material compared to LDPE and PP, thanks to their linear structure. Hence, PA is often preferred for recycling [23].

Contrary to PA, LDPE, PET, and PP can only be mechanically recycled to a limited extent and not chemically. Due to their branched structures, which can hinder depolymerization into monomers, the recycling potential of this polymer group is lower than that of PA [33].

The limited recycling potential of LDPE and PP is partly due to their frequent use in trawl nets. The continuous friction of these nets on the seabed leads to wear, while organic deposits during use pose additional challenges. These factors impact the efficient recycling of PE and PP, resulting in granules with inferior mechanical properties. A study has shown that adding new PE during the recycling of PE fishing gear debris can improve the quality of the granulate. Although products from this material combination exhibit better properties than pure recycled granules, they may still pose limitations in the production of certain items. Nevertheless, this approach represents a significant step towards promoting material recycling [25].

Furthermore, the recyclability is closely linked to the degradation of polymers, especially after prolonged exposure in the marine environment. Factors influencing polymer degradation can include the degree of decomposition, environmental factors, mechanical stress, or degradation mechanisms. Degradation in the marine environment, caused by sunlight, water, salt, and mechanical strain, can significantly impact the recycling potential [34]. Therefore, it is crucial to examine the condition of fishing gear debris upon retrieval from the water and over time to better analyse the impacts of these factors on the material's recyclability. For instance, nets and ropes made of PA6 or PET tend to sink in the sea, where they are protected from mechanical abrasion by waves, UV radiation, and oxygen depletion. In contrast, nets and ropes made of PE and other buoyant materials tend to float on the sea surface. They are eventually carried to beaches by ocean currents or deposited in the Arctic Sea [29]. Additionally, they will lose strength when exposed to UV radiation and saltwater [35]. In a six-month study, the behaviour of the four most prevalent plastics in the ocean, PA6, PE, PP, and PET, was observed under UV radiation. It was found that both thermal and mechanical properties are affected, causing the material to lose elasticity and become stiffer. These changes impact the feasibility of mechanical recycling, as the quality of the recycled

material is insufficient to ensure a high replacement for virgin material [20]. However, the characterization of these plastics in terms of their degradation in the marine environment and their thermal stability during processing is crucial and can be transformed into suitable products [36]. The recycling quality of plastics can vary depending on the type of material and its condition. Effective recycling can be achieved with high-quality plastics that are not heavily degraded. However, the recycling process for degraded plastics may be challenging, as they are often contaminated and require efficient sorting and cleaning to ensure the high quality of the recycled material [37]. These mechanisms may result in the degradation of discarded fishing nets, including hydrolytic, thermo-oxidative, photo, biological, and mechanical degradation [38].

Fig. 5: Used fishing nets and floating bodies

Metals are inherently recyclable, maintaining their physical properties throughout the recycling process. However, the recycling potential can be affected by the marine environment. In particular, corrosion and loss of strength due to saltwater exposure can lead to a reduction in reliability and durability (HAQUE et al., 2014). Recycling lead poses additional challenges due to potential environmental impacts and its toxic nature, requiring specific safety and environmental regulations [29].

The analysis of the recycling potential of fishing gear debris requires identifying additives and contaminants that may affect recyclability [39]. Contaminants must be identified, as they can compromise the quality of the recovered material [40]. The components of fishing gear are fundamentally recyclable and can undergo mechanical, chemical, and thermal recycling processes. Some plastics, such as PA, exhibit promising recycling properties, while others like PE and PP face limitations due to environmental factors and mechanical stress. Therefore, understanding the type, quality, and condition of the materials is crucial for developing appropriate recycling strategies. Metallic components generally maintain their recyclability, although they may corrode under certain conditions.

5.5. Best-Practices for implementing recycling methods for fishing gear debris

This section presents current approaches and best practices to effectively implement recycling measures for fishing gear debris. Various methods are analysed to establish an efficient recycling strategy for fishing gear debris. The focus is on successful models applied by both industries and communities, providing a comprehensive insight into current strategies. This not only allows the identification of optimization potential but also supports the development of well-founded

recommendations for the advancement of established approaches. Companies and programs with experience in the recycling of fishing gear debris are presented, including Aquafil, Plastix Global, Bureo, the Recycling Program in West Coast Port, and the Honolulu Derelict Net Recycling Program:

Aquafil: A key player in the chemical recycling of nylon nets. This process allows nylon nets to be returned to their original form, such as their most well-known product, ECONYL yarn [41]. It is used in various products, from fashion to carpet tiles. Aquafil collaborates with various partners such as Nofir AS, Net-Works, Interface Inc., ZSL, or LEHVOSS to establish, collect, and recycle take-back programs for used PA6 materials. In Norway, fishermen can submit their used fishing gear for a fee. In the program with Net-Works, Interface Inc., and ZSL, communities can sell their fishing gear debris to Aquafil for recycling [42]. Aquafil's other collaborations include partnerships with Steveston Harbour and Interface. In this context, logistical and financial challenges were identified and processes adjusted accordingly. So far, three complete nylon shipments, each around 18,000 kg, have been sent to Aquafil. Materials that did not consist of nylon were separated, with PE batches sent to Plastix Global. The separated and cleaned nylon is shredded and then transported to Slovenia for further processing. Currently, efforts are underway to expand the project along the coast of British Columbia [41].

Plastix Global, based in Denmark, is one of the leading companies in the mechanical recycling of fishing gear debris in Europe. The company collaborates globally with numerous partners, including Schoeller Plast and the British seafood company MCB Seafoods, to collect and recycle fishing gear [43]. Plastix Global employs mechanical recycling processes to produce HDPE and PP pellets from used fishing nets, trawl nets, and ropes. In their facilities, they can clean, separate, shred, and ultimately recycle various net materials [64]. While many other recycling companies selectively accept materials, Plastix Global stands out by accepting all types of used fishing gear. This leads to more efficient material collection, requiring less sorting effort at the dock. This also reduces the amount of material to be disposed of in landfills [43].

Bureo, like Plastix Global, is dedicated to net recycling through mechanical processes. In collaboration with the Chilean government, the 'Net Positiva' project was launched, the first program for collecting and recycling nets in Chile. Recycling fishing nets produces products such as skateboards and sunglasses. To promote the collection of old nets, Bureo has initiated a net buyback program for fishermen [41].

Recycling Program in West Coast Port: Recycling Program in West Coast Port: Between 1989 and 1996, the Pacific States Marine Fisheries Commission and the recycling company Skagit River Steel and Recycling collaborated on the implementation of fishing net recycling programs, supported by approximately $79,000 in grants from U.S. federal agencies and thousands of volunteer hours. Despite initial successes and the promotion of recycling initiatives in

communities and ports, especially in Washington and Alaska, recycling volumes decreased from an average of 46 tons annually (1991-1999) to 22 tons (2000-2003), possibly due to budget constraints, industry changes, and coordination issues. It is estimated that an annual investment of about $125,000 and additional resources for coordination and logistics would be necessary to revive and expand net recycling on the U.S. West Coast [44]. Skagit River Steel & Recycling continues its recycling services for fishing gear debris [45].

Honolulu Derelict Net Recycling Program: This program utilizes thermal recovery methods, with collected nets and materials transported to nearby incineration plants to generate electricity [29]. This recovery method can generally be a suitable solution for mixed-material fishing gear that is not easily disassembled [22].

Analysing different global strategies for recycling fishing gear debris makes it clear that success is based on adaptability, robust partnerships, and sustainable funding. Companies like Aquafil, Plastix Global, and Bureo illustrate that various recycling approaches, from mechanical to chemical, can be effectively implemented and that the reuse of recycled materials in new product contexts is possible. However, it is also evident that recycling programs can only be sustainable with stable financial and logistical support, as well as active community involvement. Looking forward, incorporating these experiences into new, scaled solution approaches will be crucial, with continuous optimization and adaptation to technological developments and changing conditions being essential.

International and Regional Activities: The integration of fishing gear recycling into the fishing industry is shaped internationally and regionally by various political aspects and regulations. This includes international agreements such as MARPOL and the London Convention, which relate to marine pollution, as well as UNCLOS, addressing the protection of the marine environment. The Circular Economy Action Plan and the EU Single-Use Plastics (SUP) Directive significantly influence the handling of fishing gear until the end of 2024. Various country-specific approaches, such as Taiwan's marine pollution laws and the United Kingdom's Merchant Shipping Regulation, illustrate different approaches to reducing marine litter. Globally, there is a movement toward a more sustainable plastic economy and new agreements [46].

The integration of recycling in fisheries can be promoted through legal measures. National and international laws emphasizing environmentally friendly disposal and recycling of fishing gear debris would support sustainability. Incentive systems could promote recycling, while strict rules would ensure proper disposal. Partnerships between governments, fisheries, and recycling companies could contribute to the implementation of sustainable circular systems

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6. Sustainable strategies for fishing gear debris

The developed strategies for managing fishing gear debris are based on the application and advancement of established theoretical approaches in fisheries, considering best practices. The management of this type of debris is divided into various key areas, including raising awareness among stakeholders, implementing take-back systems for fishing gear, improving retrieval methods and associated technological advancements, introducing effective reporting systems, adapting to existing laws and guidelines, developing design guidelines for fishing gear, and implementing recycling technologies and processes for this debris.

For the efficient implementation of management and reduction measures for fishing gear debris in the fishing industry, the involvement of stakeholders in the fishing industry is crucial. They play a pivotal role in the implementation of these strategies. The mentioned key areas are closely interconnected and contribute not only to reducing marine pollution from fishing gear debris but also play a crucial role in effectively increasing recycling.

6.1. Strategy for the management and reduction of fishing gear debris

To minimize the excessive loss of fishing gear and effectively manage the entire life cycle of fishing gear debris in the fishing industry, strategies are presented below. These strategies lay the foundation for sustainable management of fishing gear debris and support the seamless integration of recycling. Current approaches and strategies are drawn upon to derive well-founded conclusions. Specifically, focus is placed on individual areas:

- **Stakeholder awareness**
- **Take-back systems for fishing gear**
- **Improvement of retrieval methods and technological advancements**
- **Reporting and documentation**
- **Compliance with laws and Guidelines**
- **Design Guidelines for fishing gears**

6.1.1. Strategy for awareness of fishing gear debris

Public awareness plays a pivotal role in driving sustainable changes in fisheries regarding fishing gear debris. It is crucial for society to comprehend the extent of the problem, enabling active participation in the collection and recycling of this debris. A heightened awareness of the negative environmental impacts can foster innovative solutions, including the prevention of fishing gear debris [47]. Awareness is structured into specific categories for the efficient allocation of targeted strategies and measures. This categorization encompasses education, communication, and information dissemination, as well as incentive systems. The strategies in these areas will be initially examined individually.

Education: The pivotal role of education in preventing fishing gear losses underscores the necessity for comprehensive awareness among fishermen and other involved stakeholders about the severe ecological consequences of lost fishing gear. Training sessions and workshops, featuring experts discussing both the environmental impacts of lost fishing gear and presenting advanced handling methods, prove to be an effective measure in this context. These training sessions not only provide insights into direct consequences but also disseminate information about current technologies and best practices contributing to more sustainable fishing practices. Additionally, collaboration with environmental and fisheries organizations facilitates the initiation of joint awareness campaigns, thereby contributing to heightened awareness. In this process, a respectful and non-blaming dialogue is essential to cultivate trust and cooperation among stakeholders, ultimately enhancing fishermen's willingness to return lost fishing gear [48].

Communication and information dissemination: To reach a wide audience, informational materials can be distributed in fishing ports, on ships, and in community centres, as well as through social and local media. An approach that avoids assigning blame can effectively enhance fishermen's openness and willingness to return lost fishing gear [49]. The intensification of community meetings in fishing villages provides a significant opportunity to raise awareness about the issue of fishing gear debris and develop collective solutions. A visually appealing design and presentation of information can contribute to making it more interesting and accessible to the public. Platforms such as newspapers, flyers, television, radio, or social media can serve as channels for communication.

Incentive systems are fundamental tools to increase motivation for the return of old fishing gear. Various strategies, such as subsidizing environmentally friendly equipment, establishing a deposit system for returned fishing gear, and direct purchase offers from recycling companies, prove to be effective mechanisms. Additionally, the introduction of technological incentive systems is of significant importance. This includes sponsored provisions of technological tools, such as GPS trackers, as well as the development of precise communication strategies. These measures are essential to comprehensively educate fishermen about effective collection and recycling methods and to encourage active participation in such programs. Flexibility in solution approaches remains a key principle. It is evident that adaptation to the specific conditions of each fishing area is essential, as there is no universally applicable approach. Current recommendations also heavily rely on the expertise of professionals, underscoring the need for continuous adjustment and evaluation of implemented strategies [50].

This section underscores the importance of a holistic approach to minimize the loss of fishing gear, emphasizing the integrative nature of education, communication, incentive systems, and preventive measures. Addressing the issue of fishing gear loss and its ecological consequences effectively necessitates targeted

collaboration among all stakeholders involved. The implementation of innovative strategies, coupled with empathetic communication, forms a central foundation for the sustainable management of this environmental challenge.

6.1.2. Strategy for return system for fishing gear debris

Strategies for return systems are crucial to ensure the retrieval of old fishing gear and its reintroduction into the product cycle. Economically, such systems can be more cost-effective than cleaning or recovery measures [51]. The extended producer responsibility (EPR) is introduced as a return system, followed by various financial mechanisms to support the system. These can be both financial measures and incentive systems. Implementation suggestions are then provided

Extended Producer Responsibility (EPR): EPR is crucial for return systems to promote the transition to a circular economy. Its primary goal is to encourage manufacturers to use resources more efficiently and establish systems for the return of products at the end of their life cycle. There are various approaches to implementing EPR, including mandatory, negotiated, voluntary, and the distinction between individual and collective responsibility [52]. Specific return systems, such as OEM return, pooled return, and third-party return, are also considered [53]. Successful models like Healthy Seas, Fathoms Free, Bureo, and the Circular Ocean Project demonstrate that circular economy systems in the maritime sector are both environmentally and economically viable. International frameworks like the British Standard 8001:2017 provide valuable guidelines for integrating fishing gear debris into circular strategies for businesses [54]. When deciding on a suitable EPR system, product type, stakeholder involvement, and existing infrastructure should be carefully considered. In the specific context of fishing gear debris, steps such as categorizing circular strategies, defining individual and collective responsibility, and selecting suitable models for return and recycling could be crucial. Given the environmental impact of certain plastic products, the EU Commission proposed measures in May 2018 to reduce these impacts, including the introduction of EPR systems for discarded fishing and aquaculture gear [55].

Financial Measures: The revision of port debris fees and the introduction of targeted sanctions can be effective financial measures. Controls in port states are crucial, especially to control and curb illegal fishing. Furthermore, a dedicated environmental tax could serve as financial support for research and educational initiatives [56].

Financial incentives, such as reducing port fees for fishing vessels, can be effective [57]. The "Fishing for Litter" program is a prominent example: it allows fishermen to dispose of collected fishing gear debris free of charge in ports during their activities. Suitable collection points in ports are essential for such initiatives. While smaller ports could use central containers or regular collection systems, larger ports should have continuous sorting and collection systems.

Deposit System: An extended step could be the introduction of a deposit system for fishing gear, encouraging the return of lost equipment and prompting producers to take continuous product responsibility [58]. Some countries are pioneers in this regard: Denmark with its return systems Frydendahl and Cosmos Trawl, Germany with the Cux Trawl, and South Korea, which has financially rewarded fishermen for returning collected debris since 2003. Countries like Iceland and Sweden with their gear acceptance systems in various ports also serve as valuable examples. These, along with diverse collection systems in OSPAR countries, provide valuable guidance for regions such as OSPAR regions [59].

Additional Implementation Proposals: In implementing a deposit system for the return of used fishing gear, a research strategy should be developed aiming for a precise determination of the optimal return time of the equipment. This considers their functional integrity and quality for subsequent recycling processes. Periodic studies, analysing new fishing gear over two years at three-month intervals, could enable this. The evaluation includes the degree of wear and the remaining efficiency in the fishing process. Marking the gear can serve for supportive identification and traceability. Furthermore, this research strategy also offers the opportunity to integrate a leasing program for fishing gear. This concept allows manufacturers not only to sell fishing gear but also to lend it for a defined period. This could enable nets to be returned in a timely manner before their suitability for recycling decreases.

The relevance of effective reduction strategies in the fishing industry, especially involving fishing gear debris, has been clearly demonstrated through various approaches and models in this work. The extended producer responsibility (EPR) and various financial mechanisms show potential to promote a circular economy approach and achieve ecological and economic benefits. Successful examples like "Healthy Seas" and "Fishing for Litter" provide practical insights and emphasize the feasibility and relevance of these strategies. The challenge now is to develop and implement adaptive recycling strategies based on the discussed concepts that consider specific local conditions and gain broad acceptance from all stakeholders involved.

Port Infrastructure: To implement this effectively, collection points should be established at central fishing ports and easily accessible locations. It allows fishermen to dispose of fishing gear debris collected during their activities free of charge in ports. These serve as points where fishermen can safely and environmentally dispose of their non-usable equipment. Suitable collection points in ports are essential. In smaller ports, central containers or scheduled collection systems could be implemented, while larger ports should have continuous sorting and collection mechanisms. It is essential to promote government-led collection programs. Additionally, considering incentive systems to promote returns is advisable. One option could be to grant discounts on the purchase of new fishing gear when old equipment is returned in return. Such measures could help counteract

the environmental impact of fishing and make the industry more sustainable overall.

6.1.3. Strategy for recovery of fishing gear debris

Various methods for the recovery of fishing gear are identified, including the use of excavators, remotely operated underwater vehicles, and, notably, environmentally friendly diving [58]. Involving fishermen in recovery efforts should be prioritized, supported by sustainable financing programs, such as license fees, to ensure their effectiveness. Providing the necessary equipment and incentives for fishermen to safely and efficiently recover lost gear are also crucial [57].

The efficiency of recovery operations can be enhanced through the use of technical tools. The introduction of technical support tools, such as recovery sensors and FAO guidelines for marking fishing gear, is considered helpful. Initiatives like the NetTag project in Portugal and Spain demonstrate that marking fishing gear can help reduce debris [59]. For precise location, the MARELITT Baltic project in Sweden has introduced technological innovations enabling the safe recovery and environmentally sound disposal of lost fishing gear. Significant progress has been made in various regions through the development of sensors that immediately report lost gear. In Norway, effective reporting systems since the 1980s have contributed to the recovery of over 1000 tons of lost fishing gear [57]. Technologies such as mapping hotspots using underwater cameras, GPS integration, and acoustic devices provide additional support in locating lost gear and preventing entanglement [59].

Current technologies, including remotely operated underwater vehicles and sensors, optimize recovery methods. The involvement of fishermen and appropriate financing models are key strategies. Initiatives like NetTag and MARELITT Baltic leverage technology for precise localization and disposal of lost gear. Success is evident in countries like Norway and the USA through effective reporting systems and the use of technology.

6.1.4. Strategy for reporting and documentation of fishing Gear debris

The systematic recording and detailed reporting of lost fishing gear play a crucial role in tracking and targeted recovery. This not only enables the efficient localization of lost gear but also facilitates the development of preventive strategies to minimize future losses. To effectively optimize measures for reporting and documenting fishing gear debris, mandatory reporting and a centralized reporting system can be introduced.

The introduction of mandatory reporting for lost fishing gear is crucial to easily locate and keep track of lost gear. According to the EU Fisheries Control Regulation, reporting lost fishing gear is mandatory in Europe, although simplifying access to these reports could enhance efficiency [59]. The Norwegian model, which includes a legal reporting obligation and supports fishermen through easily accessible reporting processes, could serve as a

benchmark for optimal systems for reporting lost fishing gear. An effective reporting system is provided by the Northwest Straits Foundation initiative in Puget Sound, USA, specifically designed to identify regions with increased loss of fishing gear [58]. An effective connection with such reporting systems requires the central storage of reports in an electronic database and a direct link to recovery systems. This ensures that recovery measures can be influenced strategically. This model not only motivates fishermen to report and recover lost equipment but also encourages close collaboration with shipowners, seamlessly integrating fishing gear loss reports into existing reporting processes. For such reports, providing comprehensive information is essential, especially accurate time and location details [57]. To leverage such systems optimally, cooperation among various stakeholders is necessary, with financial incentives motivating fishermen to report and return lost or damaged equipment [60]. Similar practices, as observed in countries like Kenya, Jamaica, and Argentina, can be used as references in this context.

Strengthening effective reporting and documentation of lost fishing gear, supported by cooperative systems and successful international models, lays the foundation for a sustainable improvement in recovery methods and the reduction of marine debris.

6.1.5. Strategy for the regulation of fishing gear debris management

The strategy for the regulation of fishing gear debris management encompasses both legal provisions and collaborations at various levels. These regulations, through clear guidelines and instructions, lay the foundation for an effective strategy in handling and reducing fishing gear debris. Such regulations manifest in concrete initiatives such as labelling, fishing restrictions, establishment of collection points, and in international and regional agreements.

Labelling Requirements: Labelling requirements for fishing gear are crucial to enhance traceability. This measure is essential for monitoring environmental impacts in fisheries and ensuring that fishing methods align with sustainability and environmental principles. Clear identification allows for improved control to ensure that fishing is in line with environmental goals and that marine resources are responsibly utilized [58].

Fishing and Spatial Restrictions: To reduce competition and minimize improper use of equipment, specific measures such as setting catch limits per boat are proposed as solutions [59]. Furthermore, the introduction of spatial separation for artisanal and industrial fishing can be a strategic measure. This involves creating a defined area specifically designated for the use of small-scale artisanal and large-scale industrial fishing activities. The goal of this strategy is to regulate the different needs, fishing techniques, and resource uses of both types of fisheries, minimize potential conflicts,

and ensure sustainable management of marine resources [61].

Collection Points: The introduction of collection points facilitates the return of fishing gear and emphasizes, as seen in numerous examples from the EU, both the potential and challenges. The implementation of specific collection points and state collection programs, as already existent in countries like Spain and Germany, proves particularly interesting in this context [59]. A clear legal basis is crucial to ensure proper disposal of fishing gear. Collaboration with national and international authorities can help create consistent and effective regulations. Incentive systems such as subsidies or tax incentives can encourage fishing operations to adopt more sustainable methods and technologies. At the same time, enforcement mechanisms such as inspections and penalties are necessary to ensure compliance with existing regulations. The combination of incentives and enforcement can steer the entire fishing industry towards a more sustainable direction and reduce negative impacts on the marine environment.

6.1.6. Strategy for sustainable design guideline of fishing gears

Die Implementing a strategy for sustainable development of fishing gear through design guidelines involves various approaches. These approaches are developed with a focus on reducing losses, recycling, and promoting sustainable fishing. The strategy development considers both established and innovative approaches based on an analysis of current challenges and practices.

To support the overall reduction of debris from fishing gear, various design approaches can be considered to optimize the fishing gear. One potential improvement to the gear itself is to attach additional reinforcements at critical points to minimize wear. These critical areas can be marked with colours to allow for efficient and quick inspection before fishing. Alternatively, critical points can be integrated into the fishing gear as replaceable parts, enabling easy replacement when needed. The connection of these replaceable parts to the fishing gear can be facilitated through the use of composite pieces.

Furthermore, traceability of fishing gear plays a crucial role, which can be ensured through the use of markings or tracking devices. This is a fundamental element for locating and recovering lost fishing gear [62].

The recyclability of debris from fishing gear depends significantly on efficiency in the pre-treatment phase, especially in the sorting process. A clear simplification of the dismantling and sorting process can be achieved by integrating an easily disassembled structure for fishing gear. When selecting materials, the use of monomers should be considered, as the high purity of these monomers supports the sorting and recycling process. For fishing gear made from different materials, colour standardization of nets by material type proves extremely advantageous, enabling efficient and precise material separation. It is advisable to refrain from using harmful substances such as lead in fishing nets

in favour of environmentally friendly alternatives. Lastly, the responsible use of chemical antifouling agents should be noted and critically examined. Although they provide protection and can extend the lifespan of nets, ropes, and cages, their potential impacts on the recycling process should be carefully considered [59].

In the next step, it is equally important to develop design proposals for sustainable fishing that promote both the minimization of debris from fishing gear and the protection of the marine environment while supporting recycling. Due to potential losses through bycatch, design adjustments can be made through a more selective fishing method, such as changes in the size and visibility of nets. In this regard, colour and pattern can be adjusted so that fishing gear is visible and attractive only to specific fish species. The visibility of nets can also be influenced by the absorption of UV light, especially for fish species capable of perceiving UV light [63]. Additionally, thoughtful escape mechanisms can be integrated into fishing gear to minimize bycatch of marine mammals, for example [50]. In the context of bycatch, especially in interaction with marine mammals, the use of innovative technologies represents a significant advancement. An example is the "Passive Porpoise Deterrent" by Aquatec Group Ltd, which makes nets acoustically detectable to marine mammals through acoustic reflectors, effectively protecting them from potential danger [60]. Other escape mechanism approaches may also include the integration of biodegradable escape devices. For already lost fishing gear, enhancing the buoyancy of the yarn materials could help prevent further bycatch [62].

Implementing design guidelines for sustainable fishing gear requires the collaboration of an interdisciplinary team of engineers, biologists, and ecologists. Close collaboration with end-users and continuous feedback are crucial to develop gear that meets the needs of fishermen and enables optimal development of sustainable fishing gear. This collaboration can be achieved through surveys during the return of fishing gear, the use of cutting-edge technologies, and ensuring sustainability. The central challenge is to find a balance between ecological responsibility and economic viability to promote a practical and application-oriented approach [54].

6.2. Strategy for stakeholders for managing and reduction of fishing gear debris

To ensure effective management of fishing gear debris and promote its reduction, it is essential to identify relevant stakeholder groups in the fishing industry. Building on this, collaborations and partnerships should be developed and strengthened to create tailored solutions for the specific needs and challenges of stakeholders. This will contribute to improving debris management from fishing gear and promoting the integration of recycling practices in the fishing industry. Stakeholders in the fishing industry are divided into primary and secondary categories. While primary stakeholders have a direct influence on fishing gear debris, secondary stakeholders have an indirect influence.

Table 5 provides an overview of primary and secondary stakeholders in the fishing industry.

Table 5: Overview of primary and secondary stakeholders in the fishing industry

Primary stakeholders	**Secondary stakeholders**
• Fishermen and fishing crew • Fishery enterprises • Recycling company • Port authority • Financing and funding institutions	• Fishing associations • Government and regulatory authorities • Environmental organizations • Research facilities

Primary stakeholders in the fishing industry encompass various entities directly involved in fishing gear and its life cycle. These include the fishing industry, fishermen, recycling entrepreneurs, port authorities, financing and funding institutions, and fishing gear manufacturers. Each of these stakeholders is individually described below, along with recommended strategies.

Fishermen take centre stage as they interact with fishing gear on a daily basis, having the most immediate experience with it. Their practices and knowledge are crucial for the development and implementation of recycling methods. Active engagement and attitudes toward recycling among fishermen are pivotal for the success of the initiative and can be promoted through economic incentives, involvement, and training. Additionally, the perspective of fishermen influences other stakeholders, and their methods and culture must be integrated into recycling plans to identify both obstacles and catalysts for sustainable practices [50].

Fishery enterprises play a crucial role in the management, reduction, and recycling of fishing gear debris, influencing their economic viability. By integrating sustainable practices, they can not only derive financial benefits from the sale of recycled products but also gain a competitive edge by complying with regulations and aligning with a sustainability-focused market [50]. Fishery enterprises can address operational challenges by adopting various approaches. This includes training personnel, implementing gear return systems, optimizing fishing methods, investing in recycling technologies, utilizing data management systems, and ensuring transparent reporting. Collaboration with stakeholders and social responsibility within communities enhances the relevance of engagement in recycling and environmental conservation. Thoughtful decisions are necessary to meet sustainability requirements and ensure the success of initiatives for the sustainable management of marine resources and environmental protection.

Financial incentives and technological support play a key role in motivating enterprises and fishermen to participate in recycling. Open communication that addresses challenges, concerns, and benefits clearly is crucial. Collaborations, meetings, and transparent information exchange foster solutions and trust. Customizable solutions tailored to specific fishing areas are essential. Economic incentives, such as subsidies for

environmentally friendly equipment or deposit systems, can boost motivation to participate in recycling programs [60].

Recycling companies play a versatile role, from the collection to the processing of fishing gear, transforming them into recyclable materials using specific technologies and processes tailored to the type and material of the equipment. The economic viability of recycling, whether through the sale of recovered materials or through incentives and subsidies, remains a central factor. Efficient optimization of the recycling process requires close collaboration with other stakeholders, especially fishery enterprises and port authorities. Furthermore, recycling companies bear significant environmental responsibility, ensuring that their processes are environmentally friendly and minimize environmental impact [50].

Partnerships with recycling companies are essential for the implementation of a recycling project or program. It is important to establish clear communication and cooperation channels. These companies can contribute their expertise to develop and implement specific technologies and processes for the recycling of fishing gear.

Port authorities, as central points for discarded fishing gear, significantly influence recycling efficiency through their debris and collection strategies. Their ability to develop supportive recycling policies and regulations, as well as initiate awareness and training measures for fishermen, is essential. Collaborations with recycling companies and equipment producers further optimize the recycling process, with the sale of recycled materials offering long-term financial benefits despite initial investments [50].

Financial and funding institutions play a supportive role by promoting innovative approaches for sustainable fishing gear and their recycling. Investment in research and development can lead to more innovative and cost-effective recycling methods. It should be noted that such investments carry risks that must be carefully weighed against potential returns. Due to their influence, these institutions can also drive regulatory measures that favour recycling. Through partnerships with other stakeholders, such as port authorities, recyclers, and manufacturers, they can further optimize and streamline the overall recycling process [50].

Manufacturers of fishing gear are responsible for producing gear that is both sustainable and durable. Their decisions influence the entire lifecycle of fishing gear, including the selection of materials and design. A focus on recyclable materials can significantly optimize the debris recycling process. Manufacturers have the responsibility to drive innovations in environmentally friendly and easily recyclable materials. Additionally, they can promote understanding and acceptance of sustainable practices among fishermen and other stakeholders through training and awareness campaigns. Economic incentives, especially in markets demanding environmentally friendly and recyclable fishing gear, can also influence the development process. Collaborations for the development of sustainable designs and materials, as well as the exchange of

information on effective recycling methods, should be supported [64]

Secondary stakeholders in the recycling of fishing gear include various actors who, while not directly involved in the process, possess decisive influencing capabilities. These include fishing associations, government and regulatory bodies, environmental organizations, and research institutions, each of which is elaborated upon with corresponding recommendations.

Fishing associations often represent the interests of fishermen, ensuring that their concerns, especially regarding fishing restrictions and fairness, are taken into account. Their expertise allows them to act as intermediaries between different stakeholders. Public opinions and consumer decisions significantly influence the market, increasing pressure on the industry and emphasizing the need for implementing sustainable practices [50]. By establishing fishermen as essential intermediaries through regular forums, and simultaneously raising public and consumer awareness through information campaigns, the implementation of sustainable practices in the fishing industry is promoted.

Governments and regulatory authorities have the capacity to significantly influence the recycling process by shaping the legal framework. The enacted legal requirements have the potential to either facilitate or hinder this process. Collaboration with these institutions on the level of secondary stakeholders is essential to develop and solidify a legal framework that supports the implementation and efficiency of recycling processes [59].

Environmental protection organizations: In parallel, environmental protection organizations and non-governmental organizations (NGOs) influence events through their commitment to protecting marine ecosystems and can act as supporters or critics depending on the project's implementation [50].

Research institutions provide fundamental insights through expertise and research, promoting sustainable fishing practices through the development of environmentally friendly fishing gear and educational measures [59]. The combination of local ecological knowledge and the specialized knowledge of fishermen is essential for resource management, especially in data-limited systems, and provides in-depth insights into marine ecosystems. An example is a study that analysed the lifecycle of fishing gear by incorporating fishermen's information [50].

The successful introduction of recycling processes in the fishing industry requires coordinated collaboration among various stakeholders. The inclusion and consideration of different perspectives are crucial for the success of such initiatives. Close cooperation among primary stakeholders is indispensable for the effective integration of fishing gear debris recycling. Furthermore, the proactive involvement of authorities, fishing associations, and environmental initiatives as secondary stakeholders shapes the design and implementation of sustainable projects. Lastly, it is important to create incentive systems for

fishermen and fishing enterprises that support environmentally responsible disposal of their fishing gear. Significant progress in the integration of recycling into the fishing industry can be achieved through targeted cooperation and strategy.

Best Practice - Global Strategies & Partnerships: International cooperation and partnerships are crucial to advancing sustainable solutions in fisheries and ocean conservation. Initiatives such as "Healthy Seas" and "Fishing for Litter" have done valuable work by highlighting marine conservation and mobilizing communities to combat ocean pollution [59]. Learning from such initiatives and adopting best practices can enhance the effectiveness of one's own efforts. Companies like Aquafil, which produces nylon from old fishing nets, and Bureo, which manufactures skateboards and sunglasses from recycled fishing nets, are examples of innovative approaches in recycling. Partnering with such companies can lead to the development and implementation of new recycling solutions that not only reduce environmental impact but also offer economic benefits. Establishing strong partnerships on a global level allows the exchange of resources, knowledge, and experiences, creating a network of actors working together for more sustainable marine practices. The integration of different stakeholders is crucial for the success of recycling in the fishing industry. In this context, the establishment of an interdisciplinary committee, consisting of both primary and secondary stakeholders, aiming to define common goals and guidelines, is of great importance. Continuous communication and collaboration between different groups, such as fishermen, fishing enterprises, authorities, fishing associations, environmental initiatives, and recycling experts, are essential. Regular meetings and workshops ensure continuous information exchange. To promote efforts related to the recycling of fishing gear, incentive systems should be developed. These could include financial incentives for fishermen or highlight their efforts through public recognition.

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7. Product development from recycled fishing gear debris

The development of products from recycled fishing gear debris is an innovative approach to reducing environmental impacts and promoting sustainability. Success factors can be divided into distribution and development phases:

In the Distribution Phase: It is crucial to target environmentally conscious customers, emphasize their values through appealing marketing strategies, and highlight quality and functionality. Adapting to changing customer needs, transparent communication about origin and environmental impacts, collaboration with environmental organizations, and efficient order processing and customer service are also key factors.

In the Development Phase: Clear goals, sufficient quantities of high-quality recycled granules, appealing product designs, and the selection of environmentally friendly materials are required. Planning sustainable production processes, integrating recycling technologies, and collaborating with sustainability experts are additional success factors. Companies that consider these factors can develop high-quality and sustainable products while reducing environmental impact. Table 6 lists examples of products derived from recycled fishing gear debris, including the production country.

Table 6: Examples of products from recycled fishing gear debris and their production country

Products	**Country**
Flooring; Mats; Baskets; Handplane (Surfing)	America
Bicycle accessories	Canada
Sunglasses; Granules	Chile
Granules	Denmark
Accessories; Leash; Bags; Shoes	Germany
Socks; Swimwear; Flooring; Mats; Sunglasses; Fishing Nets; Filaments; Chairs	England
Swimwear	Greece
Wetsuit	Ireland
Shoes; fishing nets; bags; filaments; swimwear	Italy
Fishing nets	Norway
Backpacks	Sweden
Jackets	Spain

The integration of fishing gear debris into the recycling process at the port enables efficient local recycling and contributes to sustainable development. Specifically, the production of building materials for port facilities from recycled fishing gear offers ecological and economic benefits. Manufacturing robust plastic products such as piles, planks, and shields from recycled fishing gear debris enables the resource-efficient use of existing materials. This not only reduces the ecological footprint but also minimizes environmental

impacts by avoiding long transport distances for building materials. The local processing of fishing gear debris into high-quality recycled plastic provides the opportunity to produce locally needed products such as packaging materials, containers, or bins. Avoiding regional material transports significantly reduces logistical emissions, contributing to the reduction of carbon emissions. Furthermore, the introduction of recycling infrastructure at the port presents the opportunity to create local jobs and strengthen the local economy. These economic benefits go hand in hand with the environmentally friendly aspects of recycling fishing gear debris locally.

Overall, the local integration of recycled products from fishing gear debris at the port demonstrates a forward-thinking approach to sustainable resource management, promoting both ecological and economic sustainability.

8. Conclusion

This study underscores the complexity of introducing recycling methods for fishing gear debris, encompassing various technical, economic, organizational, and political aspects. In the context of efforts to reduce ocean pollution caused by the fishing industry, it becomes evident that both challenges and opportunities must be considered.

The analysis of recyclable materials from fishing gear debris reveals promising potentials for sustainable recycling in the fishing industry. However, further research is needed to address specific challenges, such as the removal of lead and contamination from biofouling and antibiofouling coatings. Targeted research aimed at optimizing the sustainability and recyclability of fishing gear debris is therefore of great significance.

The proposed strategy for reducing and managing fishing gear debris emphasizes the importance of awareness, take-back systems, recovery measures with reporting, frameworks, and optimizing gear design to promote the recycling of fishing gear debris and minimize environmental impacts. Economic aspects and the involvement of fishermen should also be considered in this context. The analysis of best-practice examples in the fishing industry showcases promising recycling approaches that need adaptation to specific geographical and infrastructural contexts.

The identification of potential products from recycled fishing gear debris opens a wide range of possibilities but requires thorough market analysis and cost-benefit analysis.

In summary, this work emphasizes that reducing ocean pollution from fishing gear debris is a complex task requiring a holistic approach. The presented recommendations serve as a guide for a successful move towards sustainable fishing and environmental protection. It is our responsibility to protect the oceans and ensure the sustainable use of resources to preserve them for future generations.

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