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Review on marine plastic pyrolysis oil: Turning pollution into a maritime fuel

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HIGHLIGHTS

- Marine plastic waste yields 45 %–60% oil via pyrolysis, with little upgrading needed.
- Plastic pyrolysis oil suits existing marine fuel systems without major changes.
- Ports are ideal hubs for pyrolysis units in marine litter-to-fuel conversion chains.
- Proposes a novel route for marine litter mitigation through fuel substitution.
- Presents new insights, challenges and policy aspects of marine plastic pyrolysis.

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ABSTRACT

Marine litter, predominantly plastic waste, represents both an escalating environmental crisis and a potential resource for sustainable fuel production. This review offers the first comprehensive assessment of using marine litter as a feedstock for pyrolysis to generate alternative fuels for the maritime sector. Among various litter types, beach and floating plastics are identified as the most suitable for pyrolysis, given their accessibility and high plastic content, while seafloor litter presents additional collection and pretreatment challenges. Literature indicates that pyrolysis can yield 45 %–60 % oil from plastic-rich waste, requiring minimal upgrading to meet marine fuel standards. The resulting marine plastic-derived pyrolysis oil demonstrates high compatibility with existing maritime infrastructure, allowing for seamless blending with conventional fuels. However, limitations such as restricted production capacity and the fossil origin of plastic suggest that marine plastic-derived pyrolysis oil should be considered a transitional solution. This work uniquely proposes the integration of pyrolysis units within port reception facilities as a strategic and efficient approach to manage marine litter and produce low-carbon maritime fuels. Despite technical and logistical challenges, marine litter pyrolysis shows promising potential as a complementary pathway for both ocean cleanup and low-carbon fuel transition in the maritime sector.

1. Introduction

The pollution of sea, due to marine litter, has attracted attention in recent years and initiatives, both at regional and international levels, have been proposed for its mitigation [1,2]. According to recent studies [3], plastics account for the majority of marine litter. In day by day life, plastics are widely used due to their durability, light weight, chemical resistance, and low cost. At the same time, they pose environmental concerns related to the lack of cost-effective post-consumption management, limited recyclability and the need for incineration or disposal, as the majority of plastics are not biodegradable [4–6]. It is estimated that 10 to 20 million tons of plastic waste reaching marine ecosystems annually with over 5 trillion plastic fragments, weighing more than 250,000 tons, floating in the ocean [4]. Marine plastics pollution represents an environmental threat, altering both marine and terrestrial ecosystems and impacting human livelihoods, particularly in tourism and fisheries [7]. More than 700 marine species, including coral reefs, seabirds, and sea turtles, are affected, with reports of plastics found in animal stomachs or causing fatal entanglements [6]. Additionally, plastics can leach or adsorb hazardous chemicals, which can lead to bioaccumulation in marine organisms consumed by humans, directly endangering human lives [7].

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Various initiatives have been developed to address marine litter, focusing on prevention, mitigation and cleanup, by means of innovative technologies and sustainable methods [8]. Relevant examples of marine litter cleanup projects are the Seabin, an autonomous floating device that captures floating debris, and Fishing for Litter (FFL): which encourages fishers to gather and deliver marine litter caught in their nets [9,10]. However, a key component of cleanup schemes, such as FFL, is the identification of a proper waste processing strategy [9]. Generally, plastic waste is primarily managed through landfilling, incineration, or mechanical recycling, each with its own drawbacks. Landfilling remains common but poses environmental risks, such as soil degradation and groundwater contamination, while also facing rising costs and space limitations [11,12]. Incineration allows for energy recovery but potentially releases hazardous pollutants, including dioxins and volatile organic compounds [11]. Recycling is the preferred method as it reduces virgin plastic use, however most recycling facilities rely on mechanical recycling, which is inefficient for mixed, multilayered, or highly contaminated plastics, a common characteristic of marine litter plastics [5,13]. Additionally, mechanical recycling degrades polymer quality, leading to 'downcycling' into lower-value products [5,13].

Another option for plastic recycling, besides mechanical recycling is the chemical recycling. Chemical recycling encompasses a group of advanced recycling technologies that convert plastic waste into valuable feedstock such as monomers, oligomers and higher hydrocarbons, which subsequently can be used in chemical industry. Current chemical recycling technologies under research and development are pyrolysis, gasification, depolymerization and hydrocracking [5]. One of the most mature and important chemical recycling technologies is pyrolysis [5,11,12]. Pyrolysis is a process which involves the thermal decomposition of materials at high temperatures without the presence of oxidants, which causes the breakdown of polymers into monomers or shorter chain hydrocarbons, and the production of oil, fuel gas, and other by-products. The advantage of pyrolysis process lies in its ability to recycle plastics contaminated with other organic materials and mixed waste plastics, thus eliminating washing and careful sorting steps, lowering pre-treatment costs [13]. Moreover, pyrolysis offers environmental advantages such as a lower carbon footprint compared to direct incineration and landfilling [13,14]. The main products from the pyrolysis of waste plastics are a gas and a liquid fractions and the solid char, which can be utilized in different industries. Among the main products, plastic-derived pyrolysis oil exhibits a high heating value (HHV) comparable to conventional gasoline and diesel fuels [4]. Additionally, it possesses lower acidity and higher stability in comparison to pyrolysis oil derived from biomass, therefore it can be utilized as fuel in various conversion technologies such as diesel engines, boilers, furnaces, etc. [4,14]. As a result, the primary focus of studies in this area focuses on the enhancement of the yield of the liquid fraction.

Despite the limited number of studies addressing marine litter pyrolysis, growing interest in the valorization of plastic waste through pyrolysis highlights its potential. Building on the existing body of research, the objective of this paper is to assess the potential of marine litter pyrolysis as both a waste management strategy and a source of alternative marine fuel. This review focuses on the entire value chain, from litter collection and processing to the technical, environmental, and economic aspects of using marine plastic-derived pyrolysis oil in the maritime sector. By doing so, it highlights the dual benefit of supporting marine litter pollution mitigation while contributing to the decarbonization of shipping. Unlike previous works that mainly focus on general plastic waste or the technical details of the pyrolysis process, this is the first review dedicated to analyzing marine litter as a feedstock for pyrolysis in the context of maritime fuel applications, including its resource analysis, processing characteristics, oil properties, and potential integration into port infrastructure.

2. Methodology

The paper provides a comprehensive analysis of the potential use of marine litter, as a feedstock for pyrolysis conversion. The work explores the possibility of using the oil resulting from the process, as an alternative fuel in the maritime transportation sector. Since the work examines the journey of marine litter from collection to its potential end use in shipping, a structured, stepwise approach was adopted to systematically explore each stage. As proposed in previous studies [15], this approach enables a systematic exploration of each stage, from feedstock availability and processing to the final application, and outlines the key challenges and opportunities along the supply chain.

Unlike broader studies that assess multiple feedstocks and conversion routes, this work specifically focuses on the pyrolysis process of marine litter. The analysis is divided into three key stages: the first stage (Feedstock Assessment) examines marine litter and its potential as feedstock for pyrolysis. The second stage (Processing and Conversion) focuses on the pyrolysis process itself and conditions required to convert marine litter plastic into oil suitable for shipping. Lastly, the third stage (End-Use in Shipping) explores the potential integration of resulting marine plastic-derived pyrolysis oil into the maritime fuel sector. This structured approach enables a systematic evaluation of marine litter as a resource, the technical aspects of its conversion, and the practical challenges of adopting the resulting marine plastic-derived pyrolysis oil as a maritime fuel.

The literature for topics relating to marine litter composition and recovery rates, marine litter plastic pyrolysis, and usage of marine plastic-derived pyrolysis oil in shipping was reviewed. The primary focus was on peer-reviewed scientific literature. However, due to the scarcity of studies on the related topics, grey literature, such as policy documents, institutional reports, regulatory frameworks, and non-peer-reviewed or pre-print publications, was also included in the search. Studies on mixed waste plastics pyrolysis were also considered, as this waste stream shares similarities with marine litter plastics and helps address gaps in the existing literature.

To identify relevant studies on marine litter, a structured literature search was conducted using the Elsevier and Google Scholar databases. The search employed combinations of general terms ('litter,' 'plastics,' 'debris') with location-specific keywords for each litter type. For floating litter: 'sea surface,' 'ocean surface,' 'pelagic,' 'floating,' and 'water column'; for seafloor litter: 'bottom,' 'seafloor,' and 'benthic'; and for beach litter: 'beach,' 'coast,' and 'shore.' Boolean operators such as, AND were used to combine terms. Articles were initially screened based on titles and abstracts, with a primary focus on studies published between 2020 and 2025 to ensure up-to-date data. Studies published in this time frame, containing relevant older survey results were retained.

This review specifically focuses on European seas, given the presence of European Union (EU) and International Maritime Organization (IMO) regulations that influence marine litter management and shipping fuel standards. Within EU, legislation including the Marine Strategy Framework Directive 2008/56/EC and the Port Reception Facilities (PRFs) Directive 2019/883, significantly influences marine litter management by setting environmental targets, waste handling protocols, and promoting cost recovery systems [16,17]. Additional regulations like the Waste Framework Directive 2008/98/EC [18] and the Packaging Waste Directive 94/62/EC [19] further support waste reduction and recycling efforts, addressing both marine and land-based sources of pollution. IMO's MARPOL Convention, specifically Annex V, is a key regulation for reducing ship-based pollution [20]. Annex V prohibits the discharge of plastic waste at sea and mandates the use of PRFs for waste disposal [21,22]. Special Areas, such as the Mediterranean and Baltic Seas, receive additional protection due to their ecological significance and high maritime traffic [23]. These policies ensure adequate PRFs, and create a regulated environment that supports the feasibility of marine litter pyrolysis. Furthermore, many European seas fall within MARPOL Emission

Control Areas (ECAs), requiring ships to use fuels with a 0.1 % sulfur content [23]. EU Sulphur directive also demands 0.1 % Sulphur content fuels from ships, which covers areas that are not under MARPOL [24]. These regulations, and the fact that some of European seas are heavily affected by marine litters provide a suitable location for adopting the process of converting collected marine litter into clean alternative shipping fuel.

However, marine litter is a global issue, affecting many areas other than European seas. United Nations Environment Programme (UNEP) Global Initiative on Marine Litter, supported by standardized monitoring guidelines, is implemented through Regional Seas Programmes such as NOWPAP in East Asia and the Caribbean Environment Programme (CEP), enabling coordinated action in high-pollution regions [16,20]. Nevertheless, these initiatives often operate in less developed regulatory and infrastructural environments compared to Europe. The European context therefore provides the most practical foundation for assessing marine litter pyrolysis and may serve as a reference for future evaluations in other high-pollution regions.

3. Converting marine litter into fuel

3.1. Marine litter: types, quality and quantity

Marine litter is defined by UNEP as “any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment” [25]. Marine litter can be found in any marine habitats, with varying densities, and it is categorized into plastics, metal, glass, processed timber, paper and cardboard, rubber and textiles [25]. To assess the potential of marine litter as a feedstock for pyrolysis process, it is crucial to perform a deep analysis of marine litter’s overall material types, plastics composition, and availability. The primary component for fuel production from marine litter is plastics with small quantities of oil being produced from rubber, wood, and seaweed, which are also present in marine litter [26–28]. In pyrolysis process, especially with plastic feedstock, the yields and quality of liquid product depend not only on operating parameters but also significantly on the type of plastics used as feedstock [14]. Typically, from among the main plastic groups, polyethylene (PE), polypropylene (PP), and polystyrene (PS) yield high amounts of oil [14]. At the same time, polyvinyl chloride (PVC), and polyethylene terephthalate (PET), generate low amounts of oil with high amounts of corrosive compounds [14]. In addition to plastic types, composition of raw materials also plays an important role in determining both the distribution and quality of pyrolysis products [29].

Marine litter can be classified by its location into beached litter, floating litter, and seafloor litter [16,20]. Such classification is also used for this study.

3.1.1. Beached litter

This group of litter accumulates on beaches and coastal areas. These litters find their way on the beaches either by direct on-site littering or they are transported to the location by wind and currents [30]. Many factors, both anthropogenic and environmental, influence the type and beached litter density [31,32]. Generally, more litter is found on beaches closer to population centers and highly visited beaches [20,32]. However, this is not always the case, since beach litter can negatively affect tourism, causing economic problems, and prompting cleaning operations [30,33]. The type of beach substrate, the direction and strength of wind, or existence of river mouths nearby can also affect amount and characteristics of debris [31]. For example, glass and hard plastics tend to accumulate more easily on rocky shores, while areas without strong prevailing winds or those protected from wind often collect higher amounts of debris, as do vegetated sections of beaches or locations farther from the reach of waves [16,20,34].

Beaches are among the most accessible environments for studying marine debris; however, due to reasons mentioned above, inconsistencies in sampling frequency, different methodologies, and quantification frameworks make it difficult to form a quantitative global assessment of beach litter distribution [16,32,35]. Despite these shortcomings, common patterns and information can be obtained by several studies: Table 1 summarizes the results of some of the studies regarding the beached litter for European seas in recent years.

The data regarding the composition of marine debris on the beaches of European seas shows that plastics are often the dominant waste type. The study by Bettencourt et al. [49], which reported plastics as the second dominant waste type, identified cigarette butts as dominant waste type with 30.9 % in terms of count, which are mainly made of cellulose acetate, a non biodegradable polymer, typically categorized under plastic group [16,54,55]. Other waste groups aside from plastics are also present on the beaches and their composition is highly variable depending on the location. Construction materials and slack/coal were also reported in some areas [33,45].

Among the waste groups within the plastic category, most of the studies showed that plastic pieces (average dimension between 2.5 cm and 50 cm), cigarette butts, food packaging, plastic caps and lids, bottles, and bags are the most abundant waste in European seas [33,36,38,41,46,51]. These findings align with the JRC technical report on the top marine beach litter items in Europe [32]. Fishing-related litter can also be found on beaches, albeit with less frequency. Its presence and abundance are highly dependent on location and the extent of regional fishing activities [34]. A notable example is European Arctic region, where litter related to fishing activities is much more prevalent [56]. Aside from cigarette butts, most of the general litter on beaches is generally made from PE and PP plastic groups, while drinking bottles are typically composed of PET [37,57]. A study by Stagnitti et al. [58], conducted to identify the constituent polymers of litter, confirming that PE (HDPE + LDPE) accounted for 41 %, PP for 27 %, PET for 14 %, PS for 9 %, and PMMA and PLA together for 9 %. Regarding the plastic fragments, Haseler et al. [38] analyzed a sample of plastic pieces and found that 50.38 % are composed of PE, 26.6 % are PP, 14.6 % are PS, 2.2 % are other polymers and the rest could not be identified.

Finally, the mass composition of litter on beaches is also important to consider for the pyrolysis process. Data regarding the mass of beach litter is scarce. Table 1 clearly shows this, only a handful of studies have reported density by weight for beach litter. The mass of marine litter is generally not reported, likely due to the inherent challenges in its gathering and measurement. Even though mass data could provide a significantly more accurate assessment of the overall pollution situation [59]. Nevertheless, studies do exist that report the marine litter by weight. Andriolo et al. [60] analyzed 80 publications that provided data on both the abundance and weight of beached macro-litter worldwide. The study reported values ranging from 53 % to 64 % for Europe and its adjacent seas, including the Black Sea, the Mediterranean Sea, and the Atlantic Ocean [60]. The remaining weight composition can vary significantly. In most cases, metals, processed wood and glass or ceramics make up the rest, and in some cases, they may even be the dominant materials on the beach by mass [40,47,61]. Similar patterns are observed in many marine regions worldwide. Globally, plastics account for approximately 75 % to 90 % of beached litter by number, and 35 % to 60 % by weight [60]. The situation is particularly critical in Asia, where China, Indonesia, and the Philippines are among the largest contributors to mismanaged plastic waste [62]. Moreover, 15 of the top 20 most polluting rivers, leading to estimated 67 % of plastic waste entering the oceans via rivers, are located in East Asia [63]. For Asia 77 % by count and 46 % by weight of beached litter are composed of plastics [60].

3.1.2. Floating litter

This group of marine litter consists of litters floating on the sea surface, which can travel over long distances due to currents and winds [64]. Over time, this debris may sink to the seafloor due to biofouling and density changes, accumulate on beaches or broken into smaller fragments due to degradation, eventually becoming microplastics, which are typically defined as plastic particles smaller than 5 mm [16,64]. Floating litter distribution is not homogeneous across the oceans, as its movement and accumulation are primarily influenced by ocean currents [3]. While much of this litter gathers in the five subtropical gyres, coastal areas and enclosed basins are also severely affected [65]. Generally, in coastal areas, rainfalls and local inputs and coastal currents play a major role in litter transport, while in offshore it is affected by wind-driven surface transport and large-scale oceanic currents, further adding to the heterogeneous nature of floating litter distribution [66].

Monitoring floating litter is done by observation from a ship following certain paths and net trawls: litter density is reported in the form of items per unit of surface area and mass-based data can only be estimated [16]. Table 2 presents recent litter density data for European seas. In general, floating marine litter density follows a decreasing gradient from river mouths and bays to coastal areas, and further to the open sea, with the highest concentrations typically found near river inputs and enclosed coastal zones [66–68]. Plastic debris comprises 90 % to 100 % of floating litter [65–71]. Studies by Compa et al. and Moigne et al. [52,72] reported lower values but clarify that this discrepancy is due to the inclusion of natural debris in the calculations, and differences in litter categorization such as separating fishing-related litter from general plastic litter. Small quantities of processed wood or paper materials are also present alongside plastic debris, typically making up less than 10 %, while other materials are negligible [66–70]. Data on floating litter mass composition is generally unavailable, however since plastic debris accounts for nearly 100 % of this type of litter, it is reasonable to assume that the total mass of floating litter is primarily composed of plastics.

Plastic fragments, bags, sheets, and bottles are typically the main comprising waste of floating litter [65–67,69,71]. A study on floating plastics of North Pacific subtropical gyre showed that the majority of waste plastics are fishing gears and items related to them. Through analysis of markings and language on recovered objects, over 70 % of the debris was traced back to Asian countries [74]. This aligns with broader regional trends, as some of the highest reported litter densities have been observed in various parts of Asia [75]. Determining the plastic groups of floating litter can easily be done by comparing each plastic group density with seawater density. Table 3 provides information on density values of plastic groups generally found in the marine environment. Based on the table, it can be expected that the majority of the wastes floating on the sea surface consists of PP, PS, and PE polymers.

3.1.3. Seafloor litter

This group includes submerged debris and litters accumulated on the seafloor. The seafloor is widely considered the primary sink and final accumulation zone for marine litter [77,78]. While negatively buoyant materials naturally settle, even items with positive buoyancy can eventually sink due to physical, chemical and biological processes, such as biofouling, which increase their weight and reduce buoyancy, which over time led to transfer of floating debris to the seabed [77,79]. It is

Table 1
Comparison of beach litter density between different European regions, with their plastic share.

Location	Average density (item/m^2)	Density (g/m^2)	Composition	Reference
Southern Black Sea, Türkiye	0.838 ± 0.33 to 4.01 ± 0.55	~3–133.76	80.4 ± 1.18 % plastics	[36]
Adriatic Sea	0.12–3.5	0.065–19.12	57 % to 94 % plastics	[37]
Mediterranean Beaches of Egypt, Morocco, Tunisia	1.71 ± 2.28	3.63 ± 4.22	79 % to 91 % artificial polymers[a]	[38]
Bulgarian Coast, Black Sea	0.44 ± 0.04	n.d.	83.99 % artificial polymers	[39]
Homa Lagoon, West Türkiye	581 ±0.168	n.d.	75 % artificial polymers	[41]
Atlantic Coast of Cadiz, Spain	0.06	n.d.	88.54 % plastics	[42]
Danish Beaches	n.d.	n.d.	87 % plastics	[43]
England East Coast	67 ± 49.53	n.d.	>90 % plastics	[44]
South Mediterranean Sea, Tunisia	1.01 ± 1.08	n.d.	59.2 % plastics	[45]
Sea of Marmara, Turkey	66.2	0.073	76 % plastics	[34]
Przine Island, Northern Adriatic Sea	527 ± 177	n.d.	>95 % artificial polymers	[46]
South Mediterranean Sea, Morocco	0.2 ± 0.098	6.4 ± 4.09	68 % plastics	[47]
Albania Coastline	0.14	n.d.	65 % artificial polymers	[48]
South Coast of Madeira Island, Portugal	0.29	n.d.	30.7 % plastics	[49]
Polish Coasts, Southern Baltic Sea	0.03–6.15	0.13–44.3	n.d.	[50]
Island of Cyprus	0.19 ± 0.18	n.d.	86.3 % plastics	[51]
Cabrera Archipelago, Western Mediterranean	1.9 ± 2.4	n.d.	>90 % artificial polymers	[52]
Central Italy, Mediterranean	0.16	0.125	99 % plastics	[53]

[a] Artificial polymers are human-made synthetic materials, such as plastics and rubbers.

Table 2
Floating plastic densities and composition in different marine locations.

Location	Average density (item/km^2)	Plastic composition	Reference
Italian waters, Mediterranean Sea	95.8 ± 6.4 (Coastal[a], Items >2.5 cm) 20.7 ± 2 (Coastal, Items >20 cm) 2.7 ± 0.18 (Offshore[b], Items >20 cm)	94 % (Coastal) 91 % (Offshore)	[66]
Malta Coast, Central Mediterranean	292 ± 85 (Coastal) 3242 ± 1880 (Inshore)	91 %	[67]
Bay of Biscay	3.7 ± 2.34	87.50 %	[69]
Mediterranean Sea	1 ± 0.1 to 314 ± 302.6	80 % to 90 % (Overall) 97 % (Coastal)	[68]
Black Sea	93.6 ± 128.3	95.80 %	[70]
Coast of Catalonia, NW Mediterranean Sea	16.4 ± 21.7 to 19.7 ± 25.8	98 % to 100 %	[65]
Balearic Islands, Mediterranean Sea	2028 ± 2084	69 %	[52]
English Channel	0.08 ± 0.16 to 0.43 ± 0.88	69 %	[72]
Bay of Biscay and Celtic Sea	0.06 ± 0.23 to 0.18 ± 0.42	77.10 %	[72]
Mediterranean Sea	1.88 ± 2.3 (Aerial) 0.89 ± 1.61 (Vessel)	68.30 % (Aerial) 95.88 % (Vessel)	[73]

[a] Areas near the coasts.

[b] Areas faraway from the coasts.

Table 3
Density of different plastic groups and seawater.

Plastic group	Density (g/cm^3)
PP [58]	0.92–0.93
HDPE [58]	0.95
LDPE [58]	0.91
PS [58]	1.02
PET [58]	1.35
PVC [76]	1.4
Seawater [57]	1.28

estimated that globally over the 90 % of all marine litters settles on the seafloor [52]. Waste plastics comprise 62 % of debris on the seafloor [80]. The Mediterranean Sea and Southeast Asia are among the most severely affected regions, where in some areas plastic waste constitutes nearly the entirety of marine litter found on the seafloor [80]. Marine litter on the seafloor can pose significant environmental threat by causing habitat degradation through smothering, entanglement and scouring, while also altering benthic communities by providing artificial surfaces for species colonization and the spread of invasive organisms [81,82]. Moreover, due to the lack of sunlight, consistently low temperatures and generally low-energy conditions (excluding shallow coastal waters) plastic litter on the seafloor tends to persist with minimal degradation, leading to its gradual and ongoing accumulation [80].

The composition and density of seafloor litter are extremely variable (even comparing with beached and floating litter) and it influenced by a range of factors including sampling methods, depth, possible fishing grounds, hydrodynamics, seafloor topography, proximity to coastal areas, population density, river inputs, and oceanographic conditions [83–85]. Table A.7 depicts this variability, for the European seas. Compared to both beached and floating litter, the seafloor litter values, both average density and composition, are subjected to much larger fluctuations. While plastics are still the dominant class of litter by number in most areas, other material classes such as glass and metal can be found in higher abundance compared to beach and sea surface environment, due to their higher density and thus higher chance of sinking [52,86–89]. Determining the plastic composition by weight is more difficult. Based on the studies reporting composition by weight values in Table 5, plastic group of seafloor ranges from 2 % to 88 %. The average value of all studies reporting composition by weight is 37.5 %, such value can be considered a general estimate. Mistri et al. [90] reported that from 6755.2 kg litter collected from Adriatic seafloor, approximately 2.4 tons of plastics were recovered, corresponding to a plastic composition of around 35.5 %, which is consistent with the estimated mean value.

A significant fraction of seafloor litter is Abandoned, Lost or Otherwise Discarded Fishing Gear (ALDFG). These items are primarily made from plastic polymers with long lifespans, and they can continue to trap marine organisms for decades by ghost fishing, making them one of the most hazardous wastes for marine life [91,92]. They include diverse range of items such as nets, lines, floats, and traps [93]. In general, based on the literature reviewed, ALDFG is found in higher concentrations in deep seas and off-shore areas [82,94,95], while it is far less common in coastal regions [78,96,97], though outliers do exist [98,99].

The plastic composition of seafloor litter is also significantly diverse compared to other groups. Unlike beached litter which is mostly packaging waste plastic and floating litter which is pre-dominantly made of polymers with densities lower than seawater, almost any plastic type can be expected on the seafloor. However, certain types of plastic litter are more common and can be found in higher quantities. Barry et al. [100] reported the top ten marine litter items on the seafloor of Baltic Sea, Celtic Sea, Bay of Biscay and Greater North Sea by analyzing data from trawl surveys conducted from 2012 to 2020. For Greater North Sea, Celtic Sea, and Bay of Biscay, synthetic ropes, plastic sheets, monofilament lines, plastic bags, and fishing lines were the top five litter items [100]. For Baltic Sea plastic sheets, other natural litters, other plastic items, plastic bags, and bottle glasses occupied the top five spots [100]. Waste plastic types are highly dependent on the location for Mediterranean Sea, but overall bags, plastic bottles, sheets, nets, and fishing lines are the most common seafloor plastic waste [47,52,77,82,83,99,101].

Several studies have analyzed the polymer types of seafloor litter: PE and PP groups are the most abundant polymer groups on the seafloor [90,94,102]. Other polymer groups such as PVC, PET, PS, Polyamide (PA) and other less known types of polymers can also be found on the seafloor with lower quantities [94,102]. PA is also notable, since it is used along with PE and PP in fishing gears [92,93,103]. The PA, particularly in the form of nylon-6 and nylon-66 is mostly used in monofilament fishing lines, while PE and PP are more common in synthetic ropes, braided nets, and twisted-knotless nets [103]. Based on these findings, it can be concluded that seafloor litter is predominantly composed of PE, PP and PA, reflecting the widespread use of these polymers in fishing activities.

3.2. Marine plastic conversion

Plastic components decompose across a broad temperature range and produce a variety of products in liquid, gas and solid form. The composition and yields of these products depend not only by the key process parameters such as temperature and residence time but also by the specific composition of the waste plastic used as feedstock. To determine the expected outputs and to assess whether the resulting pyrolysis oil may be suitable for marine applications, it is essential to analyze existing studies on plastic pyrolysis. While numerous studies have investigated the pyrolysis of single plastic types, documenting their behavior during the process, only few address the marine litter pyrolysis. Marine litter typically consists of a complex mixture of multiple plastic types, often contaminated with other materials. To prepare the marine litter for the process and ensure optimal conditions, a pretreatment step is therefore necessary (see Fig. 1).

3.2.1. Pretreatment

It is crucial to properly prepare the feedstock for the main pyrolysis process, to ensure efficiency, quality of the product and equipment durability. This phase may include sorting, washing, drying, and shredding. The sorting step is not as intensive as mechanical recycling [104], however depending on marine litter source, it is crucial to remove large non-plastic items such as ship anchors, metal chains and car tires to ensure a smooth process [87,105]. In particular, cigarette butts can be problematic during the pyrolysis process. As previously mentioned, cigarette butts are primarily made of cellulose acetate, which is produced by reacting cellulose fibers with acetic acid in the presence of a homogeneous catalyst such as sulfuric acid [106]. Experimental studies that pyrolyzed cellulose acetate alone have shown that the resulting oil is predominantly composed of acids, with acetic acid making up approximately 25 % to 40 % of the total yield [55,106], making cellulose acetate extremely undesirable within the process, especially when it comes to fuel production. Regarding other foreign materials, it is shown that presence of metals and glass can promote gas production and formation of aromatic compounds [107,108], which at higher levels can be problematic. Furthermore, glass and metals are inert materials that increase the amount of solid residue produced during pyrolysis, complicating its disposal or further processing. Wood, and biomass pose minimal issues within plastic pyrolysis setting. The ratio of waste marine plastic to biomass within marine litter can significantly influence the overall outcome of the pyrolysis process [109]. However, due to the highly variable composition of marine litter it is impossible to accurately predict this ratio. Overall, experiments have shown that co-pyrolysis of plastics and biomass (both algae and wood), lowers the activation energy compared to pure plastic pyrolysis [110,111]. This occurs because biomass degrades at lower temperature than plastics, and generates free radicals, facilitating depolymerization of long polymer chains of the plastics [110–112]. This mechanism also improves

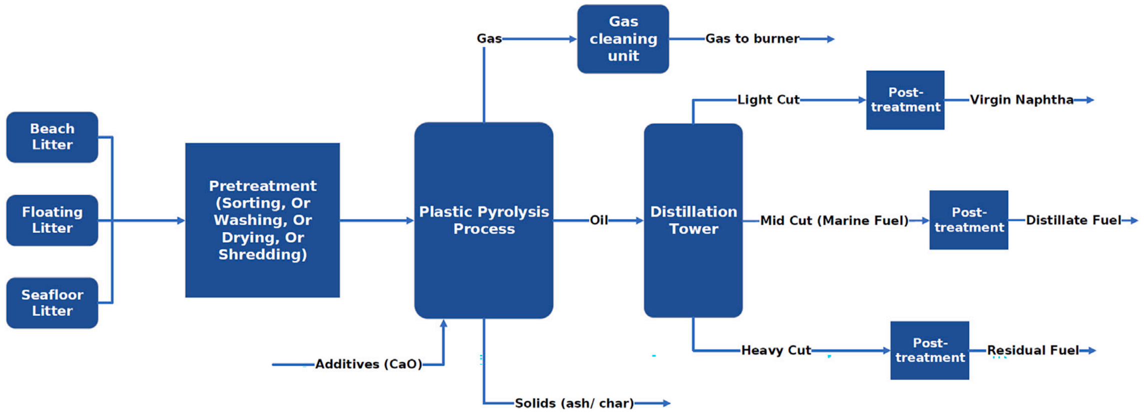

Fig. 1. Block flow diagram of marine litter pyrolysis process.

the quality of bio-oil by inhibiting the formation of oxygen-containing functional groups [112], however depending on plastic type it can also promote aromatic compound formation [27,112].

Marine plastic litter is often encrusted with dirt, biomass, and contaminated by salts, potentially requiring pre-washing [113]. In particular, salt contamination can pose challenges to both the pyrolysis process and the quality of the final product. Studies on this topic are scarce and mainly limited to experiments on the thermal pyrolysis of waste fishing nets. In these studies, the comparison between new and waste fishing nets showed that the chloride content of plastics increased from 0.03–0.07 wt% to 1.2–2.0 wt% [114,115]. Presence of chloride can lead to formation of toxic byproducts such as HCl and chlorinated compounds within pyrolysis oil [14]. Additionally, presence of salts can lead to increase in sodium content within the resulting oil [113]. Sodium content is a critical parameter in the standards for residual marine fuels, and elevated levels could hinder the adoption of marine plastic-derived pyrolysis oil in the shipping sector [116]. Despite these challenges, it may be possible to avoid pre-washing step in marine litter pyrolysis. PVC is already present in marine litter, and it can be speculated that measures commonly used to mitigate chlorine release from PVC, such as the addition of CaO during pyrolysis [117], can also address chlorine contamination originating from salt. Regarding sodium content, its impact on residual marine fuels is primarily critical when vanadium concentrations are significant, as sodium can act as a paste for vanadium slags [113]. However, it is shown that vanadium content of oil from marine litter pyrolysis is extremely low, thus lowering the risk of slag formation [113]. Moreover, it can be speculated that the elevated presence of salts may necessitate the use of more corrosion-resistant materials in reactor construction and gas handling systems, potentially increasing capital expenditure. Nevertheless, to fully analyze the effect of washing step for marine litter pyrolysis process requires further dedicated research.

Other pretreatment steps include shredding and drying. A drying step is necessary to eliminate moisture introduced by seawater or the washing process. Shredding is also required to enhance heat transfer within the main reactor, since smaller plastic particles lead to an increase in oil and gas yields [4]. For slow pyrolysis, which is the relevant process for marine litter, a particle size between 5 and 50 mm is considered appropriate [14].

The level of pretreatment varies depending on the waste marine litter plastic sources, with each having their own set of advantages and challenges. Floating litter is expected to require minimal pretreatment, since seawater can act as a density separator. Moreover, the level of biofouling is also minimal, meaning only a light washing, followed up by drying and shredding is required. Due to presence of cigarette butts and some other foreign materials such as metal cans and glass bottles, a sorting step is most likely necessary for beached litter. Pretreatment of seafloor litter is more challenging. Depending on the location, plastic waste might not be the dominant waste group, which requires a relevant sorting stage. Furthermore, presence of dirt, organic materials and salt contamination are much more significant with seafloor litter, increasing the necessity for washing.

3.2.2. *Pyrolysis process*

Numerous studies have examined the pyrolysis of mixed waste plastics (MWP or MPW) but they typically do not refer to marine litter. Since feedstock composition is a critical factor in plastic pyrolysis, it is essential to focus on studies that used marine litter as feedstock. A summary of several studies on plastic pyrolysis with feedstock similar to marine litter and their main parameters is reported in Table 4.

Among the studies listed in the table, only three focused on marine litter pyrolysis. Of these, only Faussone et al. [113] and Hee et al. [118] used marine litter in its original form without any pretreatment. The limited availability of studies focusing on marine litter shows the process still has a significant potential for research. Nevertheless, based on available studies [62,113,118–121], marine litter pyrolysis can yield between 16 wt% and 65 wt% oil, depending on the litter composition, with most of the values falling in the 45–55 wt% range. It can be expected that beached litter and floating litter produce more oil, since their main components are PE, PP, and PS, which result in larger amount of oil compared to other polymer groups due to their higher volatile content [4].

Several characteristics sets marine waste plastics apart from the conventional MWP, which also influence the oil yield. Unlike urban MWP, plastic from marine litter, especially seabed litter, contains a significant share of PA. Miskolczi et al. [122] reported that existence of PA within MWP feedstock increases solid residue and promotes the formation of polyaromatics. PA is mostly found within fishing gear in the form of nylon-6 and nylon-6.6 [113]. During individual pyrolysis nylon-6 is mainly recovered as its monomer caprolactam [123], while nylon-6.6 generates crust-like residue, large quantities of water, cyclopetanone, carbon dioxide and small amount of carbon monoxide and hydrocarbons [124]. PA polymers contain nitrogen within their structure, that can form amine and amide compounds within the pyrolysis oil, which can be problematic when used as fuel [125]. Additionally, nitrogen can make its way into the gas fraction of the pyrolysis product in the form of Ammonia and Hydrogen cyanide, causing problems and requiring gas cleanup operations further downstream [113].

Weathering and salts also influence oil yield and its quality: they contribute to oxidize waste plastics, lowering volatiles, and fixed carbons [114]. Lodh et al. [62] showed the temperature degradation of weathered plastics is lower than that of non-weathered plastics. Such plastics also produce more ash due to inorganic salts [114]. Furthermore, the weathering and salts effect results in increased oxygenated compounds and chlorine in pyrolytic oil [62,114].

Table 4
Pyrolysis oil yield from different feedstocks similar to marine litter.

Temperature [°C]	Feedstock	Catalyst	Oil yield [wt%]	Scales	Reference
430	MWP PE/PP/PS/PVC PE/PP/PS/PVC/PET	–	MWP: 59 % 3P/PVC: 70 % 3P/PVC/PET: 53 %	20 g/cycle	[119]
450	Lightweight packaging Construction waste Insulation composite Auto. shredder residue Waste electronics	–	Lightweight packaging: 40 % Construction waste: 53 % Insulation composite: 75 % Auto. shredder residue: 48 % Waste Electronics: 40 %	1 kg/h	[120]
500	Four samples from reject streams of waste separation	–	Sample 1: 53 % Sample 2 (film rich): 65.7 % Sample 3 (paper rich): 35.1 % Sample 4 (Glass rich): 40.9 %	100 g/cycle	[29]
500	MPW (LDPE and HDPE) MPW-N (PA present) MPW-Cl (PVC present)	Ni/ZSM-5 Ce/Ni/ZSM-5 La/Ni/ZSM-5 Ce/La/Ni/ZSM-5	MPW: 54 %–60 % MPW-N: 50 %–57 % MPW-Cl: 50 %–55 %	50 g/cycle	[122]
450	Automotive Plastic Waste	–	49 %	1 kg/h	[121,126]
700	ML Sylt (marine litter on beach after high tide) ML Norderney (marine litter on beach)	–	ML Sylt: ~24 % ML Norderney: ~22 %	500 g/cycle	[118]
450–600	Beach marine litter (clean)	$AlNaO_6Si_2$, $Ni\text{-}Al_2O_3$	No catalyst (550 °C): 78 % $AlNaO_6Si_2$ (550 °C): ~58 % $Ni\text{-}Al_2O_3$ (550 °C): ~62 %	200 g/cycle	[62]
450	Marine litter (seafloor and floating)	–	45 % (mean)	10 kg/cycle	[113]

Temperature is considered as the most important operating parameter in plastic pyrolysis [4,14,127]. At high temperatures, increased molecular vibrations overcome Van der Waals forces, which destabilize polymer chains and lead to their breakdown through depolymerization, random chain scission and side-group elimination [128,129]. Thermogravimetric analysis (TGA) reveals that individual plastics exhibit different thermal degradation patterns, in similar temperature ranges, with varying points at which degradation begins and reaches its peak. Within mixed plastic systems, interactions between different polymers can influence degradation pathways, often leading to delayed degradation, synergistic effects and peak convolutions. After reviewing multiple plastic pyrolysis experiments, Mirkarimi et al. [14] reported that temperature range of 450 to 600 °C is often selected as an optimum for mixed plastic pyrolysis. Conversely, Chang et al. [4] reported a much wider range of 380 to 730 °C for thermal pyrolysis and 350 to 500 °C for catalytic pyrolysis. Regarding marine litter plastic, a lower degradation temperature range of 270 to 470 °C has been reported [62]. Furthermore, the comparison between fresh and waste fishing nets also revealed that mass loss occurs at lower temperature for used or aged fishing nets [114,115]. This lower temperature was attributed to degradation of polymer structure within marine environment due to weathering and absorption of impurities [114,115]. Additionally for PA, the mass loss mainly occurs in the range of 375 to 475 °C, due to weaker C–N bonds compared to C–C bonds [62,114]. And lastly, the mixture of PA and PE undergoes thermal degradation more rapidly than either PE or PA alone [130]. Considering these information and pyrolysis experiments presented in Table 6, it can be concluded that 450 to 500 °C is a preferable range for pyrolysis of marine litter plastics; higher temperature can also be possible depending on the feedstock composition (e.g., high PE and PP content) but they can lead to rapid gas formation [118]. Moreover, higher temperatures can lead to the generation of more aromatic compounds and toxic PAHs via Diels-Alder reactions [4,131].

Heating rate and residence time are important operating parameters, closely linked to each other and to temperature. Heating rate is defined as the rate at which the temperature of the reactor increases (°C/min), while residence time defines as the amount of time the feedstock stays in reactor. Vapor residence time, on the other hand, indicates how long the vapor-phase products stay within the reactor. Increasing the heating rate leads to a delay in thermal degradation and growth in maximum degradation rate, this means that higher heating rate requires higher temperature for degradation, and decreased residence time due to higher reaction rate [132,133]. Conversely, with low heating rate, degradation occurs at lower temperatures but feedstock requires more time to remain in the reactor [132]. Additionally, lower heating rates cause volatiles to remain longer in the heating zone, promoting the formation of shorter-chain hydrocarbons in the oil and increase in gas yield [14,132]. These dynamics highlight how temperature, heating rate, and residence time parameters are connected and help explain

Table 5
Calorific values of different fuels and plastic oils.

Fuel/oil	Calorific value (MJ/kg)	Reference
Gasoline	46.8	[14]
Diesel	43	[14]
LPG (Liquefied Petroleum Gas)	46.1	[14]
HFO (Heavy Fuel Oil)	39.5 (LHV)	[144]
MGO (Marine Gas Oil)	42.8 (LHV)	[144]
MDO (Marine Diesel Oil)	41 (LHV)	[144]
FAME (Fatty Acid Methyl Ester)	38 (LHV)	[142]
HVO (Hydrotreated Vegetable Oil)	43 (LHV)	[142]
Biodiesel	37.5 (LHV)	[144]
DME (Dimethyl Ether)	28 (LHV)	[142]
HDPE	43.97–45.38 (HHV)	[4]
LDPE	44.25–47.23 (HHV)	[4]
PP	45.23–46.05 (HHV)	[4]
PS	38.51–43.58 (HHV)	[4]
PVC	15.06–24.57 (HHV)	[4]
PET	21.64–24.15 (HHV)	[4]

Table 6
Performance of fishing for litter programs (OSPAR).

Countries	No. harbours	No. vessels	Tonnes	Tonnes per vessel
Germany	3	60	1.2	0.02
Netherlands	12	91	285.2	3.13
Sweden	2	33	491	14.88
UK	25	474	142.7	0.3
Total	42	658	920.1	1.4

the differences between slow and flash pyrolysis. Within plastic pyrolysis context, slow pyrolysis, is defined by moderate temperatures (250–600 °C), low to moderate heating rates (5–200 °C /min), extended residence times (15–240 min), and short vapor residence time (less than 1 minute) favors the production of plastic oil with minimal gas and char formation [4,14]. On the other hand flash pyrolysis is characterized by high temperatures (600–1000 °C), rapid heating rates (in order of milliseconds) and short residence time (Less than 3 s), leads to high yields of gaseous compounds such as C1-C4 hydrocarbons and small amount of plastic-derived pyrolysis oil and char [132,134,135].

The number of studies on the pyrolysis of marine litter plastics is too limited to allow for a precise estimation; existing research on the topic appears to rely on guidelines and values established for conventional mixed waste plastics. In general it was observed that plastic pyrolysis processes focusing on oil formation use heating rate in range of 10 to 30 °C/min and residence times of 30 to 60 min [29,62,118–120,131]. The quality of oil is also heavily influenced by vapor residence time, as short vapor residence time leads to formation of long-chain, wax-like hydrocarbons, while excessively long vapor residence times promote secondary cracking, resulting in lighter, gasoline-range compounds [62,136]. At temperatures around 450 °C vapor residence time between 4 to 12 s have been reported to produce 50 % to 65 % oil with carbon range of C14-C19 [136], corresponding to the diesel fraction [14]. Such values align with the reported ranges for oil production in plastic pyrolysis processes [4,14]. The only notable anomaly was Faussone et al. [113], which reported two hours feedstock residence time. It is speculated that, this higher residence time was due to the significantly larger feedstock mass, 10 kg per cycle in this case, compared to the 20–1000 g used in other experiments.

Final parameters to consider are pressure and the presence of catalyst. All the experiments reported in Table 4 were carried out under atmospheric pressure. It is shown that increasing pressure leads to higher gas yield and the formation of lighter compounds both in oil and gas [137]. Regarding plastic pyrolysis under vacuum conditions, studies have shown that it improves the production of diesel range compounds [107,138]. However, the feedstock of these studies was not mixed waste plastics, thus their results may not be accurate for the pyrolysis of marine litter plastics.

A variety of catalysts have been used for plastic pyrolysis, including zeolites and their derivatives, metal catalysts, minerals, fluid catalytic cracking (FCC) catalyst and fly ash [4,14]. Due to the lack of experimental studies on the catalytic pyrolysis of marine litter, deriving accurate insights into optimal process parameters remains challenging. Furthermore, the more variable the feedstock, the more difficult it becomes to define specific catalyst characteristics. It is demonstrated that for MWP, inclusion of silica-alumina, zeolite, and FCC catalysts leads to reduction in oil yield and increase in gas yield [122,131]. Furthermore, these catalysts promote the production of oil with a carbon number range typical of gasoline (C5–C12) [14]. Zeolite catalysts also tend to produce more aromatic content, while silica-alumina promotes olefinics compounds [14,62,131]. Consequently, these catalysts may not be ideal for converting marine litter into marine fuels. Bentonite clay, particularly when modified with Fe- and Al-pillared structures, has been shown to enhance liquid yield and promote the formation of diesel-range hydrocarbons [14]; however, its effectiveness for marine litter plastics remains to be tested. While it is not a catalyst, inclusion of alkaline earth metal oxides or carbonates additives, most notably calcium oxide (CaO), might be crucial for marine litter plastic pyrolysis. These additives are used to inhibit the formation of acidic compounds during the pyrolysis process, particularly from PVC [117]. Marine litter, especially seafloor debris, often contains significant amounts of PVC. Moreover, as shown in Section 3.2.1, chloride content of waste plastics can increase in presence of salt water, highlighting the need for a mitigation strategy even more. Experimental studies have shown the effectiveness of CaO in absorbing HCl and preventing the formation of chlorinated compounds in the oil [117,139]. Moreover, CaO was also employed in pyrolysis of marine litter, further demonstrating its effectiveness in mitigating chlorine-related issues [113]. However, minor issues do exist with CaO. This additive can not completely prevent the formation of chlorinated compounds within the oil [117,140]. Additionally, it can also contribute to calcium concentration in pyrolysis products, which could affect steam cracking performance, particularly if the lighter fractions are intended for further processing [140].

3.2.3. *Oil quality and post-treatment*

The resulting oil from plastic pyrolysis is a dense, viscous liquid oil with dark brown appearance. Unlike bio-oil from biomass, plastic oil has far lower oxygenated and moisture content, meaning it is more stable and has a high calorific value comparable to conventional fuels [4,141]. Calorific value is a crucial property of a fuel which represents the energy content, indicating the amount of energy released by oxidizing the unit (kg) of that fuel. Using a fuel with a significantly different calorific value may require modifications or replacements in the engine and fuel distribution system [142]. Table 5 reports the calorific value of some conventional and alternative fuels used in maritime sector. While the use of different calorific values (HHV and LHV) complicates the direct comparison between each fuel and oil, it is evident from the table that plastic-derived pyrolysis oil with high content of HDPE, LDPE, PE, and PS can easily substitute/be blended with conventional fossil fuels in terms of energy. On the other hand, PVC, and PET with a calorific content in the magnitude of 15 to 25 MJ/kg are less suitable for fuel applications in existing converters. Studies of mixed waste plastics and marine litter plastics reported values from 30.8 to 45.9 MJ/kg, with the average value of 39 MJ/kg [29,62,118,126,143]. While calorific value of plastic-derived pyrolysis oil heavily depends on feedstock composition and operating parameters, it is generally comparable to conventional marine fuels, with only minor variations.

Calorific value is not the only important parameter when considering a potential fuel, physio-chemical properties of the marine plastic-derived pyrolysis oil should fall within the specified range set by the marine fuel standards. Marine applications utilize a variety of fuel options, which are generally categorized into three primary groups: Distillates, Residual fuels, and Gaseous Fuels such as Liquefied Natural Gas (LNG) [145,146]. In the context of marine plastic-derived pyrolysis oil, the focus is primarily on the Distillate and Residual fuel categories. Distillate fuels contain exclusively distilled fractions and no residual fuels, while Residual fuels are the remaining residue in fractional distillation, which did not pass into gas phase [146]. Each category encompasses multiple fuel types, each with distinct properties. ISO 8217, which is the primary standard for marine fuels, has specified these properties for both marine distillate and residual fuels [116]. Although direct marine engine tests on plastic-derived pyrolysis oil remain limited, several studies have evaluated its fuel characteristics and engine performance in land-based diesel engines. Plastic-derived pyrolysis oil, especially oil derived from PP and PE types, have fuel properties, such as kinematic viscosity, density, and calorific value, that are largely comparable to commercial diesel [14,62,147]. It is reported that diesel engines can run with crude plastic-derived pyrolysis oil without any engine modification [147,148], albeit engine performance is modestly below optimal and produced emission is higher than diesel combustion [14,147,148]. This is mostly attributed to aromatic nature of plastic-derived pyrolysis oil and slightly elevated density and viscosity of plastic-derived pyrolysis oil [14,147]. Furthermore, it is shown that blending plastic-derived pyrolysis oil with diesel can mitigate the negative aspects of plastic oil [148]. It is also important to highlight that these studies were conducted with automotive diesel engines, which are subject to more stringent fuel standards than those applied in marine applications [14]. S.M.R. Mirkarimi et al. [14] analyzed 19 plastic-derived pyrolysis oils from various studies and compared their properties to ISO 8217 marine distillate fuel standards. He concluded that almost all samples met the standard's requirements, except for flash point [14]. Low flash point, which is due to the presence of low temperature boiling fraction is most likely the main barrier preventing plastic-derived pyrolysis oils from becoming fully dropped-in fuels. Using a distillation tower to separate the lighter cut can bring the flash point to the desired value, the lighter cut can also be used in chemical industry as Virgin Naphtha or as feedstock for gasoline production [113]. Blending with conventional marine fuel can also be a cheaper alternative to full separation [149].

Another possible challenge for marine plastic-derived pyrolysis oil is the presence of olefins and aromatics. Unlike fossil-based oils, which mainly contain long chain paraffin, oil from plastic pyrolysis can contain a variety of components. Aromatic compounds within plastic-derived pyrolysis oil can originate from multiple sources. PS and PET have aromatic rings in their structure, which upon thermal degradation they release as mainly styrene and benzoic acid respectively [11,29,150]. PVC degradation also results mainly in aromatic oil [150]. Other possible sources of aromatic formation are the presence of glasses and metals with plastic waste feedstock and the Diels-Alder reaction pathways [29,131]. High aromatic content within the fuel is problematic and can cause engine performance issues and increased emissions of NO_X, unburned hydrocarbons, and particulates [14].

Less problematic than aromatic compounds are olefins, which indicate high PP concentration of waste plastic feedstock [140]. Due to the high reactivity of olefins, they can compromise fuel stability and increase the tendency to form gums and deposits [151,152]. The olefin content of a fuel is measured by the Bromine Number and is regulated under EN 590, the standard for automotive diesel, which imposes stricter limits compared to marine fuel standards [151]. The absence of this parameter in marine fuel standards suggests that olefin content is either less critical for marine fuels or inherently maintained within acceptable limits by other fuel quality requirements [116]. ISO 8217 introduces a parameter called Oxidation stability for distillate fuels, however no studies were found on the results of this test on plastic-derived pyrolysis oil.

To address quality challenges, purification and hydrogenation refining techniques may be applied. As a viable option, hydrotreatment of plastic-derived pyrolysis oil has been often proposed [151,153]. Steam cracking has also been proposed for virgin naphtha from fossil sources, municipal waste plastic pyrolysis and marine litter pyrolysis [140]. This study found that naphtha derived from marine litter had significantly lower olefin and aromatic content compared to naphtha from municipal plastic waste. This difference was attributed to the lower presence of PS and PP in marine litter plastics and the higher proportion of PE, which typically produces long-chain paraffins during pyrolysis. Coupled with the less stringent standards for marine fuels, it can be speculated that the aromatic and olefin content may not be a significant concern for marine fuels derived from marine litter plastic pyrolysis.

Depending on the feedstock used, different upgrading strategies may be identified. As mentioned in Section 3.2.2, nylon-6.6 generates water during the pyrolysis process: for this reason, dehydration process may be required [154]. Distillation unit can fit for purpose, as the formed water can be separated with the light cut [113]. When solid particles are present (e.g., including calcium and silicon), filtration unit should also be considered. Filtration techniques (e.g., mechanical filtration using filters and separators, as well as more advanced methods like centrifugation and coalescing) may also remove cokes from the liquid oil to improve the stability of the fuel [155]. Lastly, to ensure low final sodium content, fuel washing process may be required [156].

Other parameters of plastic-derived pyrolysis oil are mainly within the range of marine fuel standards and in some cases even better: e.g., the cetane index is generally higher than prescribed value of 40 [14,113]. Sulfur content is very low and often negligible, making fuel derived from marine litter plastics to potentially qualify as ultra-low sulfur fuel oil (ULSFO) [62,113]. These insights and results indicate that marine plastic-derived pyrolysis oil has significant potential as a fuel for the maritime sector. Although further analysis is required to assess its performance in engines and fuel distribution systems, existing evidence indicates that plastic-derived pyrolysis oil is broadly compatible with conventional diesel engines and fuel infrastructure, making it a viable candidate for blending with marine fuels or potentially serving as an alternative fuel.

The gaseous product of pyrolysis primarily consists of CO_2, CO, and light hydrocarbons, with occasional traces of hydrogen [11,29]. In fuel production, gas is considered the secondary product and the efforts are to minimize its production. However, this does not mean that it is an undesirable product. For marine litter pyrolysis 20 to 30 wt% gas yield can be expected, typically when moderate process parameters are applied [62,113]. Such gases are generally burned to provide the process energy All in all, evidences [29,126] allow us to assume that at scale the process results self-sustaining. Clearly process gas yield is heavily dependent on the feedstock and the process parameters. Due to the presence of PA, PVC, and salt contaminants, the pyrolysis process may generate nitrogenous and chlorinated compounds in both gas and liquid phases, requiring gas scrubbing and careful handling of residues to prevent environmental harm. This is particularly relevant before burning the gas for energy [113].

Another product of plastic pyrolysis is the solid residue left in the reactor, primarily consisting of carbonaceous char formed during the process and inorganic materials originally present in the feedstock [4,107]. The solid yield of plastic pyrolysis is generally low ranging from 1 to 10 wt% [157], and having calorific value of 9 to 18 MJ/kg [107,118,126], the solid part is usually burned along with gas to provide energy for the pyrolysis or it is landfilled [4,126]. In the pyrolysis of marine litter, the presence of salts, high levels of organic contamination, and the variability of polymer types can greatly increase the yield of solid residue compared to conventional mixed plastic pyrolysis [107,113,118]. Marine litter pyrolysis can generate more than 50 wt% solids when non-plastic materials dominate the feedstock [113]; however, solid yields typically range between 20 and 30 wt% under standard conditions [62,113,118]. Additionally, it is speculated that due to presence of inorganic materials with marine litter feedstock and usage of CaO (or any similar additives) the solids from marine litter pyrolysis have lower calorific value and are potentially contaminated with chlorine and other hazardous elements [139]. These characteristics significantly hinder the valorization of the solid fraction, potentially leaving landfilling as the only viable option. It may be possible to use solid products as additives in concretes [157], however further analysis is required to assess its impact on concrete properties and the concentration of hazardous elements.

3.3. End-use in shipping industry

Shipping sector is a crucial part of the global economy, handling 80 % of global trade by volume, and 70 % by value [158]. In 2015, the total fuel consumption in this sector was estimated to be 298 million tons, of which 72 % was residual fuels, also known as Heavy Fuel Oil (HFO) [15]. HFO is a low quality fuel, which often contains high concentrations of mineral pollutants such as sulfur and heavy metals and it results in high pollutant emissions of SO_X and NO_X [144]. In 2016, IMO's Marine Environment Protection Committee (MEPC) made a decision to lower the Sulphur content of marine fuels to 0.50 % starting from 1 January 2020 [158]. This action led to drastic changes in HFO uptake. Data on fuel consumption of ships of and above 5000 gross tonnage showed a sharp decrease of HFO consumption by ships, replaced by light fuel oil, and diesel/gas oil [159]. The adoption of sulfur cap law by IMO, and other relevant policies and initiatives at regional level, such as European Green Deal, promoted the transition to cleaner alternative fuels for maritime applications.

The shipping industry predominantly relies on internal combustion engines (ICE), which is supplied by petroleum-based fuels, with only a few exceptions [160]. The type of fuel is influenced by ship type and operational purpose [15]. Compared to sectors like aviation, maritime transport has greater flexibility in fuel selection and several alternative fuel options are already available [160]. However, the transition

Infrastructural

- Bunkering
- Availability
- Production capacity
- Competition from other end users

Technical

- Technology maturity
- Energy density
- Fuel standards
- Fuel stability
- Engine Compatibility

Economic

- Capital cost
- Fuel price
- Retrofitting costs

Environmental

- NO_x reduction
- SO_x reduction
- PM reduction
- GHG emission
- Fuel LCA

Fig. 2. Different dimensions involved in the transition to alternative fuel solutions for shipping sector.

to low-emission fuels faces significant challenges due to the long lifespan of ships. Additionally, decarbonization requires not only vessel modifications, such as fleet renewal or retrofitting, but also extensive infrastructure upgrades at ports and terminals.

To evaluate any alternative fuel for maritime sector, it is crucial to assess multiple factors beyond just technical aspects. Foretich et al. [144] evaluated various alternative shipping fuels using 20 criteria, assigning scores ranging from unfavorable to favorable. Similarly Prussi et al. [160] analyzed several alternative fuels utilizing 10 criteria. Moreover, Ren et al. also introduced 15 criteria for a sustainability assessment of alternative fuels for marine applications [161]. Analyzing every criteria in detail for marine plastic-derived pyrolysis oil is outside the scope of this study, nor information is available for each of these criteria. The studies mentioned previously, categorized their evaluation criteria into distinct groups, allowing for a structured assessment of alternative fuels [144,161]. The primary groups identified across the studies are Economic, Environmental, Technical, and Infrastructural [15,144,161]. While other group classifications, such as Socio-political, Safety, and Regulatory aspects, have also been reported, these four categories remain the most widely emphasized [15,144,160,161]. Fig. 2 summarize the criteria present in each of the main groups, and each are further discussed in the following text.

3.3.1. Infrastructural

For an alternative fuel to achieve widespread adoption among ships engaged in global trade, adequate bunkering infrastructure is required, since one of the main obstacles to introducing new fuels is the insufficient bunkering and concerns over their long-term supply [15]. The necessary infrastructure includes production capacity, storage facilities, fuel delivery, and combustion by ships [144]. One of the key benefits of marine plastic-derived pyrolysis oil is its strong resemblance to conventional marine fuels in terms of key properties and the possibility to be easily blended. It can be expected that marine plastic-derived pyrolysis oil can be used with minimal and possibly with no modifications to ship engines, fuel storage, or delivery systems at ports and terminals, therefore eliminating the need for specific infrastructure. The minimal or no of changes to the current infrastructure gives an advantage to marine plastic-derived pyrolysis oil compared to several other alternative marine fuel candidates. Moreover, it is likely that marine plastic-derived pyrolysis oil adhere to the same standards as conventional marine fuels, offering a better chance of adoption compared to fuels that lack standardization [144].

However, production capacity remains a significant challenge. Research on the pyrolysis of marine litter plastics is still in its early stages, therefore currently, no pilot or commercial plants exist to convert this waste into oil. Pyrolysis of general waste plastics is far more established, with most technology providers based in Europe: the plastic pyrolysis input capacity in EU in 2023 is 275 kt/year, with 63 kt/year of this capacity is used for fuels and energy [162]. However, for 2019, it was estimated that EU shipping consumption was approximately 48,000 kt/y [160]. Additionally, another major challenge of production is the availability of feedstock. The main feedstock of this fuel is marine litter, which is a waste. While in the earlier sections it was concluded that it is quite widespread around the seas, its concentration is not homogeneous and it is necessary to collect this waste, which creates a large uncertainty regarding its supply, thus a major barrier for its adoption [144].

Despite these major issues, marine plastic-derived pyrolysis oil can still be utilized in shipping sector. Marine plastic-derived pyrolysis oil could for instance fuel the marine litter cleanup boats. Marine litter cleanup operations can be particularly costly, ranging from 3.4 to 9.2 EUR/kg for waste removal from the sea [163]. Converting the collected plastic waste into marine plastic-derived pyrolysis oil could help offset operational costs and improve the economic feasibility of cleanup efforts.

3.3.2. Technical

Most aspects related to the technical evaluation of marine plastic-derived pyrolysis oil were covered in Section 3.2.2. In summary, plastic oil, after the separation of its lighter fraction, closely resembles conventional marine distillate fuel, allowing it to be used within existing regulatory frameworks, engines and fuel distribution systems with minimal or no modifications required. Another technical aspect that should be considered is the overall maturity of the plastic pyrolysis technology. While the number of commercial scale pyrolysis plants is still low and technology is not widespread, slow plastic pyrolysis is a well-established process with a solid technical foundation, rather than an emerging or experimental concept requiring fundamental research [162,164,165]. Among chemical conversion routes, plastic pyrolysis is the most mature and widely implemented process, with a TRL of 8–9 [104,166].

The type and configuration of reactor play a crucial role in plastic pyrolysis process since it has a direct impact on reaction rates and subsequently the yield of target products [12]. Multiple reactor types exist for plastic pyrolysis, each offering advantages and limitations [14]. Batch and semi-batch reactors are simple, easy to operate, and able to control different operating parameters [4,14]. However, the batch nature of process leads to product variability between runs, limited production, and high labor cost, making this type of reactor only suitable for lab or small-scale operations [4,14]. On the other hand, fluidized-bed reactors allow for continuous production, and can provide excellent heat and mass transfer, making them suitable for large-scale applications [12]. This type of reactor is considered the best option for both thermal and catalytic plastic pyrolysis, but its high capital costs makes them unsuitable for small-scale capacities [4,12,14]. Another group of reactors are rotary and screw kiln reactors have a simple design and operation and have a low capital cost [12,14]. These reactors are extensively used for treating waste streams and can handle mixed waste plastics with wide range of particle shapes and size distributions [12,14]. Nonetheless, these types of reactors require long residence time for plastic pyrolysis, and if the design is not optimal, it may lead to uneven heat distribution and limited temperature control [12,14].

Considering the characteristics of marine plastic waste, rotary and screw kiln reactors present a more practical option. Marine litter is a mixed waste stream with different size distributions and compositions. Fluidized-bed reactors can not handle large particle sizes, thus for marine litter they require extensive pretreatment [14]. In contrast, rotary kiln systems can tolerate larger and irregularly shaped particles, and their use in waste plastics pyrolysis is well documented [12,164]. Additionally, the high capital cost of fluidized-bed reactors requires a significant initial investment compared to rotary kilns. This is exacerbated by the variability of marine litter as a feedstock and for majority of areas it may not need large-scale process capacity.

3.3.3. Economic

Economic considerations are a key factor in selection of alternative fuels by ship owners. Regarding costs related to changes and modifications to the engines and ports infrastructure it is safe to assume that no significant expenses will be required for shipbuilders and port operators. The cost of marine litter collection varies widely depending on location, litter density, and cleanup methods, and can fluctuate from 0.035 to 31.98 $/kg of marine litter [163]. This variability can result in significantly higher feedstock costs. For comparison land-based waste plastic is reported to be between 0 and 0.6 $/kg [167]. However, the economic damages caused by marine litter to different industries such as fisheries and tourism should also be considered when discussing the costs of marine litter cleanup. Similarly, the benefits of removing marine litter highly depends on the location and can be as high as 55 $/kg of marine litter [163]. Furthermore, the costs of treating and disposing the marine litter via conventional ways should also be considered as well. This shows that unlike land-based waste plastics, marine litter does not have a fixed acquisition cost and should instead be evaluated within a broader cost-benefit framework that includes externalities regarding the removal of marine litter.

Determining capital costs of building pyrolysis plants and operational costs, which significantly contribute to the final fuel price is challenging. No studies were found on the topic of feasibility studies or techno-economic analysis (TEA) of pyrolysis of marine litter. However, there are numerous studies regarding TEA of land-based waste plastics, which can offer valuable insights. While marine litter poses unique challenges related to collection and contamination, its pyrolysis process follows broadly similar steps to those used for land-based plastic waste. TEA of waste plastic pyrolysis has identified feedstock price and plant operating capacity as the key factors determining the economic feasibility of the process. In a study Larrian et al. [168] found that a plastic pyrolysis plant for mixed plastics requires at least 70 kt per year could be economically feasible. In another study Yadav et al. [169] demonstrated that feedstock price of 0.6 $/kg results in the minimum selling price (MSP) of 2.18 $/kg for the naphtha product, which is four times higher than market virgin naphtha. In general, waste plastics that have undergone some degree of sorting or pretreatment tend to have a higher feedstock price [167]. Such rigorous separation is not intended for marine litter pyrolysis and given that this waste stream is highly unfavorable and of low value, a minimal or even zero feedstock cost can be expected. In such a scenario, Lubongo et al. [13] demonstrated that plastic pyrolysis process at 35 kt per year or 60 tons per day will be economically viable. Despite the possibility of having a plant with lower capacity, the capital cost of building a plant of such capacity is still high. The capital cost of a 35 kt per year plant was reported to be $22.8 million [13]; for a smaller plant with a capacity of 3.75 kt per year, a cost up to $10 million was evaluated [126]. The price of the produced oil heavily depends on the plant's capacity: Lubongo et al. [13] estimated a selling price of $300/ton. In the case of 3.75 kt per year, the minimum selling price (MSP) of $1277/ton or 1182 €/ton was defined [126]. It was also shown that increasing the capacity to 25 kt per year leads to a sharp decrease of MSP to $754/ton, or 698 €/ton, showcasing the effect of economy of scale [126]. Marine fuel prices vary over time and depend on the fuel type, grade and port location, typically ranging from $500/MT to $1000/MT [170]. This demonstrates that with large-scale plants it is possible to have plastic oil that is competitive with conventional fossil-based fuels.

Providing an accurate assessment of the economic feasibility of marine litter pyrolysis and the financial performance of its resulting oil in maritime sector remains challenging in the absence of a dedicated TEA for the process. A comprehensive TEA of marine litter pyrolysis should also consider the broader economic impacts, including the damage costs to industries like fisheries and tourism, which are directly affected by marine litter pollution [163]. Furthermore, the economic viability of plastic pyrolysis for fuel production highly depends on policies. Market outcomes can vary significantly depending on the presence or absence of supportive regulations, incentives, or environmental levies, further highlighting the need for a context-specific analysis.

3.3.4. Environmental

A key consideration in assessing alternative marine fuels is their ability to meet both current and future environmental regulations. As discussed in Section 3.2.2, marine plastic-derived pyrolysis oil has low to negligible sulfur content, enabling it to meet the strict sulfur emission requirements. Determining NO_X and carbon soot emissions is more challenging, since there are no dedicated studies on the engine performance of marine plastic-derived pyrolysis oil. Due to presence of PA some nitrogen based compounds does exist within the marine plastic-derived pyrolysis oil but their extent and level of emissions are unknown [125].

However, the major drawback of marine plastic-derived pyrolysis oil may be its greenhouse gases (GHG) emissions. The life cycle assessment (LCA) studies performed on pyrolysis for maritime [171] fuels suggest a significant potential for GHG savings offered by this pathway: upgraded pyrolysis oil can deliver significant GHG savings and this contribution is linearly dependent of its energy share when blended with standard Heavy Fuel Oil.

With respect to the specific case of the plastic derived oil, being a fossil-based feedstock may introduce specific concerns. Specifically the conventional plastic pyrolysis process itself has shown it has lower GHG emissions compared to incineration [167]. However, it is difficult to determine the impact of marine plastic-derived pyrolysis oil on environment without a well-to-tank based LCA, which considers emissions from waste collection, processing, and transportation and the proper counterfactual scenario. Additionally, the environmental impact of marine litter removal operations must be taken into account, as these activities mostly involve fuel consumption and emissions from collection vessels. At the same time, removing marine litter itself provides environmental benefits by reducing ocean pollution. These factors highlight both the necessity and complexity of conducting an LCA for marine litter pyrolysis, suggesting to consider marine litter derived oil as a transitional fuel suitable for promoting plastic recovery rather than a full option for sector decarbonization.

4. Discussion

The previous chapter focused on the characteristics of marine litter as a feedstock, its conversion into plastic oil via pyrolysis and the suitability of the resulting fuel for maritime applications. This chapter examines key aspects related to the recovery, collection, and efficient utilization of marine plastic waste for fuel production. Additionally, it outlines a potential system for organizing and optimizing the collection and processing of marine plastic waste, aiming to enhance both efficiency and accessibility.

4.1. Recovery of marine litter

As established in previous sections, large quantities of plastic exist in the form of marine litter in the seas. It is difficult to accurately estimate the overall amount of marine litter present in a location. However, estimates do exist. For example, it is estimated that over 1 million tons of plastics are currently present in the Mediterranean Sea, with approximately 229,000 tons of plastic waste entering the basin each year [172]. Pyrolysis of this waste can be beneficial but these litters must be removed first from the environment. Recovering marine litter is a challenging task, contributing to the persistence of this environmental issue. Various methods and technologies were introduced, with the majority of them investigated in the last decade [173]. Among these methods and technologies, river booms/barriers, sea cleaning vessels, and FFL are among the most frequently discussed and implemented approaches for marine litter removal [9,163,173]. Most of these technologies capture and remove surface litter, [173,174].

Fishing for Litter or FFL in short, is a scheme that encourages fishers to gather litter caught in their nets and deliver them to PRFs free of charge [91]. FFL program originally was implemented for North Sea and only recently have pilot schemes were carried out in a number of other countries including Italy, Slovenia, Croatia, Montenegro, and Greece [9]. FFL activity can be either active or passive. Passive FFL is carried out by fishers during day-to-day fishing activities with no financial incentives. On the other hand, in active FFL is specifically performed to remove litter and fishers are paid for this activity [175]. Regarding quantities, the Table 6 reports the performance of FFL initiatives organized through OSPAR [176].

Moreover, specific information was found for Netherlands. During the period of 2020–21, the scheme saw the highest-ever participation of fishing vessels, with a total of 137 joining it, while 756 tons of litter were collected, which was the largest quantity of annual litter. Between the years 2011 and 2021, the annual collection of litter amounted to an average of 381 tons, resulting in a total quantity of 4189 tons over the 11-year period [9]. In another study, which focused on the effectiveness of different solutions for cleaning floating litter, two fishing vessels, one operating 249 days in 2017 and 2018, and the other operating 102 days in 2017, gathered close to 45 tons of marine litter in south-east of the bay of Biscay [163]. Mistri et al. [90] investigated marine debris in the fishing grounds of the Northern Adriatic, collecting 6755 kg of marine litter using 14 stern trawlers over the course of 256 trawl surveys, covering an area of 265 km^2 in one year. Lastly, in a study aimed at estimating the potential of bottom trawl fleets to remove marine litter from the seabed along the Catalan Coast, it was determined that the fleet could potentially remove 237 ± 36 tonnes of marine litter annually. The maximum recorded value was 308 tonnes in 2020, while the minimum was 187 tonnes in 2019 [174].

All these studies and numbers indicate the variability of marine litter recovery by FFL. The value of recovered marine litter is influenced by several factors, including the fleet's size and capacity, the type of fishing operation, the extent of the covered area, pollution level of the target region, and the seasonal variability of marine litter [9,163,174]. These complexities make it challenging to predict recovery rates in FFL schemes.

Dedicated cleaning operations is another method of clearing and recovering marine litters. These operations can be carried out on beaches, port areas, near-shore area and open seas [177]. There is extensive data on the amounts of marine litter collected during these operations, however, reporting specific figures here would be impractical due to the significant variability in litter density across different locations. Nevertheless, Andrés et al. [163] showed that marine litter cleaning boats are economically more effective compared to fishing vessels in collecting marine litter. This was mainly attributed to higher operational costs, and cleaning boats ability to select areas with more litter density, while fishing boats only operated in designated fishing grounds. Regarding beach cleaning operations, they are generally cheaper, can be a great tool for awareness, and logistically less complicated [163,178].

When it comes to marine cleaning operations, funding is a major challenge. FFL scheme mostly relies on voluntary activities and private funding [9]. The costs of other cleaning activities and treatment of collected waste are typically covered by local public authorities [91,163]. Pyrolysis of marine litter can offer a potential solution to the challenges of funding and operational costs associated with marine waste management by generating value from recovered plastics.

4.2. Other possible waste streams for pyrolysis

In the previous sections, it was discussed that maritime sector requires large quantities of fuel to operate. Additionally, the availability of marine litter for marine fuel production via pyrolysis is highly variable and subject to significant uncertainty. To mitigate the possible disruption in the supply and ensure a constant production of fuel, alternative feedstock options should be considered. Within the marine environment boundaries, other polymer-based waste streams exist in the form of waste from operation of ships. A fraction of this waste is composed of plastics and, while this waste stream is not classified as marine litter, effective management and treatment of it is challenging and improper handling can directly contribute to the accumulation of marine litter [91,92].

Plastic waste can be generated in various types of vessels and commonly originates from domestic provisions and supplies used for on board operations [179]. The amount of plastic waste generation varies greatly from ships to ships. The majority of recorded data are between 0.001 and 0.008 m^3 per crew member per day, with an average of 0.006 m^3 per crew member per day [91,146,179]. Under MARPOL Annex V, disposal of this waste at sea is prohibited and ships should deliver them to PRFs. The waste plastics generated on board are either be stored separately and later delivered to PRF or it can be incinerated, and the resulting ashes treated as incinerator ash [179]. However, incineration is not often carried out due to the lack of expertise among ship crews to accurately assess the type of plastic they are handling and therefore chose not to incinerate plastic at all [179]. The plastic waste abroad are mostly kept separately, with plastics that have been in contact with food are often treated as separate waste stream [91,179]. Compactors are extensively utilized on board ships, especially ships with large amount of waste like cruise ships to minimize the overall volume of the waste. This is done to facilitate delivery to PRF since delivery to PRF is usually based on volume [179]. All seven types of plastics can be found in ship-generated waste, with their composition varying significantly depending on the ship's type and operations. While an exact breakdown of polymer composition is not available, it can be reasonably speculated that plastic waste onboard ships resemble domestic plastic waste [91].

A subgroup of ship generated waste is old disposed fishing gears. Fishing activities lead to the gradual wear and degradation of gear, necessitating regular maintenance and eventual replacement. The old and damaged fishing gear is generally discarded at the ports [91,103]. The end-of-life pathways for old fishing gears are recycling, landfill, and incineration. However, because fishing gear is composed of various plastic types and is laden with fish oil and rotten biomass, recycling it is challenging, leading most of it to be either landfilled or incinerated [91,92,103].

Ship-generated waste, including old fishing gear, is delivered to PRFs, which ensure its proper treatment and safe disposal [17]. Unfortunately, as highlighted by Meel et al. [91], PRFs invest in the collection, separation, and preparation of plastic waste for recycling only if the necessary infrastructure is readily available and the operation is financially viable; otherwise, the waste is either transferred to a third party for processing, incinerated, or sent to landfill. Plastic pyrolysis presents a viable solution for ship-generated waste. This waste stream can help offset potential shortages of marine litter, ensuring a stable and sustainable fuel supply with comparable quality. By converting these waste streams into valuable fuel, pyrolysis not only reduces reliance on landfill and incineration but can also provides an economic incentive for PRFs to invest in waste processing [91].

4.3. Network for producing marine fuel from marine litter

To build on the findings of this article, it is essential to propose a structured framework for integrating marine litter pyrolysis into maritime fuel production. Fig. 3 shows a possible network for production of marine fuel from marine litter. The marine litter is collected by fishers through passive fishing efforts and/or dedicated cleaning operations. Following MARPOL guidelines, these collected debris are delivered to PRFs [21,91]. Additionally, ship-generated plastic waste and old worn out fishing gears are also delivered to PRFs following the same

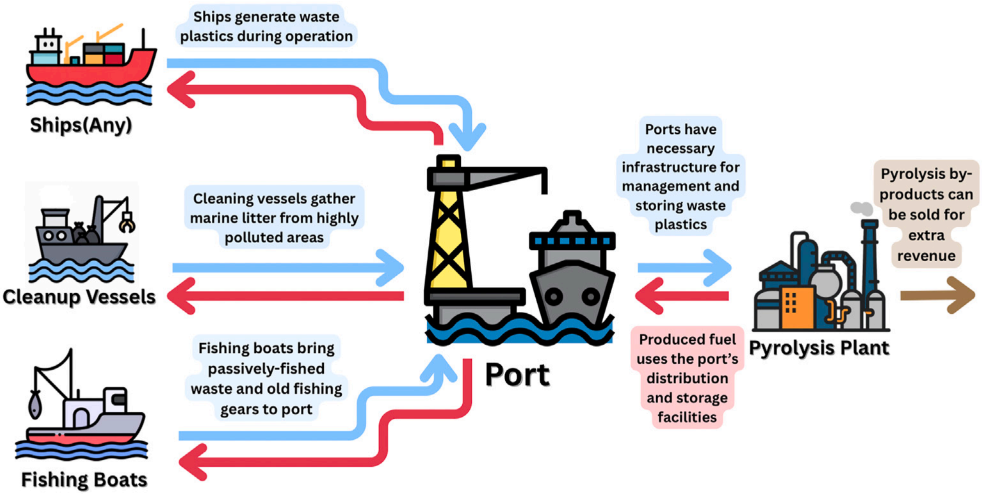

Fig. 3. Proposed system of waste plastic pyrolysis for the ports.

guidelines. These facilities can serve as centralized hubs where large quantities of plastic waste accumulate, making them strategic locations for both waste management and fuel supply operations.

By establishing an on-site pyrolysis plant within the port, the collected plastic waste can be efficiently converted into fuel, creating a self-sustaining system that aids waste management of the port and provides fuel for shipping sector. Ports are already equipped with infrastructure for waste handling, storage, sorting, and fuel distribution, which facilitates integration of this process. Establishment of these infrastructures aimed at dealing with wastes are already ensured for EU countries via directive 2019/883 [17]. Moreover, by placing the pyrolysis plant at the same location where waste is received and fuel is demanded, transportation costs and associated emissions can be significantly reduced. This localized approach enhances operational efficiency, minimizes environmental impact, and offers a practical pathway toward sustainable fuel production in the maritime industry. To the best of the authors' knowledge, this is the first work to propose a port-based integration model for waste plastic pyrolysis process as a dual waste-management and fuel supply solution.

5. Conclusions

This study delivers a comprehensive and multi-faceted assessment of marine litter pyrolysis as a viable pathway for producing alternative fuels, tailored for the maritime sector. The literature review revealed that, among the different types of marine litter, beached and floating plastics are identified as the most suitable feedstocks, for fuel production, due to their accessibility and composition. Notably, plastics account for 50 to 100 wt% of marine litter, with polyethylene (PE) and polypropylene (PP) being the dominant polymer types. These materials are particularly promising for pyrolysis, as they yield large quantities of oil that are well-suited for use as marine fuels.

The plastic pyrolysis process can yield 45 % to 60 % plastic oil. Literature indicates an optimal temperature range of 450 to 500 °C and a heating rate of 10 to 30 °C/min. The process also produces 20 % to 30 % gas with a high heating value, which is sufficient to meet the energy demands of the process, making it self-sustaining. The pyrolysis-derived oil demonstrates favorable properties, including high calorific value and compatibility with existing maritime infrastructure, requiring minimal upgrading to meet marine fuel standards.

However, the process faces limitations related to the availability and heterogeneity of marine litter, particularly seafloor debris, as well as the early-stage development of collection, pretreatment and processing infrastructure. Given its fossil-based origin and current production constraints, marine plastic-derived pyrolysis oil is best considered a transitional fuel—supporting pollution mitigation and supplementing low-sulfur fuel demand during the maritime energy transition.

To fully demonstrate the feasibility of the proposed approach, future studies should follow an integrated path, based on foundational research: investigate reaction mechanisms for target feedstock and processes (e.g., unwashed PA and PP into continuous intermedia pyrolyser). Tests should be performed at relevant scale and in continuous mode, rather than at lab scale and in batch mode. Moreover, establishing standardized protocols for feedstock sampling and characterisation, is needed, in particular in relation to the selected conversion process. Besides environmental assessment, investigating socio-economic integration allows capturing potential behavioural changes and demonstrate economic performance to accelerate adoption.

Additionally, to translate these opportunities into practical solutions, potential actions are required to support feedstock collection by employing scalable monitoring and enhancing waste-capture devices. Pilot specific sorting may be piloted, to separate the collected material in appropriate categories. Expanding feedstock sources is, in fact, crucial. To this, could be interesting to include ship-generated plastic waste and end-of-life fishing gear to enhance feedstock security and system scalability. Finally, support a sector transition toward a circular economy thinking, leveraging on regional and international regulatory frameworks.

To materialise the described potential, port reception facilities (PRFs) are strategic nodes for integrating pyrolysis units. Ports are energy and material hubs, allowing for, capitalizing on existing waste management and fuel distribution infrastructure.

Advancing this approach could offer synergistic benefits for marine pollution control and sustainable fuel production, particularly within regulated maritime zones.

CRediT authorship contribution statement

Sina Keyhani: Writing – original draft, Visualization, Formal analysis, Data curation. **Matteo Prussi:** Writing – review & editing, Validation, Supervision, Methodology. **David Chiaramonti:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Detailed seafloor litter data

See Table A.7.

Table A.7
Average density and composition of marine litter of different European regions.

Location	Monitoring method	Mean concentration by item	Mean concentration by weight	Composition by item	Composition by weight	Reference
Baltic Sea	Bottom Trawl	9.2 items/km^2	n.d.	55.6 % Plastics	n.d.	[102]
Gulf of Sant Jordi, Western Mediterranean	Bottom Trawl	130 items/km^2	n.d.	77.8 % Plastics	n.d.	[83]
Bay of Al Hoceima, Morocco, Mediterranean	Trawl Net	168 items/km^2	n.d.	57.15 % Plastics	n.d.	[180]
German Bight, Southern North Sea	Bottom Trawl	2473 ± 3116 items/km^2	n.d.	97.7 % Plastics	n.d.	[98]
Balearic Island, Spain, Western Mediterranean	Scuba diving	0–61.9 ± 105.7 items/100 m^2	n.d.	50 % Plastics	25 % Plastics	[52]
Gulf of Cadiz, South West Spain	Artisanal Trawl	24 ± 17 items/km^2	n.d.	73 % Plastics	n.d.	[181]
Ligurian continental shelf, Northwest Mediterranean	ROV	1524 items/ha	n.d.	8.3 % Plastics, 83 % ALDFG	n.d.	[99]
Lanzarote Island, Canary Islands, Atlantic Ocean	ROV (towed)	2122 ± 2464 items/km^2	n.d.	83.1 % Plastics	n.d.	[79]
Turkiye, Southern Black Sea Coast	Bottom Trawl	48,744.69 ± 7543.02 items/km^2	151.35 ± 14.04 kg/km^2	50 % to 100 % Plastics	n.d.	[182]
Northern Adriatic Sea	Bottom Trawl	n.d.	>20 kg/km^2	n.d.	17.4 % Plastics, 47.7 % ALDFG	[90]
Coast of Bejaia, Algeria, Mediterranean	Trawl	12,372.2–58,998 items/ha	509 kg/ha	n.d.	88 % Plastics	[78]
Coastal areas of Mediterranean Sea	Scuba diving	43.55 items/100 m^2	n.d.	54.5 % Plastics	n.d.	[183]
Iskender Bay, Turkiye, Eastern Mediterranean Sea	Trawl	450.94 ± 306.24 items/km^2	90.34 ± 53.47 kg/km^2	87 % Plastics	n.d.	[96]
Gulf of Cadiz, South West Spain	ROV	n.d.	n.d.	33 % Plastics	n.d.	[86]
Continental shelf of Northeastern Mediterranean Sea	Trawl	4241 ± 1333 items/km^2	368 ± 87 kg/km^2	72 % Plastics	n.d.	[184]
Algerian Coast, Mediterranean Sea	Bottom Trawl	373.04 items/km^2	262.89 kg/km^2	76 % Plastics	n.d.	[81]
North Sea and Celtic Sea	Bottom Trawl	2.2 ± 0.05 items/ha	n.d.	77 % to 92 % Plastics	n.d.	[185]
Ligurian Sea, Northwestern Mediterranean Sea	ROV	6140–38,560 items/km^2	n.d.	56.6 % Plastics	n.d.	[186]
Malta Islands	Bottom Trawl	0.93–2.29 items/km^2	n.d.	Plastics Dominant	n.d.	[187]
Italian Sea, Mediterranean Sea	ROV	0–120 items/100 m^2	n.d.	89.3 % Plastics	n.d.	[188]
Catalan Coast, Northwest Mediterranean Sea	Bottom Trawl	n.d.	5.35 ± 0.89–13.75 ± 3.25 kg/km^2	n.d.	64.2 % Plastics	[174]
Ermoupoli Bay, Syros Island, Aegean Sea	Towed Camera	211 items/ha	n.d.	n.d.	n.d.	[189]
Southern Tyrrhenian Sea, Mediterranean Sea	Bottom Trawl	128.1 ± 98.2 items/km^2	0.9 ± 0.8 kg/km^2	64 % Plastics	32 % Plastics	[77]
Turkish Coast, Mediterranean Sea	Scuba diving	10 items/km^2	13 kg/km^2	36 % Plastics	2 % Plastics	[87]
Calypso Deep, Ionian Sea	HOV	26,715 items/km^2	n.d.	88 % Plastics	n.d.	[101]
Central Eastern Adriatic Sea	Scuba diving	0.2 ± 0.24 items/m^2	0.06 ± 0.07 kg/m^2	38 % to 78 % Plastics	20 % to 50 % Plastics	[88]
Aeolian Archipelago, Western Mediterranean Sea	ROV	0.57 ± 0.08 items/100 m^2	n.d.	79.7 % Plastics	n.d.	[82]
Sardinian Channel, Mediterranean Sea	Bottom Trawl	167 ± 150 items/km^2	104 ± 261 kg/km^2	66.8 % Plastics	9.5 % Plastics	[190]
Germany, Tunisia, and Egypt port areas	Underwater Camera	0.28 (Germany), 1.63 (North Africa) items/m^2	n.d.	74 % Plastics	n.d.	[191]
Gulf of Policastro, Central Mediterranean Sea	Bottom Trawl	651.12 ± 130.61 items/km^2	n.d.	93 % Plastics	n.d.	[97]
North Sea and Baltic Sea	Bottom Trawl	9.6 ± 4.75 (Baltic Sea), 70.65 ± 38.7 (North Sea) items/km^2	n.d.	94.2 % (North Sea), 62.2 % (Baltic Sea) Plastics	n.d.	[94]
Deep sea of Azores, North Atlantic	ROV, Towed Camera, HOV	113 ± 310 items/km^2	n.d.	83 % ALDFG (mostly fishing lines)	n.d.	[95]

(*continued on next page*)

Table A.7 *(continued)*

Location	Monitoring method	Mean concentration by item	Mean concentration by weight	Composition by item	Composition by weight	Reference
Sardinia Island, Mediterranean Sea	Trawl	29.8 ± 1.22 items/km^2	9.1 ± 1.96 kg/km^2	67 % Plastics	62 % Plastics	[192]
Boka Kotorska, Montenegro Southern Adriatic Sea	Scuba diving	3 ± 1.28 items/100 m^2	0.503 ± 0.29 kg/100 m^2	46.91 % Plastics	33.92 % Plastics	[193]
Cap de Creus, Northwestern Mediterranean Sea	ROV	110 items/ha	n.d.	n.d.	n.d.	[105]
Balearic Island, Spain, Western Mediterranean Sea	Bottom Trawl	n.d.	1.39 ± 0.13 kg/km^2	n.d.	24.56 % Plastics	[194]
Southern Black Sea shelf	Bottom Trawl	460.70 ± 99.71 items/km^2	80.68 ±48.06 kg/km^2	69.03 % Plastics	16.73 % Plastics	[36]
Levantine basin, Southeastern Mediterranean Sea	Bottom Trawl	115 ± 108 (Shallow), 2885 ± 3397 (Deep) items/km^2	11.9 ± 9.4 to 83.9 ± 123.3 kg/km^2	86–89 % Plastics	n.d.	[195]
Southernmost North and Black Sea	Camera	526.8 (Baltic Sea), 305.1 (North Sea) items/km^2	n.d.	42 % (Baltic Sea), 74 % (North Sea) Plastics	n.d.	[196]
Strait of Sicily, Mediterranean Sea	Bottom Trawl	79.6 ± 3.6 items/km^2	n.d.	58 % Plastics	n.d.	[85]

Data availability

No data was used for the research described in the article.

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