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Review

The problem of small-scale marine oil spills discharged by unattributable vessels: A review

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Abstract: Oil pollution is one of the most conspicuous forms of damage to the marine environment. It can be divided into two categories: large-scale and small-scale spills. Considerable research has been conducted on large-scale spills, including investigations into the damage caused, the methods of remediation employed, the compensation paid, and the reasons for a sharp decrease in the number of major oil spills during the last 20 years. However, very little attention has been paid to small-scale spills, leaving largely unresearched the reasons for their continued occurrence, the damage they cause, and the lack of compensation paid out for them. Because the number of large-scale marine oil spills has greatly reduced in recent years, there may be a perception that the problem of marine oil spills has been broadly brought under control. However, this would be to ignore the issue of small-scale spills, which have not decreased and are causing severe problems in coastal areas. The perpetrators of these small-scale spills are very difficult to identify, so they invariably escape detection and thereby avoid having to pay for the clean-up and damages costs caused by their actions. The main aim of this review paper is to draw attention to the lack of research into this unsatisfactory situation. The paper describes the scale and type of damage caused by small-scale spills; analyzes the problem of identifying unattributable polluters; considers ways of remediating oil spills; and evaluates current procedures for obtaining compensation for clean-up operations. Given the escalating frequency of these small-scale spills and their profound impact on marine ecosystems and vulnerable communities, it is imperative that researchers, policymakers, and stakeholders prioritize the development of effective strategies to address this pressing issue. The time to act is now, as the health of our coastlines and the livelihoods of countless individuals depend on our ability to confront the challenges posed by small-scale oil spills.

Keywords: small-scale marine oil spills; polluter pays principle; traceability; remediation; compensation

1. Introduction

The literature on marine oil pollution is extensive, focusing particularly on the environmental damage it causes [1]. Researchers have discovered that oil pollution can be divided into two categories: natural and man-made [2]. Natural oil spills originate from reservoirs and volcanic activities in the deep ocean. Man-made oil spills arise from oil tanker mishaps, deliberate discharges by vessels at sea, oil transportation procedures, operations at oil refineries, oil extraction activities, and petroleum loading processes [1]. The main mode of marine pollution by crude oil is attributed to man-made activities [3]. One study found there is an annual global man-made influx of approximately six million tonnes of oil into the marine environment, comprising various hydrocarbons including crude oil [4]. A significant number of these oil spills are discharged by oil tankers and other vessels that dump not only crude oil and refined petroleum products and their by-products but also oily refuse or wastewater [2]. Studies have estimated that 810,000 tonnes of oily bilge waste and sludge by commercial shipping fleets are released annually into the oceans [5–7].

As scientists have demonstrated, this is a serious threat to the marine environment because the toxicity of petroleum hydrocarbons damages natural habitats of marine flora and fauna and has negative impacts on fisheries, seawater desalination installations, and coastal amenities such as tourist attractions, beaches, and harbors [8]. Marine oil pollution therefore threatens livelihoods, homes, businesses, and communities' economic, social, and environmental well-being [9], causing significant problems for coastal states across the world [10]. The Exxon Valdez oil spill of 1989 serves as a compelling example to underscore the devastating impact of oil spills. When the oil tanker struck a reef in Alaska's Prince William Sound, it released approximately 11 million gallons of crude oil into the environment, causing catastrophic damage. The spill led to widespread harm to local wildlife, including sea otters, seals, and bird species, while inflicting long-term ecological damage on coastal habitats. Economically, the disaster disrupted the fishing industry and affected communities dependent on tourism and natural resources [11].

In the literature, there is an important distinction made between large-scale and small-scale marine oil spills. Large-scale spills are accidental, resulting from navigational errors such as collisions or groundings [12]. The vessels involved are mainly oil tankers that leak their cargo; they are readily identifiable, and compensation for clean-up and loss of livelihood is usually obtained from the ships' owners [13,14]. Catastrophic consequences of large-scale spills have attracted massive global attention and considerable scientific investigation and have cost vessel owners millions of dollars in compensation [2]. This has led to a concerted effort to prevent their future occurrence by, for instance, building oil tankers with double hulls and increasing regulations, as a result of which the number of large-scale spills has decreased sharply in recent years [15]. It would be incorrect, however, to believe that the issue of large-scale marine oil spills has been completely resolved: there are deficiencies in current technological tools and legal frameworks which highlight the necessity for continued vigilance in halting oil pollution from large-scale spills [16]: a number of large-scale oil spills still occur worldwide, inflicting serious, if periodic, damage on marine ecosystems, wildlife, and coastal communities [1].

By contrast to large-scale spills, most small-scale spills are deliberate discharges of oily sludge and bilge water [17] that occur during routine tank-cleaning operations [18]. When the heavy fuel oil that powers oil tankers, cargo and container ships is burned, it produces an oily sludge that leaks from machinery and drains down and accumulates in the bilge tanks (located at the lowest part of a ship) [19]. The contents of the bilge tanks are stored on board until they can be discharged. Between each trip, tankers are required to clean out their tanks, but substantial amounts of sludgy waste are illicitly but routinely evacuated from them while at sea [20]. Some owners and tanker operators illegally install pipes to bypass the ship's oily water separator and pump oily water directly into the ocean.

Carpenter [21] reported that on a global scale, such operational discharges from ships contribute approximately 45% of the total annual discharge of oil from maritime activities. Additional illegalities associated with these violations include falsification of records, tampering with monitoring systems, and the obstruction of investigations [22]. The waste oil products are dumped into the sea to avoid the time and cost of legal disposal in ports [20,23,24]. It is estimated that oily water separator and disposal fees at port can cost an owner 80,000–220,000 US$ annually, depending on the ship's size, age, number of days at sea, and level of maintenance. This can equate to 5%–12% of a ship's operating costs [25].

Marine oil spills, whether large-scale or small-scale, differ significantly in their characteristics, impacts, and the mechanisms available to address them. Large-scale spills, exceeding seven tonnes and resulting from incidents like tanker accidents or platform failures, are more easily traceable using technologies such as satellite imagery and chemical fingerprinting [26]. These spills benefit from established compensation frameworks, including the International Oil Pollution Compensation (IOPC) Fund and Protection and Indemnity (P&I) Clubs, which provide financial remediation to affected areas [27].

In contrast, small-scale spills, typically under seven tonnes, arise from clandestine discharges during routine operations, such as bilge water disposal. These spills are harder to detect and trace, leaving affected communities without compensation under existing frameworks [28]. While large-scale spills cause immediate and visible ecological damage, their economic impacts are often alleviated through compensation [29]. Small-scale spills, however, lead to cumulative, long-term damage, disproportionately affecting coastal communities reliant on fishing and tourism [30], and rarely attract compensation (see **Table 1**).

Table 1. Summary of the impacts of large-scale and small-scale oil spills.

Spill Type	Examples of Areas Affected	Ecological Damage	Additional Impacts
Large-Scale Spills	The Exxon Valdez oil spill affected 1300 miles of shoreline in Alaska, which occurred on 24 March 1989.	• Extensive harm to seabirds, marine mammals, and fish. • Destruction of habitats such as coral reefs and mangroves. • Long-term biodiversity loss.	• Economic disruption to fisheries and tourism. • Persistent hydrocarbons prolong recovery times. • Public health issues.
Small-Scale Spills	The Bouchard No. 120 oil spill, which occurred on 27 April 2003, involved a tanker and affected coastal regions primarily in Long Island Sound (USA), impacting both New York and Connecticut shorelines.	• Oil can contaminate the feathers of seabirds, shorebirds and marine mammals. • Coastal habitats such as mangroves, salt marshes, tidal flats and coral reefs can be severely impacted. • Water quality toxicity can be increased. • Can cause socio-economic damage.	• Cumulative effects when frequent. • Disruptions to small-scale fisheries and local biodiversity. • Challenges in cleanup.

Source: Compiled by the lead co-author.

The literature on small-scale marine oil spills is less extensive than for large-scale spills [8], but researchers maintain that the number of small-scale spills is considerably larger than the number of large-scale spills and poses a continuous threat to coastal areas [31]. Moreover, unlike the number of large-scale spills, the number of small-scale spills is not decreasing but may be increasing [32]. Small-scale marine oil spills are conventionally defined as less than seven tonnes [33], but even one tonne of oil may spread out to cover an area of 12 km^2 with 1 mm thickness. This means that a small-scale spill may cover an area on the sea surface up to 80 km^2 and will be potentially visible from space (for example on radar/SAR image), or visually from an elevated shore or ship [34].

Small-scale spills are clandestine, often carried out in darkness, not easily traceable to particular vessels, and invariably escape claims for compensation [35]. They are deemed unattributable spills [36], and their effects on coastal habitats can be severe, damaging marine ecosystems including flora and fauna and coral reefs, and destroying the livelihoods of fishers, divers, and tourist workers [9]. Unattributable small-scale spills can have a disproportionate impact on marginalized communities who rely on fishing resources for their livelihoods [37]. Certain regions are more prone to small-scale oil spills than others because of high shipping traffic and extensive oil exploration activities [38]. For instance, regions like the Gulf of Mexico and the North Sea are hotspots for shipping and oil extraction, leading to increased risks of small-scale spills [39,40].

However, little attention has been devoted by scholars to the problem of unattributable small-scale marine oil spills, and the present study aims to draw attention to this deficiency, focusing on the three key elements of the issue—traceability, remediation, and compensation.

2. Methods and materials

The literature research for data for this review paper used four academic databases to identify peer-reviewed articles, conference papers, and other relevant publications: Google Scholar, ScienceDirect, JSTOR, and Google. Search terms such as ‘marine oil spills’, ‘recent unattributable oil spills’, ‘small-scale oil pollution’ and ‘compensation for oil spills’ were employed to retrieve pertinent literature. In addition to academic publications, items in grey literature such as government reports, non-governmental organization (NGO) publications, and policy documents were sought, including reports from the International Oil Pollution Compensation Fund (IOPC). All relevant literature was filed in a reference management software (EndNote) to facilitate easy citation and retrieval. A synthesis of the literature was then prepared, highlighting key findings, trends, and gaps in the existing research. Three main themes emerged from this synthesis: traceability, remediation, and compensation.

3. Results

The data reveal that approximately 37% of annual oil discharges from maritime activities are attributed to operational discharges, primarily involving small-scale spills during routine ship operations [41]. Notably, the International Tanker Owners Pollution Federation Limited (ITOPF) reports that small and medium-sized spills constitute 95% of all documented incidents [42]. Various studies highlight the estimated frequency of small-scale spills, with one reporting an average of 1815 illegal waste oil discharges annually from 1974 to 2015 [43,44] and another suggesting around 3000 occurrences in European waters each year [45]. In U.S. waters alone, thousands of oil spills are reported annually, with the majority being small-scale events such as those occurring during ship refueling [46]. **Table 2** shows the frequency of medium- to large-scale oil spills that occurred between 1970 and 2023 [47,19].

Table 2. The frequency of oil tanker medium and large-scale spills between 1970 and 2023.

Years in decade range	Medium scale oil spills (up to 700 tonnes)	Large scale oil spills (above 700 tonnes)
1970–1980	543	245
1981–1990	360	94
1991–2000	281	77
2001–2010	149	32
2011–2020	45	18
2021–2023	22	5

Source: [47,19].

Table 3 lists examples of the worst marine oil spills in the world during the last 50 years, all of which were readily identifiable.

Table 3. Major oil spill disasters caused by tankers at sea.

Year	Ship Name	Ship Flag	Oil Spillage (tonnes)	Location
1967	Torrey Canyon	Liberia	119,000	English Channel
1972	Sea Star	South Korea	115,000	Sea of Oman
1976	Urquiola	Spain	100,000	La Coruna, Spain
1978	Amoco Cadiz	Liberia	223,000	English Channel
1979	Atlantic Empress	Liberia	287,000	Tobago, West Indies
1979	Independenta	Romania	95,000	Bosphorus, Turkey
1980	Irenes Serenade	Greece	100,000	Navarino Bay, Greece
1983	Castillo De Bellver	Spain	252,000	Saldanha Bay, South Africa
1988	Odyssey	Liberia	132,000	Nova Scotia, Canada
1989	Exxon Valdez	United States	37,000	Prince William Sound in Alaska
1991	Abt Summer	Netherlands	260,000	Angola
1991	Haven	Spain	144,000	Genoa, Italy
1993	Braer	Liberia	85,000	Shetland Islands, UK
1996	Sea Empress	Liberia	72,000	Milford Haven, UK
1999	Erika	Malta	20,000	Northwest France
2002	Prestige	Bahamas	63,000	Northwest Spain
2007	Hebei Spirit	China	11,000	South Korea
2018	Sanchi	Panama	113,000	Shanghai, China

Source: [19,48,49].

The online literature search revealed hotspots of small-scale oil spills across the world. Two papers were particularly helpful in providing this global perspective.

Moroni et al. [31] highlighted the environmental impacts of small-scale oil spills on several marine environments, including the Eastern Mediterranean Sea, the North Sea, the Venice Lagoon, and the Gulf of Finland. Asif et al. [50] identified environmental impacts of small-scale oil spills on shorelines in the Gulf of Mexico, Norilsk in Russia, the Northeastern USA, and the Mediterranean Sea [51]. Morandin and O'Hara [52] found evidence of thousands of small-scale spills in the Gulf of Mexico due to high levels of maritime traffic and offshore drilling activities [53]. Hyder et al. 's [33] use of aerial surveys in the North Sea revealed 500 to 1200 small-scale spills annually. Onyena and Sam [54] detected frequent small-scale spills in the Niger Delta. Liu et al. [55] found illegal oil discharges from vessels in the Bohai Sea, China. Warnock et al. [56] reported unattributed tar balls on Caribbean beaches. Svejkovsky et al. [57] noted small-scale oil spills in California. Saleem et al. [58] and the Times of Oman [59] commented on small-scale oil spills without known sources along Musandam beaches in Oman.

Oil pollution is a global concern due to the toxic nature of petroleum hydrocarbons, which harm both aquatic and terrestrial ecosystems [60]. Oil discharges, particularly from tankers, cause serious damage to marine environments, including sensitive areas, as oil spreads quickly due to its lower density compared to seawater [61]. Furthermore, the cleanup of toxic hydrocarbons, which can persist for years, poses significant challenges [62]. Over time, oil spills alter biological communities, leading to the decline of dominant species like crustaceans and mollusks [63,64]. Oil pollution often lingers in rocky crevices, gravel, and mussel beds [11] and is particularly damaging to coral reefs, where oil slicks destroy coral eggs and larvae, resulting in slow recovery rates [65,66].

The effects of oil spills on wildlife are profound. Seabirds, which nest near coasts, are especially vulnerable to oil spills, as oil-fouled plumage disrupts thermoregulation, leading to stress, mortality, and reproductive losses [67]. Similarly, fish are impacted by oil ingestion through gills, affecting growth, metabolism, and reproduction [66,68]. Oil spills also harm eggs, larvae, and habitats such as coral reefs and mangroves, where less sensitive species often replace damaged species [69,70]. Additionally, oil spills increase disease risks, reduce the lifespan of flora and fauna, and raise human health concerns, such as respiratory diseases caused by air quality emissions [60,11]. Sediment and water quality also degrade due to oil pollution [71,72].

In the Arabian Gulf, studies highlight severe oil pollution impacts, including tar ball accumulation on Omani shores and oil slick dispersal caused by illegal ballast water discharge [73]. Oil spills in some Gulf areas have caused significant mangrove damage, with nearly half affected and one-third dying [73,66]. Coral reefs in the region are also under threat, with more than 85% classified as at risk, according to the World Resources Institute [74].

3.1. Traceability

Traceability in the context of marine oil spills refers to the ability to identify the source of the spill and hold the responsible parties accountable for the resulting environmental, economic and social damage [75]. The literature on traceability primarily focuses on large-scale oil spills, where the sources are usually readily identifiable due to the scale and visibility of the incidents. Studies have documented various methods for tracing oil spills, including satellite imagery, chemical fingerprinting, and forensic analysis of oil samples. For instance, research has demonstrated that chemical fingerprinting can differentiate between various oil types, aiding in the identification of spill sources [15].

However, these techniques are primarily designed for large-scale spills, where the responsible parties can be relatively easily identified. Traceability of small-scale spills is much more difficult for two reasons. First, the very existence of many small-scale spills is hard to establish. The precise number of unattributable small-scale spills is unknown because there is no definitive mechanism for recording them. The reporting of small spills (less than seven tonnes) is unreliable, and data are often incomplete [76,77]. Many small-scale spills, especially those below the seven-tonnes threshold, go unreported due to inadequate monitoring requirements [78], despite the fact that they are now a substantial source of marine oil pollution [79]. While large-scale catastrophic events attract substantial scrutiny, minor spills have received considerably less attention, and this lack of information has led to their exclusion from some assessments of marine oil pollution [80].

Unsurprisingly, therefore, estimates of the number of small-scale spills vary widely. For example, Su et al. [77] calculated that over 80% of spills recorded since 1970 were small: between 1974 and 2015, there was an average per annum of 1815 illegal waste oil discharges under 7 tonnes. Another researcher claimed that 7500 small-scale spills were detected in European waters in 2019 [35], while a third said there are about 3000 occurrences of such dumping in European waters per year [45]. According to the International Tanker Owners Pollution Federation Limited ([19] ITOPF), small and medium-sized spills make up 95% of all incidents documented. A study conducted by the National Oceanic and Atmospheric Administration [81,76] found that small-scale spills, less than seven tonnes, have accounted for 80% of total oil spill incidents since 1970.

The second reason why small-scale spills are so hard to trace is because they can occur in the sea without immediate or identifiable sources [82]. These spills are sometimes referred to as ‘unattributable’, ‘mystery’ or ‘ghost’ spills because their source is unknown or difficult to determine [83]. By the time oil from a small spill reaches a beach, it may be chemically altered by dissolution and/or evaporation [84]. Polluting oil dispersal, low boiling components, evaporation and several environmental hazards will drastically alter the footprints of oil contaminants, compounding the difficulty of identifying the pollution source [85,86]. Finding out which small-scale oil spills are caused by which vessels has hitherto proved well-nigh impossible [87]. Moreover, as Sankaran [8] noted, small-scale spills are characterized by their covert nature, making them particularly difficult to attribute to their perpetrators.

Several critical gaps remain in the literature on oil spill traceability. First, there is a lack of research focused specifically on small-scale unattributable spills, as most studies tend to concentrate on larger incidents [31]. This oversight leaves a void in understanding how to trace smaller spills that occur frequently and often go unreported. Second, the impact of existing regulatory frameworks on traceability is underexplored. There is a pressing need for research on how current policies can be adapted or strengthened to address the challenges posed by small-scale untraceable spills. Third, the absence of localized case studies limits our understanding of the specific traceability issues faced by coastal communities. There is a need for research into interdisciplinary collaboration, investment in technology, and robust policy frameworks to improve our ability to trace and manage unknown-source oil spills effectively.

The 2019 mystery oil spill in Brazil serves as a compelling case study in addressing traceability issues. This event impacted over 2000 km of Brazil's coastline, causing extensive ecological damage to coral reefs, mangroves, and marine wildlife, while severely affecting the local fishing and tourism industries [88]. Despite its large scale, the spill's source remains unidentified, attributed to 'ghost ships' or untraceable vessels. Clean-up efforts largely fell to local communities and volunteers due to the absence of a clearly liable party. The incident revealed critical weaknesses in Brazil's national oil spill response framework and highlighted the limitations of international compensation mechanisms for unattributable spills. It underscores the pressing need for enhanced monitoring systems, stricter enforcement of MARPOL regulations, and the creation of a global fund to address such incidents effectively.

Emerging technologies like AI and satellite imagery are revolutionizing oil spill detection. Real-time systems leveraging Synthetic Aperture Radar (SAR) and machine learning algorithms can identify oil slicks and predict their spread with remarkable accuracy [89]. A case study in the Bohai Sea, China, demonstrated the efficacy of these technologies in tracing illegal oil discharges from vessels, showcasing their potential to improve traceability and response times [55]. These advances offer significant benefits, including enhanced detection of small-scale spills, even in remote areas, and faster response times, mitigating environmental and economic impacts. However, challenges such as high implementation costs, limited accessibility for developing countries, and the need for international collaboration to standardize data sharing remain significant barriers to widespread adoption of these technologies.

3.2. Remediation

Remediation refers to the processes and strategies employed to clean up and restore environments affected by marine oil spills. The literature on remediation primarily focuses on large-scale oil spills, where extensive research has been conducted on various clean-up techniques, their effectiveness, and the ecological recovery of affected areas [90,91]. The three main remediation methods are mechanical recovery, chemical dispersants, and natural attenuation.

Tewari and Sirvaiya [92] explained that mechanical remediation involves physical methods to manage and mitigate oil spills, focusing on the containment and recovery of oil from surface waters or affected soils to reduce immediate environmental impacts. Mechanical recovery methods are widely employed for the containment, recovery, and removal of spilled oil from the marine environment [93]. One such method involves deploying physical barriers, such as booms, which are filled with air for buoyancy, to contain and prevent the spread of oils [93]. **Figure 1** illustrates the deployment of booms around oil spills in Oman. Different types of booms—fence, curtain, and fire-resistant—are designed to suit various conditions, optimizing their effectiveness. Skimmers, which use oleophilic belts, disks, or chains to remove oil from the water's surface and transfer it to storage tanks for recycling, work best in still waters and with thick oil layers [94,95]. Skimmers can be either vessels equipped with specialized equipment or floating devices designed to collect oil [96].

Another mechanical method of remediation is sorbent materials that absorb oil. Absorbent pads, booms, and specially designed polymers are deployed to soak up the oil while repelling water, and they are made from both natural options like peat and hay and synthetic polyethylene-based materials with high absorption capacities [97]. These materials can be effective in removing oil from the water surface or shoreline. A third mechanical technique is in situ burning, which involves igniting the oil on the water surface and allowing it to burn in a controlled manner [98]. This method can be effective for removing large quantities of oil quickly, though it is only suitable for certain types of oil and specific spill scenarios because it can generate air pollution and produce residue that requires further clean-up. Mechanical remediation is a critical first line of defense in spill response. By physically managing spills, mechanical remediation limits environmental damage and paves the way for further remediation processes.

Figure 1. Deployment of booms around oil spills in Oman (source: Oman's Environment Authority).

In the literature, researchers have shown that the efficacy of mechanical methods in oil spill clean-up depends on five factors. The first factor is timing: a swift deployment of equipment and resources is essential to contain and recover oil promptly, preventing its spread and reducing the complexity of mitigation efforts [99]. The second factor is spill characteristics: the type of oil and its viscosity play a crucial role in determining the effectiveness of mechanical methods [100]. The third factor is environmental conditions: weather, currents, and waves exert considerable influence on the efficiency of mechanical methods. Adverse conditions, such as rough seas and strong winds, can impede containment and skimming efforts [101]. The fourth factor is scale: the magnitude and extent of the oil spill significantly influence the feasibility and efficiency of mechanical methods. The larger the spill, the more difficult and expensive it is to remediate [102]. The fifth factor is cost: mechanical methods can be costly and logistically challenging to deploy, particularly for small-scale spills that may not warrant the employment of extensive resources required for mechanical recovery [102].

Chemical dispersant methods are another man-made approach to the removal of oil spills. Dispersants are chemicals that are applied by aircraft or vessels to the oil slick to divide the oil into smaller droplets that can mix with the water and be subject to natural degradation processes by exposure to microbial and chemical breakdown in the water column [97,103]. Dispersants are most effective when applied during the initial stages of an oil spill, as they can prevent the formation of a thick surface slick and reduce the spread of oil [96]. They are particularly useful for offshore spills where mechanical methods, such as skimming, are challenging because of distance or environmental conditions [76]. Their advantages include rapid response capabilities, protection of sensitive habitats by reducing prolonged oil exposure, and cost-effectiveness compared to expensive mechanical recovery efforts.

However, the use of dispersants may be less effective on heavy or weathered oil—i.e., oil that has undergone physical and chemical changes after being spilled into the environment. Over time, exposure to elements such as sunlight, wind, and water causes lighter components of the oil to evaporate, while heavier components may become more viscous and less mobile. Weathered oil can be more challenging to disperse and clean up compared to fresh oil, as its altered properties can affect the effectiveness of remediation techniques. Moreover, the use of dispersants comes with other limitations, including potential toxic effects on marine life [104,105]. They may have harmful effects on marine life, particularly on sensitive species such as fish and invertebrates. Additionally, their efficiency can be severely compromised by adverse weather conditions, such as high winds and rough seas, which can limit their contact time with the oil [106]. They also require strict adherence to regulatory guidelines to minimize ecological harm [107]. While chemical dispersants are essential in mitigating oil spill impacts, therefore, their application requires careful evaluation of environmental conditions and potential risks [92].

Natural attenuation methods, or leaving oil spills to nature, are where natural processes are relied upon to remove and degrade the spilled oil [108]. When oil is spilled into the environment, it undergoes physical and chemical processes that contribute to its breakdown: wave action and wind can cause the oil to disperse, spread, and evaporate. Additionally, exposure to sunlight and air can initiate chemical reactions that lead to the degradation of certain components of the oil [109]. Microorganisms, particularly bacteria and fungi, can play an important role in the natural biodegradation of oil [110]. Naturally occurring microbial populations can utilize the spilled oil as a source of energy and carbon, breaking it down into simpler compounds through metabolic processes. These natural biodegradation processes are influenced by temperature, nutrient availability, oxygen levels, and the type of oil spilled [111].

Although natural attenuation aligns with ecological principles and minimizes human intervention, it requires extensive monitoring to ensure effectiveness in mitigating potential long-term impacts. Its efficacy depends on oil type, environmental conditions, and the availability of nutrients essential for microbial activity. In some cases, the oil may persist in the environment for extended periods, leading to prolonged ecological damage. Das and Janardhan [112] reported how 58.7% of a spill that occurred on the southeastern coast of Mauritius in 2020 and was left to natural attenuation beached along the shorelines of Mauritius, while only 31.4% evaporated, and 7.9% naturally dispersed. This method is not, therefore, suitable for all spill scenarios, particularly in sensitive ecosystems where immediate action is necessary [113]. While it is a sustainable and low-cost approach, its slower pace may limit its applicability [92].

Mechanical and chemical methods of remediation are primarily researched for and applied to large-scale spills [114]. There is very little published research on the remediation of small-scale spills. This is understandable since mechanical recovery and chemical dispersants are logistically difficult and costly to apply and may be judged an excessive deployment of expensive resources to deal with a multitude of scattered and comparatively small hazards [115]. In general, therefore, natural attenuation is the default method employed to deal with small-scale spills. In many cases, natural attenuation is an adequate mode of remediation for small-scale spills because natural forces dilute and separate small-scale oil spills to the point that they are absorbed by the marine ecosystem and prevented from reaching coastal areas [116].

However, in many other cases, natural attenuation fails to break up small-scale spills, and they inflict damage on both the marine ecology and the socio-economic systems along the coastline. In these circumstances, the work of remediation is generally carried out by local residents and stakeholders by physically removing oil spills at their own expenditure of time and effort. This is an unsatisfactory situation because it breaches the polluter pays principle [117].

Gaps in the literature on remediation include the lack of research on ecologically tailored remediation methods—approaches that consider the specific characteristics of different ecosystems, such as mangroves, coral reefs, or coastal wetlands, which may require bespoke strategies for effective cleanup. Additionally, there is limited data on the long-term ecological impacts of remediation techniques like chemical dispersants, in-situ burning, and bioremediation, especially in sensitive environments. Another significant gap lies in comprehensive studies comparing the effectiveness of emerging technologies, such as bio-sorbents. This lack of comparative data makes it challenging to determine the most effective solutions for specific types of oil or environmental conditions.

Furthermore, the literature lacks a focus on remediation scalability and real-world application, with many studies confined to laboratory settings rather than field trials in diverse environmental conditions. There is also a need for integrated frameworks that connect spill traceability and remediation, enabling response teams to choose remediation methods based on the spill's origin and composition. Finally, the socioeconomic and health impacts of different remediation approaches on local communities remain understudied. Given that some methods may have unintended consequences for human health or local economies (such as fisheries and tourism), more research in this area would allow for more balanced, informed decision-making when selecting remediation methods. All these gaps in the literature on remediation are especially evident in the case of small-scale unattributable spills.

3.3. Compensation

In the literature, the issue of compensation for marine oil spills concentrates on large-scale spills. Because those spills are generally accidental, highly visible, and readily attributable to particular vessels, compensation is normally obtained directly from the spillers [15] or from their insurers. Compensation claims are made up of two elements: clean-up costs and recompense for loss of livelihoods [118]. Clean-up costs depend on a range of complex factors, including the volume of oil spilled, the nature of the spilled oil product, the location, the time of the spillage, the clean-up techniques, the weather and sea conditions, the transportation costs, the costs of disposal at landfill sites, administrative support costs, and the cost of hiring experts to analyse damage [21,119]. Recompense for loss of livelihoods generally entails payments to fishers, divers and other coastal users for damage to equipment and lost days at sea [120].

As scholars have shown, there are international and national mechanisms in place to ensure compensation is paid to impacted countries for clean-up costs and livelihood losses for large-scale marine oil spills [121]. International mechanisms are divided into two types—intergovernmental and the private sector. The most important intergovernmental organisation is the MARPOL Convention under which the International Oil Pollution Compensation (IOPC) fund scheme [122] was established in 1992 with the help of the International Maritime Organization (IMO) to provide compensation to victims of damage caused by oil spills from identified vessels [123–126]. The IOPC fund is financed by levies taken from the oil beneficiaries in member states who receive annually more than 150,000 tonnes of crude or heavy fuel oil [127,125]. However, victims of large-scale oil spills can have problems in getting full compensation via the IOPC fund due to the limits of liability in international conventions [125,128]. Soto-Oñate and Caballero [129] reported that in instances of large-scale spills like the Prestige, the Hebei Spirit, or the Nakhodka, the compensation provided did not sufficiently cover the permissible costs outlined in the convention resulting from the spills.

The 1992 Fund is currently managing claims and recourse actions related to 14 ongoing incidents, which are displayed on the map below (see **Figure 2**). Detailed reports for each active incident, along with several recently closed cases, are available for viewing or downloading as PDFs. Since its inception in 1978, the IOPC Funds have addressed 158 incidents and disbursed approximately £770 million as of 30 June 2024.

Figure 2. Map of oil spill incidents (source: IOPC Fund website).

With regard to the private sector, Protection and Indemnity (P&I) Clubs are not-for-profit private organizations established by ship owners and operators who collectively underwrite third-party liability risks of their businesses and handle compensation claims [130]. P&I clubs offer an alternative option to the IOPC fund for oil companies to insure themselves against expensive liability claims arising from accidental oil spills. P&I clubs insure most tankers operating in international trade, providing insurance coverage of up to US$ 1 billion for compensation for damage by oil pollution from laden tankers as well as tankers in ballast [131].

However, international organisations are much more effective in obtaining compensation for large-scale attributable spills [132] than they are in obtaining compensation for small-scale unattributable spills [123,125,133,49]. Neither intergovernmental nor private sector organizations explicitly cover unattributable oil spills: Both the IOPC fund and P&I clubs require complainants to provide evidence that the damage was caused by a tanker or other vessel. In the case of spills whose source is not known, it is hard to demonstrate that the damage resulted from a tanker or other vessel [134,135]. It is true that in two exceptional circumstances the IOPCF paid compensation for marine oil pollution from unidentified sources. These are the "Incident in the United Kingdom" in 2002 [136] and the "Incident in Bahrain" in 2003 [137]. In these two cases, claimants proved that the spills did not originate from port facilities or production platforms but rather likely resulted from tankers transporting crude oil. But in general, the requirement of proof that a tanker caused the spill is a serious obstacle for countries because this is extremely difficult to demonstrate, especially in the case of small-scale spills.

There are, however, five countries—Canada, the USA, China, New Zealand, and Finland—that have developed their own national compensation frameworks that include explicit provisions for both traceable and untraceable spills. In Canada, the Ship-source Oil Pollution Fund (SOPF), which is funded by a tax levied by the

Canadian government on all vessels, whether working, abandoned, derelict, or wrecked, pays out compensation for every kind of marine oil pollution incident in Canadian waters, from both known and unknown sources [138]. It reimburses claimants for a comprehensive range of costs, including clean-up and restoration of the environment. In the USA, the Oil Spill Liability Trust Fund (OSLTF) is a federal fund established by the government in 1986 and administered by the US Coastguard [139,140]. Under the 1990 Oil Pollution Act (OPA) of 1990, during 2004–2008 the OSLTF provided a total of US$ 16,189,470 compensation for six cases of unattributable spills [141]. China’s 2012 Compensation Regime for Vessel Source Oil Pollution operates the Vessel-Source Oil Pollution Compensation Fund (CVOPCF) funded by organizations that receive crude and heavy fuel oil [132,142]. The CVOPCF uses these funds to compensate victims of oil pollution from both known and unknown sources.

In New Zealand, the New Zealand Oil Pollution Fund, which is governed by the 1994 Maritime Transport Act, operates under the polluter pay principle for cost recovery in oil pollution incidents across the country’s EEZ. According to Read [143], the New Zealand Fund makes every effort to obtain payment from the spiller, but it acknowledges it is not always possible to identify a responsible party (see also [144]. De Cola [145] reported that in the case of unattributable spills, the Fund covers the costs of response. The Fund is financed through the Oil Pollution Levy [146] which is imposed on ships (both domestic and foreign vessels) and oil facilities. The fund is underwritten by the government, and any payment that exceeds its current balance is provided by the government. The Finnish Oil Pollution Compensation Fund pays out compensation for oil spills on land and sea when the party that caused the spill is unknown or when the guilty party is unable to pay the costs [147].

Compensation frameworks provided by these five countries play a pivotal role in addressing both traceable and unattributable oil spills. However, their implementation faces significant challenges that limit their effectiveness, particularly in cases of small-scale and unattributable spills. These challenges include lack of public awareness and accessibility; complicated and stringent documentation requirements; funding limitations such as compensation caps; legal and regulatory constraints such as strict liability limitations and jurisdictional discrepancies in cross-border cases; and lack of accountability mechanisms, which often places the burden of cleanup on local communities [148].

There are four gaps in the literature on compensation. First, there is a lack of research on compensation for small-scale marine oil spills. Most studies concentrate on large-scale spills, leaving a deficiency in our understanding of the compensation mechanisms available for small-scale spills. Second, there is a gap in the literature on compensation mechanisms available for unattributable marine oil spills: most researchers have focused almost exclusively on compensation for attributable spills. Third, no researchers have identified the problems faced by marginalized people suffering from the damage caused by small-scale and unattributable marine oil spills. Fourth, researchers have not studied what new compensation mechanisms could be put in place to give redress to sufferers of small-scale unattributable marine oil spills. For example, tailored compensation mechanisms, such as community-based programs or simplified claims processes or the establishment of a pooled fund or micro-insurance scheme specifically for small-scale unattributable spills, could be evaluated for their effective implementation in marginalized communities.

4. Discussion

The management of small-scale unattributable marine oil spills faces numerous challenges including bureaucratic hurdles, enforcement issues, and legal loopholes, which together hinder effective response and accountability. On bureaucracy, regulatory frameworks often lack specificity regarding small-scale spills, creating inefficiencies and delays as agencies with overlapping jurisdictions struggle to coordinate actions. The absence of standardized reporting mechanisms exacerbates the issue, leaving many spills unreported and untracked. Enforcement is another critical weakness, as the covert nature of small-scale spills and limited resources for monitoring and investigation result in a lack of accountability and a culture of impunity among offenders. Legal frameworks further complicate the situation by failing to adequately address the nuances of small-scale pollution. Legal definitions of liability often exclude small-scale discharges, leaving victims without access to compensation. Additionally, complex legal processes deter affected communities from seeking justice, particularly when they lack the resources or expertise to navigate the system.

The review underscores the need for a multifaceted approach to addressing the challenges of small-scale marine oil spills, highlighting critical gaps in legal frameworks, economic assessments, and social justice considerations. On legal frameworks, the study reveals that current international maritime laws inadequately address unattributable spills. Conventions like the International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC) offer a foundation for spill response but lack specific provisions for small-scale incidents. To enhance accountability and response, there is a need for clearer liability definitions, collective responsibility mechanisms for shipping companies, and standardized cross-border reporting and monitoring practices, potentially via new treaties or amendments to existing ones.

On economic assessments, the paper emphasizes the importance of understanding the broader costs of small-scale spills. Beyond immediate cleanup expenses, long-term economic impacts on communities dependent on fishing and tourism are often overlooked. A comprehensive cost-benefit analysis comparing these economic impacts with the expense of preventive measures such as advanced monitoring technologies and stricter enforcement shows the potential for significant long-term savings. Social justice considerations focus on the disproportionate impacts of small-scale spills on marginalized communities. These spills violate the concept of environmental justice, exacerbating existing inequalities for those reliant on marine resources, yet barriers to remediation and compensation persist. A robust social justice framework is needed to prioritize the rights and needs of these communities, ensuring their inclusion in spill response strategies and long-term recovery efforts.

On the last point, it is worth noting that communities can fruitfully work together with government agencies in cleaning up spills. Naggea and Miller [149] emphasized the pivotal role of local stakeholders in the remediation of small-scale oil spills, highlighting the significance of their efforts through notable case studies. For example, in the Huntington Beach spill of 2021, local residents worked alongside government agencies and non-governmental organizations to contain and clean up 78 tons of crude oil within 10 days, showcasing the value of community involvement in rapid response. Similarly, during the 2020 MV Wakashio spill in Mauritius, which released 1000 tonnes of oil, local communities, volunteers, and environmental groups collaborated with authorities to mitigate environmental damage and protect the fragile marine ecosystem. These cases demonstrate that local stakeholders, with their deep understanding of the environment and commitment to their communities, are essential in ensuring effective and timely responses to oil spills, ultimately minimizing ecological and societal harm.

5. Conclusion

In this review paper, we have examined the current literature on three issues arising out of the occurrence of marine oil spills—traceability, remediation, and compensation. We have found that researchers have investigated these three issues at length in relation to large-scale and traceable spills, but hardly at all in relation to small-scale and untraceable spills. As a result, there are many gaps in our understanding of the existence and impact of these small spills and of attempts to deal with them. We have identified some of these gaps, and we urge researchers to take an interest in filling them because the problem of small-scale unattributable oil spills is neither trivial nor diminishing.

In particular, we highlight four areas of concern that warrant deeper research. First, regulatory frameworks lack specificity regarding small-scale spills, creating inefficiencies and delays as agencies with overlapping jurisdictions struggle to coordinate actions. Second, the absence of standardized reporting mechanisms leaves many spills unreported and untracked. Third, enforcement is weak, and the covert nature of small-scale spills and limited resources for monitoring and investigation result in a lack of accountability and a culture of impunity among offenders. Fourth, complex legal processes deter affected communities from seeking justice, particularly when they lack the resources or expertise to navigate the system.

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