



Assessment of oil contamination from the El Grillo shipwreck in Seydisfjörður, Iceland: implications for aquaculture

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Abstract

This study evaluates current and historical oil contamination from the El Grillo shipwreck in Seydisfjörður, Iceland, to assess potential risks for planned aquaculture operations. The British oil tanker El Grillo has been lying on the seabed at 30–40 m depth since being sunk during a German attack on 10 February 1944, with ongoing concerns about oil leakage. Sediment and seawater samples are collected along a transect from the wreck and analyzed for polycyclic aromatic hydrocarbons (PAHs), heavy metals, and total organic carbon (TOC). The results indicate that all measured PAH values in both sediment and seawater are below the reference threshold values for environmental concern. PAH compounds in sediment samples decreased with distance from the wreck and exhibited pyrogenic signatures characteristic of burned oil. Heavy metals also show a decreasing trend from the shipwreck, with copper and zinc above threshold levels, but lower than probable effect levels. Cadmium and lead are below the threshold levels at all sampling stations. The findings suggest that there has been ongoing natural breakdown of leaked oil during the 80 years since the attack, and therefore, the proposed fish farming operations in Seydisfjörður would not be adversely affected by contamination from the El Grillo shipwreck.

Keywords El Grillo · Seydisfjörður · Oil contamination · PAHs · Heavy metals · TOC · Sediment · Seawater · Aquaculture · Environmental impact

Introduction

The global transition toward environmental sustainability has accelerated in recent years, driven by the urgent need to reduce dependence on fossil fuels and mitigate their environmental impacts. This transition encompasses both the

development of clean energy technologies and the implementation of advanced remediation strategies to address legacy contamination from industrial activities. Understanding the intersection between renewable energy innovation and environmental remediation is essential for achieving comprehensive sustainability goals.

Renewable energy technologies have advanced significantly in recent years, with photovoltaic systems representing one of the most promising pathways toward decarbonization. Innovations in dye-sensitized solar cells have expanded the potential applications of solar energy harvesting; for example, flexible photoanodes based on TiO₂ nanotubes grown on titanium foil, combined with metal-free organic dyes and iodine-free electrolytes, have demonstrated the feasibility of low-cost, non-polluting solar cells suitable for portable and wearable electronic applications (Pugliese et al. 2014). Complementary technologies for energy conservation have also progressed substantially, with photoelectrochromic smart windows offering viable solutions for reducing building energy consumption. Recent developments in platinum-free devices utilizing graphene nanoplatelets as counter electrodes and copper-based redox electrolytes have

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achieved exceptional long-term stability exceeding 400 days, overcoming previous limitations related to corrosion and the use of expensive critical raw materials (Lavagna et al. 2021).

Beyond energy generation and conservation, sustainable process technologies are essential for reducing the environmental footprint of industrial activities. The production of ammonia for fertilizers exemplifies this challenge, as the conventional Haber-Bosch process generates approximately 1.5 tonnes of CO₂-equivalent emissions per tonne of ammonia produced while consuming significant energy. Electrochemical approaches to ammonia synthesis, particularly lithium-mediated nitrogen reduction in aprotic media, have emerged as promising alternatives capable of enabling decentralized production using renewable energy sources (Mangini et al. 2025). Similarly, advanced oxidation processes have been developed to remediate contamination from agricultural and industrial activities. Photo-Fenton processes enhanced with humic-like substances extracted from urban wastes have demonstrated effectiveness for treating scarcely soluble pollutants such as fungicides, with the added benefit of valorizing waste materials while extending process applicability to circumneutral pH conditions suitable for in situ treatments (Caram et al. 2018).

Despite these technological advances toward sustainability, the legacy environmental impacts of the fossil fuel era persist, particularly in marine environments where historical infrastructure continues to pose contamination risks. Marine shipwrecks represent significant long-term environmental concerns due to their potential to release petroleum hydrocarbons, heavy metals, and other hazardous substances into surrounding ecosystems over extended time periods (Michel et al. 2005; Brennan, 2024). While modern remediation technologies offer solutions for controlled industrial waste streams, submerged wrecks present unique challenges due to their inaccessibility, structural degradation, and the continuous nature of contaminant release. The intersection of historical pollution sources with contemporary marine resource development, particularly aquaculture expansion, necessitates comprehensive assessment of contamination levels and potential ecological risks.

The *El Grillo*, a British oil supply vessel with a capacity of approximately 9000 tons, was sunk during a German air raid on February 10, 1944, in Seyðisfjörður, eastern Iceland. The wreck currently lies at a depth of 30–40 m (Iceland Review 2019) and has been continuously releasing oil into the surrounding marine environment for over 80 years. The site has gained renewed attention following proposals to establish a 10,000-ton salmon aquaculture facility in proximity to the wreck location.

Aquaculture operations are particularly sensitive to petroleum contamination, as fish and other marine organisms can accumulate hydrocarbons through multiple exposure pathways. Previous studies have documented adverse effects

of oil exposure on salmonid species, including impacts on growth, reproduction, immune function, and overall survival (Bernhoft et al. 2017; Brette et al. 2014; Forsberg et al. 2012; Hylland et al. 2008; Meador et al. 1995, 2006; Olsen et al. 2015). The proximity of the proposed aquaculture site to a continuously leaking oil source raises significant concerns regarding product quality and food safety.

Polycyclic aromatic hydrocarbons (PAHs) are among the most concerning contaminants associated with petroleum releases. These compounds are characterized by their environmental persistence, tendency to bioaccumulate in marine food webs, and well-documented carcinogenic and mutagenic properties (Yunker et al. 2002; Balmer et al. 2019). PAHs have been shown to cause cardiovascular dysfunction, developmental abnormalities, and reduced fitness in fish populations exposed to contaminated sediments. The ratio of specific PAH compounds can provide valuable information regarding contamination sources and weathering processes.

In addition to organic contaminants, heavy metals represent another category of pollutants commonly associated with shipwreck sites. Vessels typically contain various metallic components and cargo that can release toxic elements including lead, mercury, cadmium, and zinc into surrounding sediments. Total organic carbon (TOC) content serves as an important indicator of organic matter accumulation and can influence the binding, transport, and bioavailability of both organic and inorganic contaminants. Assessment of heavy metal concentrations in relation to established food safety guidelines is essential for evaluating potential risks to aquaculture operations and human consumers.

The present study represents the first formal scientific investigation of environmental contamination associated with the *El Grillo* shipwreck. The primary objectives were to (1) characterize PAH concentrations and composition in sediments at various distances from the wreck site; (2) determine heavy metal concentrations and assess potential ecological risks; (3) evaluate TOC distribution patterns; and (4) assess the suitability of the area for aquaculture development based on comparison with established environmental quality guidelines. These findings provide essential baseline data for informed decision-making regarding marine resource utilization in the vicinity of this historical pollution source.

Materials and methods

Study area

Seydisfjordur is a narrow fjord located on the eastern coast of Iceland (65° 16' N, 13° 59' W), approximately 17 km in length with a maximum depth of about 200 m. The fjord has relatively limited industrial activity, with a small town with a population around 700 located at its head. The *El Grillo*

wreck lies at a depth of 30–40 m near the town of Seyðisfjörður (Fig. 1).

Sampling design and collection

Samples of bottom sediment and seawater were collected at five stations along a north–south transect from the El Grillo shipwreck in January 2024. The sampling stations were positioned at increasing distances from the wreck: 100 m, 1 km, 2 km, 4 km, and 8 km, with exact coordinates shown in Table 1. At each distance, multiple samples were taken to ensure comprehensive coverage.

Bottom sediment samples (designated B1–B9) were collected using a Van Veen bottom grab with an area of 250 cm². Seawater samples (designated V1–V10) were taken using a water sampler at 50 cm below the surface. Grain size analysis was performed on a subset of sediment samples (designated with an asterisk in Table 1).

All samples were frozen immediately after collection in 500 ml containers with screw caps (Cole-Parmer, 99540-42) and glass bottles with screw caps (Cole-Parmer 99540-33)

before being transported to the Department of Pharmacology and Toxicology at the University of Iceland for analysis. Sampling was conducted from the service vessel FDA Finn.

Analysis of heavy metals and TOC in sediment

Heavy metals including lead (Pb), cadmium (Cd), iron (Fe), copper (Cu), and zinc (Zn) were analyzed in sediment samples following DIN EN ISO 17294-2 (E29): 2017-01 standards. Total organic carbon (TOC) was determined according to DIN EN 15936: 2012-11(AN,L8: Ver.A; FG,F5:Ver.B). Analysis was conducted at Syni laboratory, Iceland (www.syni.is).

Analysis of PAHs in sediment and seawater

Sediment PAH analysis

For sediment samples, approximately 3–4 g of each sample (1 g of the reference sample) were extracted. Recovery

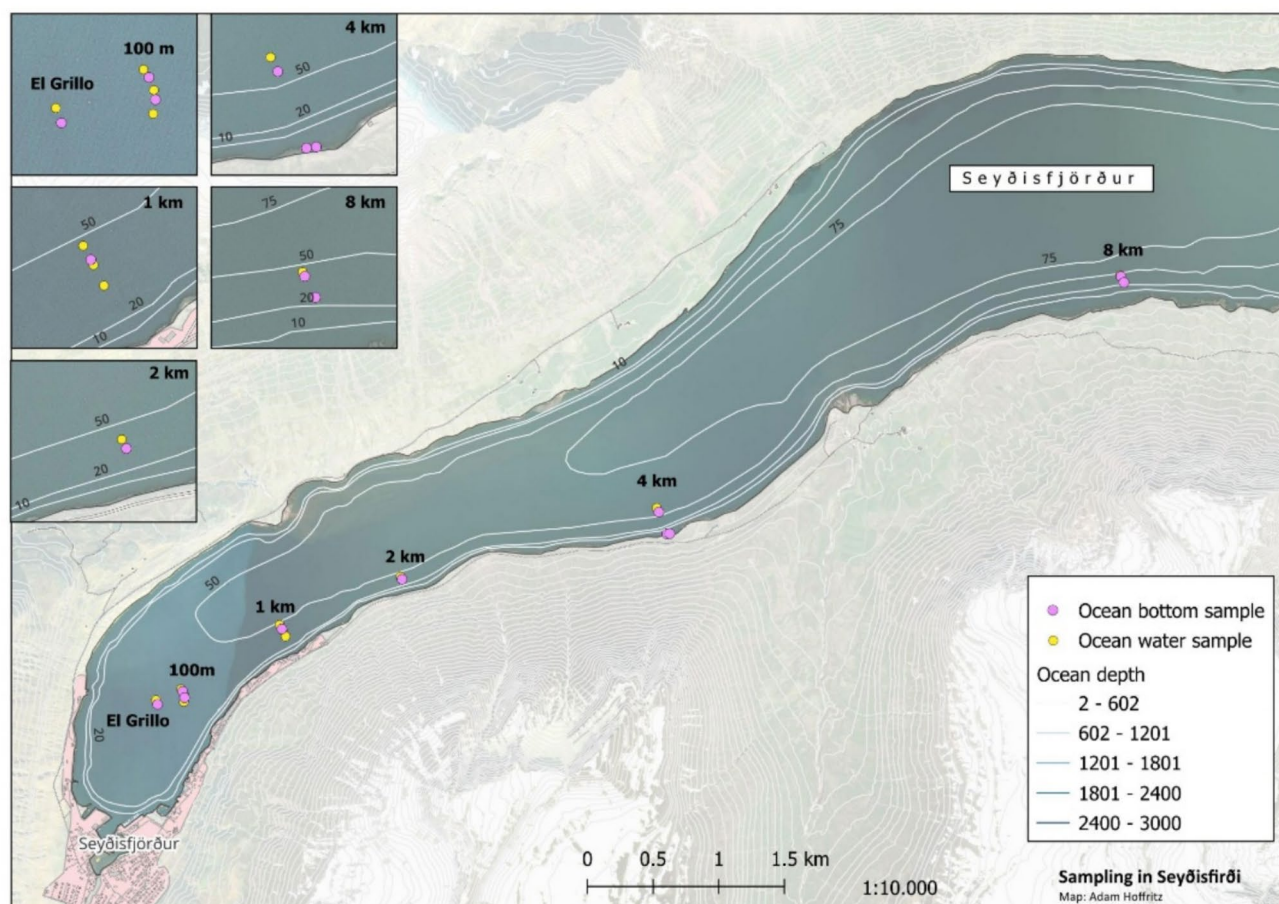


Fig. 1 Overview of Seyðisfjörður on the eastern coast of Iceland, showing the position of the El Grillo shipwreck. Sampling points are indicated with B1–B9 (yellow, sediment) and V1–V10 (pink, water) (Adam Hoffritz, 2025)

Table 1 Coordinates of sampling points at different sampling locations in Seydisfjörður. Sampling points marked with an asterisk (*) were analyzed for grain size

Distance from wreck	Station	North	West	Depth meters	Bottom type
1 m	V1	65° 16.306199'	13° 59.795582'	43	Black sand
100 m	V2	65° 16.318012'	13° 59.517996'	43	-
100 m	V3	65° 16.290371'	13° 59.525312'	-	-
100 m	V4	65° 16.343013'	13° 59.542334'	-	-
1 m	B1*	65° 16.288295'	13° 59.783285'	43	-
100 m	B2	65° 16.333308'	13° 59.528689'	47	-
100 m	B3	65° 16.306741'	13° 59.515903'	-	-
1 km	V5	65° 16.549749'	13° 58.506309'	45	-
1 km	V6	65° 16.573327'	13° 58.531011'	-	-
1 km	V7	65° 16.524740'	13° 58.481569'	-	-
1 km	B4*	65° 16.556198'	13° 58.512534'	-	-
2 km	V8	65° 16.731324'	13° 57.311911'	43	-
2 km	B5*	65° 16.720162'	13° 57.300833'	60	-
4 km	V9	65° 16.927697'	13° 54.758608'	60	-
4 km	B6*	65° 16.910349'	13° 54.741605'	-	-
4 km	B7	65° 16.918243'	13° 54.678896'	-	-
8 km	V10	65° 17.724252'	13° 50.048484'	44	-
8 km	B8*	65° 17.719035'	13° 50.04329'	-	-
8 km	B9	65° 17.693336'	13° 50.018174'	-	-

standards (PCB-116 and PCB-198) were added before samples were placed in an ultrasonic bath for 5 min and tumbled for 1 h with acetone. Subsequently, an acetone/hexane mixture was added, samples were sonicated for 5 min and tumbled for 2 h. Organic solvents were then evaporated, and the residue dissolved in 1 ml of isooctane containing an internal standard (TCN). Dry weight of sediment samples was determined by drying in a fume hood for 48 h.

The samples were cleaned with KOH in ethanol and analyzed using gas chromatography. A Thermo Scientific Trace 1300 gas chromatograph with an HP-5MS column (25 m, 0.200 mm id, 0.33 µm film) coupled to an ISQ LT mass detector and Thermo autosampler was used for analysis. Chromeleon software from Thermo was used for data processing.

For quantification, standards of all 16 PAH compounds (Accustandard, USA) diluted in isooctane with added internal standard of TCN were used.

Seven standard mixtures were prepared in the concentration range of 2.5–500 pg/µl, containing: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(ghi)perylene. The quantification and confirmation ions used for the analysis are listed in Table 2.

Table 2 Quantification and confirmation ions used for PAH analysis by GC-MS

Compound	Quantification ion	Confirmation ion
Naphthalene	128	127
Acenaphthylene	152	153
Acenaphthene	153	154
Fluorene	166	165
Phenanthrene	178	176
Anthracene	178	176
Fluoranthene	202	200
Pyrene	202	200
Benz(a)anthracene	228	226
Chrysene	228	226
Benzo(b)fluoranthene	252	250
Benzo(k)fluoranthene	252	250
Benzo(a)pyrene	252	250
Indeno(1,2,3-cd)pyrene	276	274
Dibenz(a,h)anthracene	278	276
Benzo(ghi)perylene	276	274
TCN (internal standard)	266	264
PCB-116 (recovery standard)	326	328
PCB-198 (recovery standard)	430	428

Seawater PAH analysis

For seawater samples, the entire sample volume (0.78–1 L) was extracted with hexane after adding recovery standards (PCB116 and PCB198), after which the hexane was evaporated to 200 µl before adding an internal standard (TCN). Samples were cleaned using KOH in ethanol and analyzed using the same gas chromatographic method as for sediment samples.

Quality control

Quality control was performed using certified marine sediment reference material from Quasimeme (QPH140MS) with known concentrations of all 16 PAH compounds. Table 3 shows the measured concentrations in the reference sample along with the deviation from the true value. Recovery rates were in the range of 60–70% for sediment samples and 95–105% for water samples.

Blank samples were analyzed alongside both sediment and water samples using the same procedures and materials. Any compound detected in blanks was subtracted from all samples to account for background contamination.

Detection limits (LOQ) for sediment samples were estimated at approximately 0.51 ng/g dry weight, with an uncertainty of $\pm 20\%$. For water samples, detection limits (LOD) were approximately 1 ng/l (0.001 ppb).

Table 3 Measured concentrations in the reference sample (Quasimeme QPH140MS) compared to assigned values. Z-scores between -2 and $+2$ are considered satisfactory analytical performance

Compound	Reference value (µg/kg)	Measured value (µg/kg)	Z-score
Naphthalene	20.3	19.6	−0.27
Acenaphthylene	2.42	1.99	−1.42
Acenaphthene	2.20	2.24	0.16
Fluorene	6.60	6.45	−0.18
Phenanthrene	43.7	43.4	−0.05
Anthracene	4.45	4.40	−0.08
Fluoranthene	42.5	41.7	−0.15
Pyrene	32.9	31.8	−0.28
Benz(a)anthracene	22.1	21.5	−0.21
Chrysene	24.6	23.6	−0.33
Benzo(b)fluoranthene	100	99.9	−0.03
Benzo(k)fluoranthene	38.9	39.7	0.16
Benzo(a)pyrene	27.6	26.7	−0.27
Indeno(1,2,3-cd)pyrene	115	113	−0.11
Dibenz(a,h)anthracene	17.4	17.3	−0.07
Benzo(ghi)perylene	90.1	88.3	−0.16
Sum	591	582	−0.12

Data analysis and environmental quality assessment

Results were evaluated according to Norwegian sediment quality criteria as outlined by Bakke et al. (2010), which classify contamination levels into five categories:

- Class I: Background levels.
- Class II: Good condition.
- Class III: Upper limit of natural background.
- Class IV: High levels.
- Class V: Very high levels.

PAH diagnostic ratios, including anthracene/(anthracene + phenanthrene), fluoranthene/(fluoranthene + pyrene), and BaA/(BaA + chrysene), were calculated to determine the likely source of PAH contamination (pyrogenic vs. petrogenic) following methods described by Yunker et al. (2002) and Tobiszewski and Namiesnik (2012).

Results

PAHs in seawater

No PAH compounds were detected above the detection limit (approximately 1 ng/l or 0.001 ppb) in any of the seawater samples, indicating very low or non-detectable levels of PAH contamination in the water column.

Heavy metals and TOC in sediment

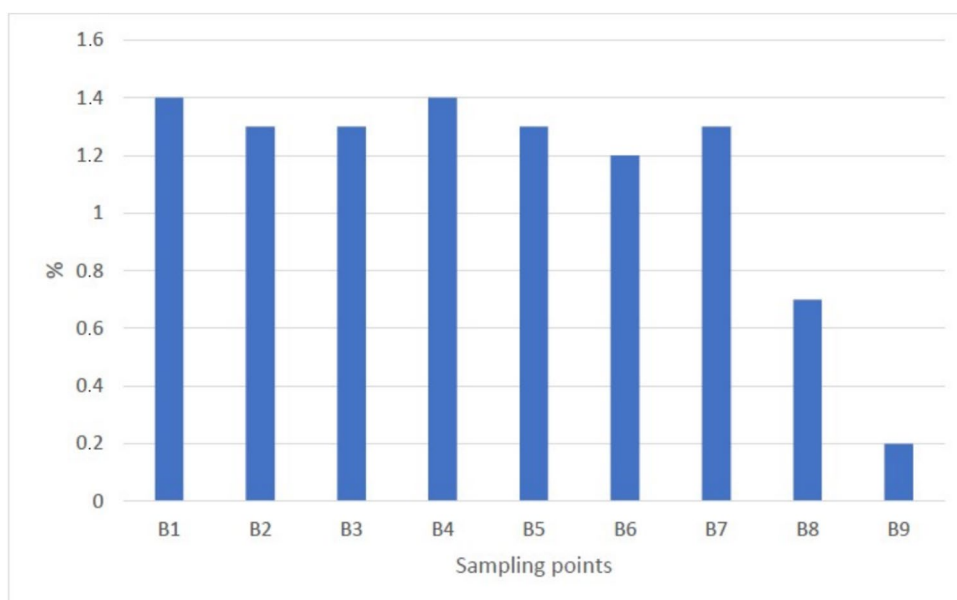
Results of heavy metal and TOC analyses in sediment samples are presented in Table 4. None of the analyzed heavy metals (Cu, Zn, Cd, Pb, Fe) in sediment samples showed harmful concentrations according to Norwegian sediment quality criteria. Copper (Cu) concentrations ranged from 53 to 113 mg/kg dry weight, zinc (Zn) from 87 to 135 mg/kg, cadmium (Cd) was mostly below 0.2 mg/kg, and lead (Pb) ranged from 3 to 26 mg/kg, with the highest concentration observed at station B1 closest to the wreck. All of these metals fall within groups II or III according to the Icelandic regulation no. 796/1999 on marine sediment. Iron (Fe) concentrations showed considerable variation (40,200 to 95,000 mg/kg), but no clear pattern with distance from the wreck. No reference values were found for iron in sediments and no reference limits have been set by the Icelandic Environmental Agency.

The TOC content ranged from 0.2% to 1.4%, with the lowest values observed at stations B8 and B9, furthest from the shipwreck (Fig. 2). A general trend of decreasing TOC with increasing distance from the wreck was observed.

Table 4 Heavy metal and TOC concentrations in sediment samples from Seydisfjörður. Colors signify different environmental limits/thresholds according to the Icelandic regulation no. 796/1999, where

gray is very low (group I), green is low (group II) and yellow upper natural limits (group III)

Parameter	Unit	B1	B2	B3	B4	B5	B6	B7	B8	B9
Copper (Cu)	mg/kg d.w	109	110	103	112	113	76	98	68	53
Zinc (Zn)	mg/kg d.w	135	128	115	125	124	87	112	116	135
Cadmium (Cd)	mg/kg d.w	0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	<0.2	<0.2
Lead (Pb)	mg/kg d.w	26	11	9	8	8	4	5	4	3
Iron (Fe)	mg/kg d.w	76,800	95,000	70,900	40,200	64,200	59,900	76,300	74,200	44,800
TOC	%	1.4	1.3	1.3	1.4	1.3	1.2	1.3	0.7	0.2

Fig. 2 Total organic carbon (TOC) content in sediment samples at different distances from the El Grillo shipwreck, showing a clear decrease with increasing distance

PAHs in sediment

PAH compounds were detected in eight of the nine sediment samples, with the highest total concentration of 524 ng/g dry weight observed at station B2, while no PAHs were detected above the detection limit at station B9, the furthest station from the wreck (Table 5).

Fluoranthene was consistently the most abundant PAH compound, followed closely by pyrene. The pattern of individual PAH compounds was similar across all samples where PAHs were detected, suggesting a common source (Fig. 3). The total concentrations of PAHs decreased with increasing distance from the wreck, showing a strong negative correlation with distance ($r = -0.87$, $p < 0.01$).

The distribution of PAHs by ring number showed a predominance of 4-ring and 5-ring PAHs, which together constituted approximately 70–80% of the total PAH content in all samples. This distribution pattern is characteristic of pyrogenic (combustion-derived) PAH sources rather than petrogenic (crude oil) sources, which would typically show

higher proportions of 2-ring and 3-ring PAHs (Yunker et al. 2002).

The PAH diagnostic ratios further supported the pyrogenic origin of the PAHs:

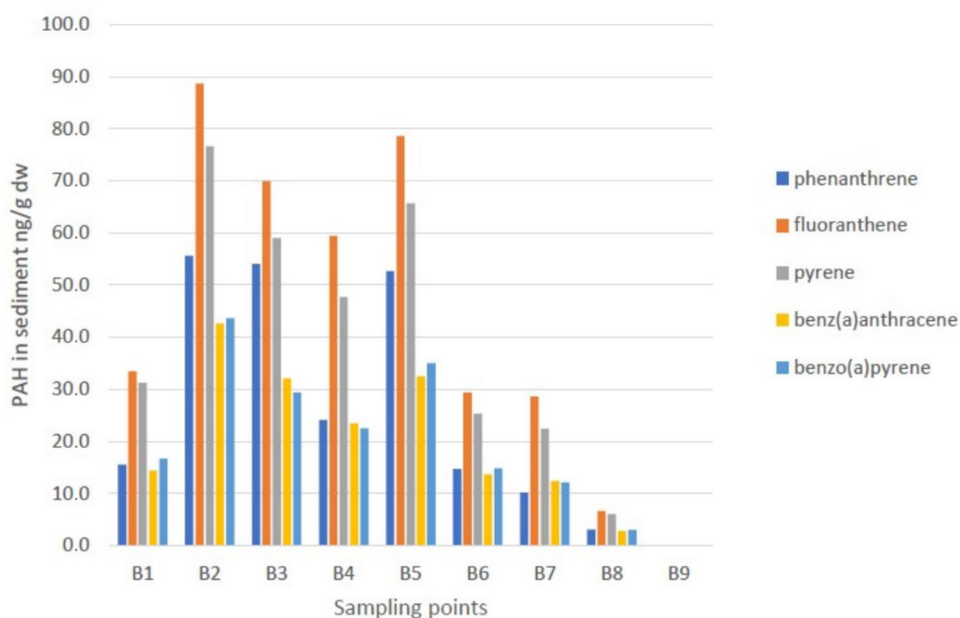
- Anthracene/(anthracene + phenanthrene) ratios were > 0.1 in all samples (range: 0.13–0.21);
 - Fluoranthene/(fluoranthene + pyrene) ratios were > 0.5 in all samples (range: 0.51–0.57);
- BaA/(BaA + chrysene) ratios were > 0.35 in all samples (range: 0.36–0.42).

These ratios strongly indicate that the source of these compounds was likely burned (pyrogenic) petroleum, diesel oil, or heavier petroleum fractions rather than unburned oil (Tobiszewski and Namiesnik 2012; Yunker et al. 2002).

When compared to Norwegian sediment quality criteria, all sediment samples fell within Class I (background, < 300 ng/g d.w.) or Class II (good condition, < 2000 ng/g d.w.) for total PAH concentrations. Only one compound

Table 5 PAH concentrations (ng/g dry weight) in sediment samples from Seydisfjörður. Classification according to Bakke et al. (2010)

Compound	B1	B2	B3	B4	B5	B6	B7	B8	B9	Class II	Class III
Naphthalene	< 1	3.1	2.6	2.1	3.1	1.4	< 1	< 1	< 1	290–1000	1000–2000
Acenaphthylene	2.55	4.08	2.96	3.48	5.78	2.60	1.62	0.52	< 0.5	33–85	85–850
Acenaphthene	< 0.5	2.12	2.24	0.67	1.19	0.51	< 0.5	< 0.5	< 0.5	160–360	360–3600
Fluorene	1.39	5.42	5.75	2.46	4.59	1.65	0.95	< 0.5	< 0.5	260–510	510–5100
Phenanthrene	15.6	55.6	54.0	24.1	52.6	14.7	10.1	3.07	< 0.5	500–1200	1200–2300
Anthracene	2.90	11.9	11.0	5.11	7.81	3.00	2.30	0.54	< 0.5	31–100	100–1000
Fluoranthene	33.4	88.6	69.9	59.4	76.6	29.4	28.6	6.65	< 0.5	170–1300	1300–2600
Pyrene	31.3	76.5	58.9	47.7	65.6	25.3	22.5	6.04	< 0.5	280–2000	2000–5600
Benz(a)anthracene	14.4	42.5	32.1	23.4	32.5	13.7	12.4	2.83	< 0.5	60–90	90–900
Chrysene	12.7	35.1	27.8	19.4	27.0	12.3	11.2	2.42	< 0.5	280–280	280–560
Benzo(b)fluoranthene	21.7	51.4	35.2	30.0	42.2	18.6	15.6	4.45	< 0.5	240–490	490–4900
Benzo(k)fluoranthene	10.4	25.3	17.1	13.8	21.2	9.0	7.65	1.99	< 0.5	210–480	480–4800
Benzo(a)pyrene	16.6	43.6	29.4	22.5	35.0	14.8	12.1	3.03	< 0.5	420–830	830–4200
Indeno(1,2,3-cd)pyrene	17.0	37.3	25.8	20.7	30.5	15.2	13.1	3.49	< 0.5	47–70	70–700
Dibenz(a,h)anthracene	3.07	7.49	5.50	3.96	6.49	2.38	2.01	< 0.5	< 0.5	590–1200	1200–12000
Benzo(ghi)perylene	16.8	33.8	23.2	19.6	26.3	13.1	11.5	3.87	< 0.5	21–31	31–310
Sum of 16 PAHs	200	524	404	298	443	178	152	38.9	< 1	2000–8000	8000–20000
% dry weight	43%	45%	48%	47%	47%	42%	40%	58%	69%	-	-

Fig. 3 Distribution patterns of the five most abundant PAH compounds in sediment samples from different sampling points, showing consistent patterns across stations with fluoranthene and pyrene dominating

(benzo(ghi)perylene) in sample B2 reached Class III (33.8 ng/g d.w., slightly above the 31 ng/g d.w. threshold), which may indicate potential for adverse effects after long-term exposure. All other individual PAH compounds were within Class I or II limits.

A strong positive correlation was observed between TOC content and total PAH concentrations ($r=0.79$, $p<0.01$), consistent with the tendency of hydrophobic PAH compounds to associate with organic matter in sediments.

Discussion

This study represents the first formal assessment of potential contamination from the El Grillo shipwreck in Seydisfjörður, focusing on PAHs, heavy metals, and TOC as indicators of oil pollution. The results indicate that, despite nearly 80 years of the wreck's presence on the

seabed, contamination levels are relatively low and generally within acceptable environmental quality standards.

PAHs in seawater and sediment

The absence of detectable PAHs in seawater samples is consistent with previous studies in Arctic and sub-Arctic regions, where concentrations are typically below 1 ng/l (Balmer et al. 2019). Several factors may explain this finding: (1) the ongoing containment measures, including the oil barrier positioned above the wreck, (2) the natural degradation and dispersion processes in the water column, and (3) the tendency of PAHs to bind to particulate matter and settle to the seafloor rather than remaining dissolved in the water column, (4) due to low solubility in cold water. This finding is significant for the proposed aquaculture operations, as it suggests minimal exposure to water-borne PAH contaminants for farmed fish.

In sediment samples, the clear gradient of decreasing PAH concentrations with increasing distance from the wreck strongly indicates the El Grillo as the point source of contamination. However, even at the closest sampling stations, total PAH concentrations remained below thresholds associated with adverse biological effects. According to Norwegian classification criteria (Bakke et al. 2010), all samples fell within Class I (background) or Class II (good condition) categories for total PAHs, with only one compound in one sample reaching Class III.

The PAH compound ratios observed in this study, particularly the anthracene/(anthracene + phenanthrene) > 0.1 and fluoranthene/(fluoranthene + pyrene) > 0.5, are characteristic of pyrogenic sources rather than petrogenic sources (Yunker et al. 2002). This suggests that the PAHs may originate from burned petroleum products, possibly related to the circumstances of the ship sinking during the German attack, when the ship was reportedly set on fire, or subsequent weathering processes. Recent comprehensive reviews have emphasized the critical role of biomonitoring in assessing PAH contamination and associated risks in aquatic ecosystems. Costa et al. (2024) documented PAH concentrations in coastal sediments globally, reporting ranges from 7.00×10^4 to 1.00×10^9 ng/g, with benzo(a)pyrene detected across all environmental media. The PAH levels observed in Seydisfjörður (maximum 524 ng/g d.w.) fall at the lower end of this global distribution, supporting our assessment that the El Grillo site represents relatively low contamination despite 80 years of wreck presence. Furthermore, their review underscores the importance of validated biomonitoring approaches for surveillance of environmental and biota health, aligning with our multi-parameter assessment strategy.

The predominance of 4-ring and 5-ring PAHs in our samples further supports the pyrogenic origin hypothesis, as these higher molecular weight PAHs are typically enriched in combustion products compared to unburned petroleum (Tobiszewski and Namiesnik 2012). This finding has implications for environmental risk assessment, as higher molecular weight PAHs tend to be more persistent in the environment but less bioavailable than lower molecular weight compounds.

The correlation between TOC and PAH concentrations reflects the hydrophobic nature of PAHs and their tendency to associate with organic matter in sediments (Fig. 4). This relationship is well-documented in the literature (Dahle et al. 2003; Means et al. 1980; Vane et al. 2007) and helps explain the spatial distribution of PAHs in the study area. The lower TOC and PAH concentrations at the most distant sampling stations (B8 and B9) further support the hypothesis that the wreck is the primary source of these contaminants in the area.

Heavy metals and TOC

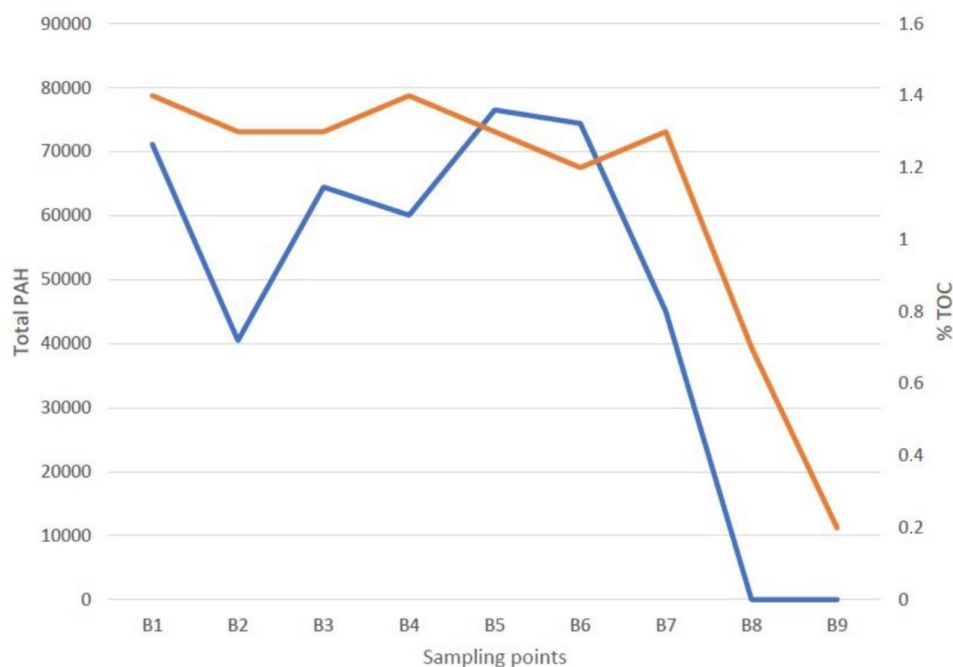
The heavy metal concentrations, while showing some elevation for copper, lead, and zinc compared to background levels, remained below thresholds of concern. The higher copper and zinc levels observed are not unusual for port areas and may reflect general maritime activities rather than specific contamination from the El Grillo (Birch and Taylor 1999; Johannesson et al. 2010; Skirnisdottir et al. 2005). The elevated lead concentrations at station B1 (nearest to the wreck) might be more directly associated with the shipwreck, possibly from lead-containing paints or other materials.

Implications for aquaculture

From an aquaculture perspective, the findings of this study are encouraging. The absence of detectable PAHs in seawater and the generally low levels in sediments suggest minimal risk of contamination affecting farmed fish. PAHs can accumulate in fish tissue and affect fish health through various mechanisms, including immune suppression, oxidative stress, and genotoxicity (Tuvikene 1995). However, these effects are typically observed at much higher environmental concentrations than those detected in the present study.

The proposed fish farming sites, which would be located away from the immediate vicinity of the wreck, showed particularly low contamination levels. The stations at 4 km and 8 km from the wreck (B6-B9) had total PAH concentrations ranging from below detection limits to 178 ng/g dry weight, well within Class I (background) levels according to Norwegian criteria.

Fig. 4 Correlation between total PAH (blue line) concentrations and % TOC of d.w. (orange line) in sediment samples, showing a strong positive relationship ($r=0.79$, $p<0.01$)



Fish farms are typically positioned to maximize water exchange, with cages positioned in areas of good current flow to ensure optimal conditions for fish health and to minimize local environmental impacts (Belle and Nash 2008). This positioning would further reduce the likelihood of any accumulated PAHs from the El Grillo site reaching the farm site in concentrations that could affect fish health or product quality.

Comparison with other studies

To provide context for our findings, we compared the PAH concentrations observed in Seydisfjörður with those reported in other studies of marine areas impacted by shipwrecks or other oil contamination sources.

PAH concentrations in sediments near the El Grillo (maximum 524 ng/g d.w.) are considerably lower than those reported near more recent shipwrecks, such as the Prestige oil spill off the coast of Spain, where concentrations exceeding 10,000 ng/g were observed shortly after the incident (Morales-Caselles et al. 2007). However, they are comparable to levels reported for older shipwrecks, such as the HMS Royal Oak in Scapa Flow, Scotland, where total PAH concentrations ranged from 100 to 500 ng/g d.w. more than 60 years after sinking (Webster et al. 2001).

The levels observed in Seydisfjörður are also lower than those typically found in industrialized harbors and estuaries, where total PAH concentrations often exceed 1000 ng/g d.w. and can reach tens of thousands ng/g d.w. in highly contaminated areas (Baumard et al. 1998).

The importance of field-validated biomarkers in environmental assessment has been well-established. Kumari and Swamy (2023) demonstrated that validated biomarker-based approaches provide robust tools for assessing impacts of multiple pollutants in aquatic systems, emphasizing that integrated multi-parameter assessments yield more reliable environmental quality evaluations than single-parameter approaches. Our combined analysis of PAHs, heavy metals, and TOC follows this validated multi-biomarker framework, providing a comprehensive assessment of potential contamination impacts from the El Grillo shipwreck.

Conclusion

Based on the comprehensive analysis of PAHs, heavy metals, and TOC in sediment and seawater samples collected along a transect from the El Grillo shipwreck in Seydisfjörður, we conclude that contamination levels are generally low and below thresholds of environmental concern. All measured parameters fell within acceptable limits according to established environmental quality standards.

The PAH compounds detected in sediments show a clear spatial pattern, with concentrations decreasing with distance from the wreck, indicating that the El Grillo is indeed a source of contamination. However, the PAH profiles suggest a pyrogenic origin, consistent with burned petroleum products rather than fresh oil leakage. This may reflect the historical circumstances of the ship sinking or transformation of leaked oil over the decades.

Specifically for the planned aquaculture operations, our findings indicate that there is no evidence that fish farming would be adversely affected by oil contamination from the El Grillo shipwreck. The absence of detectable PAHs in seawater and the generally low levels in sediments at the proposed farming sites suggest minimal risk of contamination affecting farmed fish or farm operations.

This study provides valuable baseline data for future monitoring of the wreck's environmental impact and will contribute to informed decision-making regarding coastal development in Seydisfjörður and other similar places. Further research could include the following:

1. Temporal monitoring to assess potential seasonal variations in contamination levels.
2. Biological studies to evaluate any subtle effects on local marine ecosystems, particularly focusing on benthic communities near the wreck.
3. More detailed analysis of the wreck itself to estimate remaining oil volumes and assess structural integrity.
4. Development of a long-term management plan for the wreck to minimize environmental risks.
5. Regular monitoring of PAH bioaccumulation in marine biota, both wild and farmed, to ensure continued safety.

In addition, we recommend the following:

1. Maintaining and regularly inspecting the oil containment barrier above the wreck.
2. Establishing a monitoring program that includes seasonal sampling at key locations identified in this study.
3. Creating emergency response protocols in case of increased oil leakage from the wreck.
4. Conducting environmental impact assessments for any future coastal development projects in the area.

These measures would help ensure that the El Grillo wreck continues to pose minimal environmental risk to both the natural marine ecosystem and the proposed aquaculture industry in Seydisfjörður.

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Author contribution All authors contributed to the study conception and design. Thorleifur Agustsson designed and conducted the research and prepared the manuscript. Material preparation, data collection, and fieldwork were performed by Thorleifur Agustsson and Eva Dogg Johannsdottir. Eva Dogg Johannsdottir was responsible for generating figures and data visualization. Thorleifur Eiriksson contributed to sample design, methodology, and manuscript editing. Kristin Olafsdottir was responsible for analyzing PAHs, data interpretation, and quality control. All authors commented on previous versions of the manuscript and all authors read and approved the final manuscript.

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