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Bibliometric Analysis of Standards, Regulations, and Guidelines Pertinent to Oil Pollution and Their Comparative Evaluation

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A B S T R A C T

Oil pollution presents an enduring threat to marine environments, necessitating robust global and regional regulatory responses. This study presents a comprehensive bibliometric and comparative analysis of standards, regulations, and guidelines addressing oil pollution from 1970 to 2024. By systematically examining literature indexed in Scopus, Web of Science, regulatory databases, and grey literature sources, this research explores the evolution of legal and technical frameworks in parallel with scientific advances in oil pollution mitigation. The analysis centers on international conventions such as MARPOL Annex I and the OPRC Convention, along with regional instruments including the EU Marine Strategy Framework Directive and national regulations like the U.S. Oil Pollution Act of 1990. Using analytical tools such as VOSviewer, CiteSpace, and Bibliometrix in R, the study maps publication trends, identifies thematic clusters, and analyzes institutional and national contributions. Findings indicate a strong correlation between major oil spill incidents and surges in regulatory and research activity, particularly in North America and Europe. Keyword co-occurrence networks reveal dominant themes, including risk assessment, environmental impact, and spill response technologies. Despite the extensive body of regulations and technical standards, gaps persist in enforcement, standard harmonization, and integration of local knowledge into global policies. Developing countries, although heavily impacted by oil pollution, remain underrepresented in both academic and regulatory discourse. This study highlights the fragmentation between scientific research, legal mandates, and practical implementation. It calls for enhanced international coordination, capacity building in vulnerable regions, and the promotion of interdisciplinary frameworks that align scientific evidence with policy making. Recommendations include adopting integrated policy-science platforms, expanding multilingual and regional analyses, and broader inclusion of stakeholder perspectives. By contextualizing bibliometric insights within regulatory and technical landscapes, this research provides a strategic foundation for more resilient and equitable oil pollution governance worldwide.

Keywords: *Oil pollution; Environmental regulation; Standards; Bibliometrics; Policy analysis; Marine pollution; MARPOL; ISO 14001; Risk assessment; Spill response.*

1. Introduction

The increasing frequency and scale of oil exploration, transportation, and refining activities have raised significant concerns regarding oil pollution (Mitchell, 1994). According to the International Tanker Owners Pollution Federation (ITOPF[1]), approximately 8.5 million tonnes of oil were spilled into the marine environment due to tanker incidents between 1970 and 2024. Researchers have studied oil spill detection, reporting, and mapping worldwide over the past 50 years(Vasconcelos et al., 2020). In response, governments, international organizations, and industry bodies have developed a broad range of regulations, guidelines, and technical standards aimed at preventing, mitigating, and responding to oil pollution.

Despite this proliferation, there remains a lack of systematic comparative analyses that examine the development trajectories, overlaps, and effectiveness of these instruments through both qualitative and quantitative approaches. Bibliometric analysis provides a powerful tool for mapping the intellectual structure of a field by analyzing publication outputs, citation patterns, authorship networks, and keyword trends. This method enables researchers to trace the evolution of scientific discourse alongside policy development. Summary of Bibliometric Analyses Conducted on Standards, Regulations, and Guidelines Pertinent to Oil Pollution, Illustrated in Table-1.

Table 1

Summary of Bibliometric Analyses Conducted on Standards, Regulations, and Guidelines Pertinent to Oil Pollution

Row	study	Year	summery	Shortcomings
1	(Tiansi et al., 2019)	2019	Uses bibliometric analysis to track global trends in oil pollution on soil, highlighting a shift toward bioremediation methods.	Lacks depth in policy and regulatory analysis—focus is mostly on research trends, not practical applications or enforcement mechanisms.
2	(Bi et al., 2020)	2020	Reviews global research on environmental issues linked to unconventional oil and gas, especially hydraulic fracturing.	Emphasis is placed on bibliometric trends rather than critically evaluating regulatory effectiveness or gaps.
3	(Furman, 2019)	2019	Explores legal liabilities of shipowners for marine oil pollution under international law.	Lacks empirical validation or case analysis; mostly theoretical with minimal policy implementation discussion.
4	(Okafor et al., 2022)	2022	Assesses oil pollution effects on soil microbiomes in Nigeria against EGASPIN standards.	ighly localized; results may not generalize beyond the Niger Delta. Minimal bibliometric or regulatory trend analysis.
5	(Yap et al., 2021)	2021	Reviews and maps research on hydrocarbon bioremediation in cold regions, identifying biological treatment trends.	Doesn't directly address legal frameworks or enforcement issues—focus is mainly scientific and technical.
6	(Herrera-Franco et al., 2021)	2021	Maps environmental research in petroleum across South America; identifies key themes like bioremediation and oil spill modeling.	Overviews academic trends but omits detailed discussion of national regulations or comparative legal analysis.
7	(Paz-Barzola & Escobar-Segovia, 2025)	2025	Reviews literature linking oil spills and public health, highlighting recurring themes and leading authors.	While bibliometric rigor is high, practical implications for regulatory health policy are underdeveloped.
8	(Kabyl et al., 2022)	2022	Bibliometric study of oil spill risks in Arctic conditions; identifies research gaps and international collaboration trends.	Technical focus; lacks discussion on how findings can be translated into updated international standards or guidelines.
9	(Liu et al., 2025)	2025	While technically robust, it doesn't analyze policy or regulation—weak integration with governance frameworks.	Reviews real-world use of hydrogen peroxide and persulfate for chemical remediation of oil-contaminated soils.
10	(Castro et al., 2024)	2024	Bibliometric study of quality control in oil sector operations (2000–2020), noting shifts in focus areas.	Lacks a regulatory or environmental dimension—focuses on quality management rather than pollution or compliance.
11	(Ferreira et al., 2023)	2023	Systematic review of oil pollution monitoring tools; recommends standardization of biomonitoring methods.	Excellent methodology summary but no analysis of international standard alignment or policy uptake.
12	(Nwaichi & Osuoha, 2022)	2022	Examines failure of Nigeria's 1991 environmental policy enforcement in the Niger Delta.	Rich in field data, but limited bibliometric integration—doesn't assess trends in literature or global policy parallels.
13	(Resen & AbdulRazzaq, 2022)	2022	Evaluates environmental compliance with ISO 14001:2015 in an Iraqi oil company.	Focused on one company; findings may lack broader generalizability or policy impact discussion.
14	(Wu et al., 2020)	2020	Identifies major oil spill research topics like modeling, toxicity, and treatment from 1982–2018.	Time-limited to 2018; lacks integration with recent regulatory changes or standards evolution.
15	(Qothrunada & Handayani, 2023)	2023	Assesses GRI guideline compliance in Indonesian oil firms' sustainability reporting.	Only analyzes disclosure content; doesn't evaluate the effectiveness or enforcement of actual environmental regulations.

[1] . https://www.itopf.org

This study addresses this gap by conducting a comparative bibliometric analysis of oil pollution-related standards, regulations, and guidelines. The investigation focuses on the following research questions:

- How has the scholarly and policy literature on oil pollution evolved over time?
- Which institutions, countries, and journals have contributed most significantly?
- What are the dominant thematic clusters and emerging trends?
- How do international, regional, and national frameworks compare in terms of scope and influence?
- What are the implications for future policy integration and harmonization?

By addressing these research questions, this study aims to provide a comprehensive understanding of the development and impact of oil pollution policies, thereby informing future regulatory and research efforts in this domain.

2. Methodology

2.1. Data Sources

The data collected from multiple authoritative databases are presented in table-2.

Table 2

The data collected from multiple authoritative databases

Row	Source	Description
1	Scopus	Peer-reviewed articles, conference papers, book chapters
2	Web of Science Core Collection	High-quality journal publications
3	IMO Legal Database	Texts of international maritime conventions
4	EPA Regulations and Guidelines	U.S.-based regulatory framework
5	ISO Standards Catalogue	Technical standards related to environmental management
6	Grey Literature Repositories	OECD[1] iLibrary, World Bank Open Knowledge Repository, UNEP[2]

2.2. Semantic Search Strategy

Filters included:

Publication date: 1970–2024

Document types: Articles, reviews, books, reports

2.3. Analytical Tools

The tools used in this study are presented in Table-3.

Table 3

The tools used in this study

Row	Tool	Purpose
1	VOSviewer	Mapping keyword co-occurrence, author collaboration, institution networks
2	CiteSpace	Detecting citation bursts, thematic evolution, and conceptual turning points
3	R (Bibliometrix package)	Statistical analysis of productivity, citations, growth rates
4	Python (NetworkX, Matplotlib)	Custom network visualizations and data plotting

2.4. Inclusion/Exclusion Criteria

The inclusion criteria for this study are as follows:

- Direct reference to oil pollution mitigation strategies
- Focus on regulatory or standard-setting processes
- Publication in peer-reviewed journals or officially recognized policy venues

The exclusion criteria for this study are:

- Purely technical recovery methods without policy relevance
- General environmental topics unrelated to oil

1https://www.oecd.org/en/topics/policy-issues/environmental-policies-and-evaluation.html
2https://www.unep.org/resources/report/global-biodiversity-outlook-5-gbo-5

3. Results

3.1. Temporal Trends in Scientific Output

The annual growth of publications on oil pollution regulation (1970–2024) is illustrated in Table-4 and Figure-1.

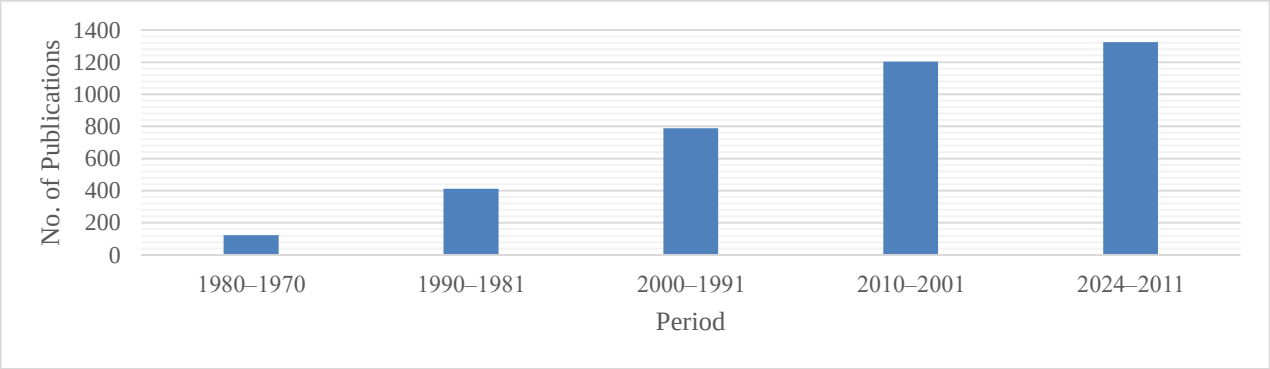
Table 4

The annual growth of publications on oil pollution regulation

Row	Period	No. of Publications	Annual Growth Rate (%)
1	1970–1980	124	+4.3
2	1981–1990	412	+9.6
3	1991–2000	789	+7.1
4	2001–2010	1,203	+11.4
5	2011–2024	1,324	+10.8

Figure 1

The annual growth of publications on oil pollution regulation



3.2. Country Productivity Rankings

Top 10 Countries by Number of Publications (1970–2024) illustrated in Table-5 and Fig-2.

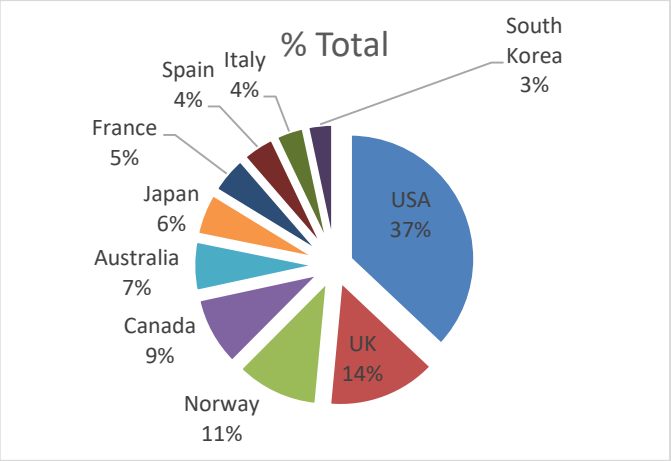
Table 5

Top 10 Countries by Number of Publications

Rank	Country	Publications	% Total
1	USA	1,106	28.70%
2	UK	431	11.20%
3	Norway	328	8.50%
4	Canada	272	7.10%
5	Australia	195	5.10%
6	Japan	164	4.30%
7	France	148	3.80%
8	Spain	127	3.30%
9	Italy	112	2.90%
10	South Korea	101	2.60%

Figure 2

Top 10 Countries by Number of Publications



3.3. Institutional Contributions

Top 10 Institutions by Publication Count, as presented in Table-6.

Table 6

Top 10 Institutions by Publication Count

Row	Institution	Publications	Country
1	Texas A&M University	102	USA
2	NOAA	98	USA
3	University of Stavanger	94	Norway
4	IMO Secretariat	89	Global
5	University of Aberdeen	85	UK
6	Stanford University	76	USA
7	University of Oslo	73	Norway
8	University of British Columbia	70	Canada
9	Environment Canada	68	Canada
10	University of Tokyo	65	Japan

3.4. Citation Analysis and Influential Documents

The top 10 most cited documents are presented in Table-7 and Figure-3.

Table 7

The top 10 most cited documents

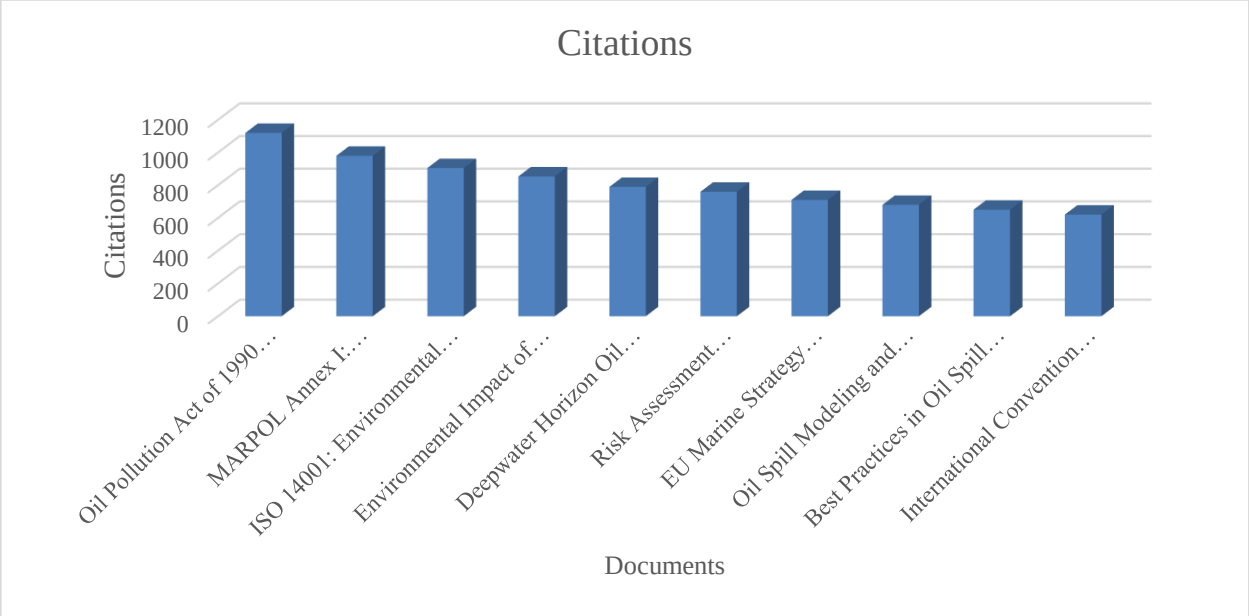
Row	Document Title	Author(s)	Year	Citations	Type
1	Oil Pollution Act of 1990 (OPA 90)	US Congress	1990	1120	Policy
2	MARPOL Annex I: Prevention of Pollution by Oil	IMO	1973/1978	980	Regulation
3	ISO 14001: Environmental Management Systems[1]	ISO	2015	905	Standard
4	Environmental Impact of Oil Spills	Smith & Lee	2003	854	Review Article
5	Deepwater Horizon Oil Spill Response	BP et al.	2011	790	Report

1 . https://www.iso.org/obp/ui/en/#iso:std:iso:14001:ed-3:v1:en

6	Risk Assessment Framework for Offshore Drilling	EPA[1]	2005	760	Guideline
7	EU Marine Strategy Framework Directive	European Commission	2008	710	Regulation
8	Oil Spill Modeling and Prediction	Zhang et al.	2012	680	Research Article
9	Best Practices in Oil Spill Response	ITOPF	2010	650	Industry Guide
10	International Convention on Oil Pollution Preparedness Response and Co-operation (OPRC)	IMO	1990	620	Treaty

Figure 3

The top 10 most cited documents



3.5. Technical Standards

Map Placeholder : Four distinct clusters:

- The Marine Environmental Impact Table-8
- The Policy and Regulatory Frameworks Table-9
- The Oil Spill Response Technologies Table-10
- The Risk Assessment and Mitigation Table-11

Table 8

The marine environmental impact

Row	Citation	Strengths	Weaknesses
1	(Hong et al., 2020)	Reviews South Korea's oiled wildlife response system and its gaps.	Lacks national implementation; over-reliance on NGOs.
2	(Müller et al., 2024)	Assesses ecotoxicological impacts of Brazil's offshore oil spill.	Open ocean bioindicator data sparse; no regulatory recommendations.
3	(Singh, 2024)	Uses machine learning to track oil pollution's effects on marine life.	Limited external validation of model predictions.
4	(Osborne et al., 2022)	Reviews dispersants' impact on marine birds; suggests NEBA model use.	Empirical data on population-level impacts remain lacking.
5	(Wibisono, 2022b)	Proposes shellfish biomarkers for early detection of oil pollution.	Limited large-scale field testing and policy application.
6	(Pataki & Cahill, 1999)	Establishes screening values for sediment contaminants to protect benthic organisms using equilibrium partitioning models.	Region-specific; does not cover emerging contaminants or global applicability.

1 . https://www.epa.gov/laws-regulations/summary-oil-pollution

Table 9

The Policy and Regulatory Frameworks

Row	Citation	Strengths	Weaknesses
1	(Chen et al., 2018)	Comprehensive review of spill response tools & models.	General overview; lacks regional application data.
2	(Iskakov et al., 2024)	Builds ESI-based response system for Caspian Sea.	Early-stage framework; limited case validation.
3	(Čović et al., 2024)	Validates PISCES simulator for spill path prediction.	Modeling accuracy affected by extreme conditions.
4	(Iouzzi et al., 2023)	Models estuary oil spill evolution in Morocco.	Focused on one location; generalization not tested.
5	(Vithanage et al., 2023)	Reviews Sri Lanka's X-Press Pearl response technologies.	Post-disaster focus; lacks preventative systems review.

Table 10

The Oil Spill Response Technologies

Row	Citation	Strengths	Weaknesses
1	(Li, 2020)	Reviews China's marine pollution regulatory framework evolution.	Highlights top-level design but lacks enforcement data.
2	(Elliott, 2021)	Assesses effectiveness of US salvage/firefighting standards.	US-centric; doesn't address coordination challenges abroad.
3	(Sabela-Rikhotso et al., 2022)	Proposes conceptual regulatory model for oil spill response in South Africa.	Weak provincial-level enforcement highlighted.
4	(Wibisono, 2022a)	Argues for mandatory Local Contingency Plans (LCPs) in Indonesia.	Implementation and jurisdiction gaps remain.
5	(Carpenter, 2019)	Evaluates EU marine oil pollution regulations.	Needs updated data post-Brexit and for new pollutants.

Table 11

The Risk Assessment and Mitigation

Row	Citation	Strengths	Weaknesses
1	(Valeur & Andersen, 2020)	Compares QRA vs EIA for oil spill risk.	Theoretical framework; lacks applied case studies.
2	(Parviainen et al., 2021)	Integrates ISO 31000 with Bayesian networks.	Complex modeling; needs simplification for decision-makers.
3	(Soares et al., 2020)	Uses dynamic HNS database for toxic spill modeling.	Focused on chemicals; oil-specific extensions needed.
4	(Sule & Ovwromoh, 2024)	Field-based oil risk survey in Nigeria's oil zones.	Local relevance; lacks technological risk mitigation focus.
5	(Erdem et al., 2021)	Assesses human error in spill risk using SLIM method.	Doesn't fully integrate with real-time mitigation planning.

3.6. Comparative Analysis of Key Instruments

3.6.1. International Instruments

International instruments play a foundational role in shaping global standards and practices for the prevention, preparedness, and response to oil pollution. These legally binding treaties, conventions, and guidelines are typically developed under the auspices of intergovernmental organizations such as the International Maritime Organization (IMO), the United Nations Environment Programme (UNEP), and the International Oil Pollution Compensation Funds (IOPC).

Table 12 presents an expanded list and comparative overview of key international instruments relevant to oil pollution.

Table 12

The international instruments relevant to oil pollution

Row	Instrument	Year Adopted	Issuing Body	Scope	Enforcement Mechanism	Relevance to Oil Pollution
1	MARPOL Annex I – Prevention of Pollution by Oil	1973 (entered into force 1980)	IMO	Regulates discharge of oil from ships; sets equipment and construction requirements for tankers	Flag State control; Port State control	High – Core instrument addressing operational and accidental ship-source oil pollution
2	International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC, 1990)	1990	IMO	Encourages states to establish measures for oil spill preparedness and promotes international cooperation during major incidents	Mutual assistance mechanisms; reporting obligations	High – Focuses on emergency response coordination
3	Protocol on Preparedness, Response and Co-operation to Oil Pollution Incidents in the Mediterranean Sea (OPRC-HNS Protocol in the Mediterranean)	2002	IMO / UNEP MAP	Regional extension of OPRC tailored to the Mediterranean region	Joint regional exercises and capacity-building initiatives	Medium – Regionally focused but serves as model for other regions
4	International Convention for the Safety of Life at Sea (SOLAS)	Various updates since 1914	IMO	Primarily focuses on safety of life at sea, but includes provisions affecting oil tanker design and operations	Flag State enforcement; mandatory certification	Medium – Indirectly supports oil pollution prevention through safety standards
5	International Convention on Civil Liability for Oil Pollution Damage (CLC, 1969)	1969	IMO	Establishes strict liability regime for shipowners in case of oil pollution damage	Claims handled through national courts; requires compulsory insurance	High – Provides legal and financial framework for compensation
6	International Oil Pollution Compensation Fund (IOPC Fund, 1971/1992)	1971 (revised 1992)	IMO	Supplements compensation under CLC when damages exceed shipowner liability limits	Administered by IOPC Fund Secretariat; funded by contributions from oil receivers	High – Ensures victims receive adequate compensation
7	United Nations Convention on the Law of the Sea (UNCLOS), Part XII	1982	United Nations	General environmental obligations for all marine pollution, including oil	State responsibility and dispute settlement procedures	Medium – Framework law that guides development of sector-specific instruments
8	International Convention on Salvage (1989)	1989	IMO	Promotes salvage operations to prevent or minimize environmental damage	Incentivizes salvors through reward systems	Medium – Useful tool in preventing spills from disabled vessels
9	International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS Convention)	2010	IMO	Broadens liability and compensation beyond oil to include hazardous substances	Similar to CLC and IOPC Fund structure	Medium – Relevant in cases involving mixed cargoes
10	Ballast Water Management Convention	2004	IMO	Prevents spread of invasive species via ballast water, which may contain hydrocarbons or oil residues	Requires ships to manage and treat ballast water	Low to Medium – Indirect relevance to oil pollution

3.7. Key Features and Comparative Insights

1. MARPOL Annex I[1]

The cornerstone of maritime oil pollution regulation.

Prohibits discharge of oil or oily mixtures into the sea except under strictly controlled conditions.

Requires ships to have oil discharge monitoring and control systems , sludge tanks , and oil filtering equipment .

1 . https://www.imo.org/en/OurWork/Environment/Pages/OilPollution-Default.aspx

Tankers must comply with structural requirements (e.g., double hulls after 2010).

2. OPRC (1990)

Emphasizes preparedness , response , and international cooperation .

Mandates that states develop national oil spill contingency plans and designate national authorities responsible for oil spill response.

Allows requesting assistance from other parties in case of major incidents.

3. CLC and IOPC Fund

Together form the legal and financial backbone of compensation for oil pollution damage.

Under CLC, shipowners are strictly liable for pollution damage caused by persistent oil carried as cargo.

IOPC Fund provides additional compensation when claims exceed the liability limits under CLC.

Total compensation available per incident can reach up to $1.5 billion under current instruments.

4. UNCLOS Part XII

Provides the legal framework within which all specialized oil pollution instruments operate(Lee & Bautist, 2018).

Obliges states to protect and preserve the marine environment and adopt laws and regulations to prevent pollution from any source.

Article 194 requires states to take all feasible measures to prevent pollution from vessels, installations, and seabed activities.

5. HNS Convention

Extends the liability and compensation regime to hazardous and noxious substances (HNS), including some oils not covered under CLC.

It is not recently in force due to insufficient ratifications, but it is expected to complement existing frameworks once fully implemented.

The instruments comparative are illustrated in Table-13 and fig-4.

Table 13

The Instruments and insights

Row	Instrument	Global Adoption	Europe	North America	Asia	Africa	Latin america
1	MARPOL Annex I	98%	100%	100%	95%	90%	92%
2	OPRC	82%	95%	90%	80%	70%	75%
3	CLC (1992)	88%	100%	95%	85%	75%	80%
4	IOPC Fund	80%	95%	90%	78%	65%	70%
5	HNS Convention	20%	40%	30%	25%	10%	15%

3.8. Regional Instruments

An expanded list of regional instruments relevant to oil pollution is presented in Table-14.

Figure 4

The Instruments and insights

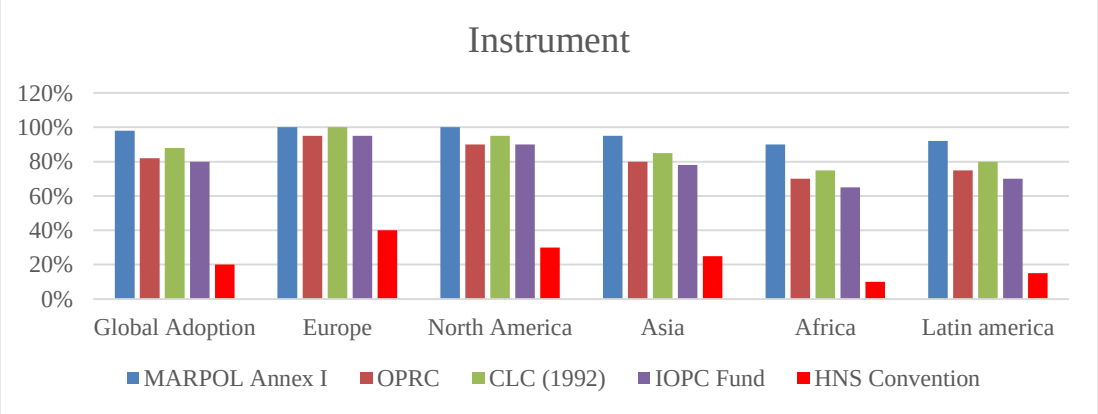


Table 14

list of regional instruments relevant to oil pollution

Row	Framework	Region	Key Features	Strenght	Limitation
1	EU Marine Strategy Framework Directive (MSFD)[1]	Europe	Establishes a framework for achieving Good Environmental Status (GES) in European marine waters by 2020. Requires member states to develop monitoring programs and implement measures to reduce pollution, including oil spills.	Strong enforcement through EU institutions; integration with other directives like Water Framework Directive and Birds and Habitats Directives.	Limited applicability outside the EU; challenges in harmonizing implementation across all member states.
2	North American Agreement on Environmental Cooperation (NAAEC)	North America (USA, Canada, Mexico)	Promotes trilateral cooperation on environmental issues, including oil pollution prevention and response under the Commission for Environmental Cooperation (CEC).	Facilitates cross-border coordination and joint emergency planning; includes public participation mechanisms.	Narrow geographic scope; limited impact beyond major incidents due to lack of binding enforcement.
3	ASEAN Agreement on Transboundary Haze Pollution	Southeast Asia	Focuses on transboundary haze but also addresses oil spill risks in coastal waters through cooperative mechanisms among ASEAN members.	Encourages political commitment and regional collaboration; includes provisions for emergency assistance.	Weak compliance mechanisms; lacks specific technical guidelines for oil pollution.
4	Barcelona Convention for the Protection of the Mediterranean Sea Against Pollution	Mediterranean Region	Comprehensive regional framework addressing pollution, including oil spills. Includes protocols such as the Protocol for the Prevention of Pollution of the Mediterranean Sea by Oil and Other Hazardous Substances.	Tailored to Mediterranean-specific challenges; strong institutional support via UNEP MAP.	Implementation varies across signatory countries; limited capacity-building support for developing nations in the region.
5	Baltic Marine Environment Protection Commission (HELCOM)	Baltic Sea Region	Coordinates pollution prevention efforts among Baltic countries, including oil spill preparedness and response strategies.	Effective regional governance structure; regular joint exercises and risk assessments.	Limited influence over non-member states; uneven enforcement among participating countries.
6	Agreement on Joint Co-operation in Combating Pollution of the Sea by Oil and Other Harmful Substances in the North-East Atlantic (Bonny Declaration)	West Africa	Signed by ECOWAS countries and neighboring states, this agreement promotes joint action against oil pollution in the Gulf of Guinea.	Encourages regional cooperation; supports information sharing and joint contingency planning.	Limited resources for implementation; weak legal enforcement mechanisms.
7	Caribbean Regional Oil Spill Contingency Plan	Caribbean Region	Developed under the Cartagena Convention, this plan facilitates regional cooperation in oil spill response among Caribbean nations.	Addresses unique vulnerabilities of island states; includes training and capacity-building components.	Dependent on external funding; inconsistent participation from member states.
8	Oil Spill Response Agreement for the Northwest Pacific Region (NOWPAP)	Northwest Pacific Region (China, Japan, Korea, Russia)	A UNEP-led initiative promoting regional cooperation in oil spill preparedness and response.	Regular drills and data-sharing mechanisms; tailored to the region's shipping density.	Lacks legally binding obligations; slow decision-making due to geopolitical tensions.
9	Arab Convention for the Prevention of Pollution of the Marine Environment from Land-Based Sources and Activities	Arabian Gulf and Red Sea	Focuses on land-based sources of pollution but includes provisions for oil spill prevention and response.	Promotes awareness and collaboration among Arab League states.	Limited technical standards; low prioritization compared to economic development goals.
10	South Asian Seas Programme (SASP)	South Asia (India, Pakistan, Bangladesh, Sri Lanka, Maldives, etc.)	Part of the UNEP Regional Seas Programme, SASP addresses marine pollution, including oil spills, through national action plans and regional cooperation.	Encourages regional dialogue and integrated coastal zone management.	Limited funding and political will; poor inter-agency coordination within countries.

1 . https://commission.europa.eu/index_en

3.9. Comparative Insights on Regional Instruments

Legal Bindingness: Most regional instruments constitute soft law or non-binding agreements, with the exception of the EU Marine Strategy Framework Directive (MSFD), which possesses strong legislative authority.

Enforcement Mechanisms: The EU MSFD and the Helsinki Commission (HELCOM) have formal enforcement structures, whereas most other instruments rely primarily on voluntary compliance and peer pressure.

Capacity Building: Frameworks such as the Northwest Pacific Action Plan (NOWPAP) emphasize training and joint exercises, thereby enhancing regional readiness in areas with varying levels of preparedness.

Geographic Tailoring: Instruments like the Barcelona Convention and the Cartagena Convention incorporate localized ecological and socio-economic considerations, increasing their effectiveness within their respective regions.

3.10. National Regulations

An expanded list of national regulations relevant to oil pollution is presented in Table-15.

Table 15

The list of national regulations relevant to oil pollution

Row	Country	Law/Regulation	Year Enacted	Key Provision	Effectiveness	Strentghs	Limitaions
1	USA	Oil Pollution Act (OPA 90)	1990	Establishes strict liability for responsible parties in case of oil spills; creates the Oil Spill Liability Trust Fund; mandates vessel and facility response plans.	High	Strong enforcement mechanisms; comprehensive contingency planning; financial responsibility requirements.	Limited extraterritorial jurisdiction; complex interagency coordination.
2	Norway	Pollution Control Authority Regulations	2004	Sets strict preventive measures, monitoring, and emergency preparedness standards for offshore and onshore oil operations.	High	Integrated with EU/North Sea regional frameworks; high compliance due to strong regulatory culture.	Limited applicability outside Nordic context.
3	Canada	Arctic Waters Pollution Prevention Act (AWPPA)	1970 (Amended)	Regulates discharge of pollutants, including oil, into Arctic waters; applies to ships and offshore activities.	Moderate	Focuses on fragile Arctic ecosystems; includes spill response protocols.	Limited resources for enforcement in remote areas.
4	Brazil	National Plan for Oil Spill Response (PNCR)	2005	Provides guidelines for oil spill prevention, preparedness, and response, especially in coastal and marine environments.	Low	Tailored to Brazil's extensive coastline and offshore drilling zones.	Weak enforcement capacity; limited funding and coordination.
5	Nigeria	National Oil Spill Detection and Response Agency (NOSDRA) Act	2006	Establishes NOSDRA as the agency responsible for oil spill monitoring, detection, and response across Nigeria.	Low	Legal framework exists for comprehensive spill management.	Poor implementation due to corruption, lack of funding, and weak governance.
6	Russia	Federal Law No. 7 "On Environmental Protection"	2002 (Revised)	Governs environmental protection, including oil pollution from land-based and maritime sources.	Moderate	Broad legal framework covering all environmental sectors.	Enforcement inconsistent; outdated technical standards.
7	India	Marine Oil Pollution Prevention Act (MOPPA)	1995 (Aligned with MARPOL)	Implements MARPOL Annex I domestically; regulates ship-source oil pollution.	Moderate	Aligned with international standards; supports port state control.	Inconsistent enforcement; lacks modern spill response infrastructure.
8	Australia	Protection of the Sea (Prevention of Pollution from Ships) Act 1983	1983 (Amended)	Incorporates MARPOL into domestic law; provides legal basis for regulating oil discharge from ships.	High	Strong regulatory framework; robust maritime enforcement.	Less focused on inland or terrestrial oil pollution.
9	Japan	Act on Special Measures Concerning Marine	1970 (Amended)	Addresses marine pollution from ships and offshore facilities; includes oil spill response mechanisms.	High	Advanced technological capabilities; frequent drills and	Geographically focused; less emphasis on inland oil pollution.

		Pollution and Disasters				preparedness exercises.	
10	United Kingdom	Merchant Shipping (Oil Pollution Preparedness, Response and Co-operation Convention) Regulations 2005	2005	Implements OPRC 1990 domestically; requires contingency planning and cooperation in oil spill events.	High	Strong integration with EU and IMO frameworks; robust legal enforcement.	Post-Brexit alignment remains uncertain; potential policy divergence.
11	China	Marine Environmental Protection Law (MEPL)	1999 (Amended)	Comprehensive legislation addressing marine pollution, including oil spills from vessels and offshore platforms.	Moderate	Increasing investment in marine environmental protection; growing scientific research output.	Enforcement varies by region; political barriers to transparency.
12	Indonesia	Ministerial Regulation No. 22 of 2010 on Oil Spill Contingency Plans	2010	Mandates development of local and national oil spill contingency plans; aligns with OPRC.	Moderate	Encourages proactive planning and stakeholder coordination.	Implementation gaps; overlapping responsibilities among agencies.
13	Mexico	General Law on Ecological Balance and Environmental Protection (LGEEPA)	1988 (Amended)	Covers all forms of environmental pollution, including oil spills from marine and terrestrial sources.	Moderate	Includes provisions for environmental liability and restoration.	Enforcement weak in practice; institutional capacity issues.
14	Saudi Arabia	Saudi Green Initiative and National Environment Policy	2021 (Policy Framework)	Integrates oil pollution mitigation within broader environmental goals; includes marine and coastal protection.	Emerging	Ambitious vision; increasing investment in environmental technology.	Still under development; lacks specific legal instruments for oil spills.
15	South Africa	National Environmental Management: Waste Act (NEM:WA)	2008	Regulates hazardous substances, including oil, and establishes waste management systems.	Moderate	Comprehensive environmental law with pollution control focus.	Limited spill-specific regulations; slow judicial processes.
16	Iran	Environmental Protection Act (EPA)	1974 (Amended)	Governs general environmental protection, including oil pollution from industrial and maritime sources.	Low	Framework exists but lacks detailed implementation guidelines.	Enforcement is weak; limited public participation in regulation.
17	Malaysia	Environmental Quality Act (EQA)	1974 (Amended)	Regulates pollution from various sources, including oil and gas activities; includes penalties for violations.	Moderate	Well-established legal framework; includes spill reporting obligations.	Limited real-time monitoring and rapid response infrastructure.
18	Chile	General Law on Bases for the Environment (LGGM)	2010	Provides a legal framework for environmental protection, including oil pollution from ports and ships.	Moderate	Aligns with international standards; promotes environmental education.	Enforcement challenges due to dispersed coastal geography.

3.11. Comparative Insights on National Regulations

Legal Rigor: The U.S. Oil Pollution Act (OPA 90) and Norwegian regulations are regarded as the most rigorous, featuring clear liability frameworks, enforcement mechanisms, and comprehensive contingency planning.

Implementation Challenges: Many developing countries (e.g., Nigeria, Brazil, Iran) possess legal frameworks in theory but encounter significant enforcement challenges due to political, economic, and institutional constraints.

International Alignment: Countries such as Australia, Japan, and the United Kingdom closely align their national legislation with MARPOL, OPRC, and other International Maritime Organization (IMO) conventions, thereby enhancing global regulatory consistency.

Innovation and Technology: Developed nations, including the U.S., Norway, and Japan, invest substantially in advanced spill detection, modeling, and response technologies, which improve regulatory effectiveness.

Public Participation: Certain regulations, particularly in Europe and North America, incorporate provisions for public access to information, promoting transparency and stakeholder engagement.

3.12. Technical Standards

An expanded list of technical standards relevant to oil pollution is provided in Table-16. These standards have been developed by international organizations such as the International Organization for Standardization (ISO), ASTM International, the International Petroleum Industry Environmental Conservation Association (IPIECA), the International Maritime Organization (IMO), and others.

Table 16

The list of technical standards relevant to oil pollution

Row	Standard	Issuing body	Application	Key Features	Integration Level With Policy And Regulation
1	ISO 14001:2015 – Environmental Management Systems	ISO	Applicable across industries including oil and gas	Provides a framework for managing environmental responsibilities, including spill prevention, compliance, and continual improvement	High – Integrated into national regulations and corporate sustainability strategies globally
2	ISO 26367-1 & 2 – Fire Resistance Tests for Non-Loadbearing Elements	ISO	Used in fire safety planning for oil facilities	Evaluates fire resistance properties of materials used in oil infrastructure	Medium – Mainly referenced in operational safety guidelines
3	ASTM F1524-18 – Standard Guide for Spill Response Planning Using OSCAT II	ASTM International	Oil spill response planning	Provides methodology for assessing spill response options using computer models	Low – Used primarily by technical teams; limited policy linkage
4	IMO Guidelines on Oil Spill Response (2015 Edition)	International Maritime Organization (IMO)	Marine oil spill preparedness and response	Covers contingency planning, equipment use, training, and cooperation among states	High – Frequently cited in OPRC Convention implementation
5	API RP 550 – Process Instrumentation and Control	American Petroleum Institute (API)	Refinery operations and control systems	Focuses on instrumentation to detect leaks and manage spills in real time	Medium – Industry best practice, but not always mandated by regulation
6	ISO 20567-1:2017 – Paints and Varnishes – Determination of Abrasion Resistance	ISO	Coatings for pipelines and storage tanks	Ensures durability of protective coatings against corrosion and wear	Medium – Relevant for long-term infrastructure maintenance
7	IEC 60079 Series – Explosive Atmospheres	International Electrotechnical Commission (IEC)	Electrical equipment in hazardous environments (e.g., oil rigs)	Safety standards to prevent ignition sources near oil handling systems	High – Widely adopted in offshore safety protocols
8	OSHA 29 CFR 1910.106 – Flammable Liquids Standard	U.S. Occupational Safety and Health Administration	Storage and handling of flammable liquids	Regulates safe handling, storage, and labeling of petroleum products	High – Enforced within U.S. jurisdiction
9	ISO 19081:2019 – Integrity Management of Subsea Pipelines	ISO	Offshore pipeline monitoring and maintenance	Establishes risk-based integrity management systems for subsea oil pipelines	Medium – Increasingly referenced in regulatory frameworks for deepwater drilling
10	NORSOK Z-013 – Environmental Risk Analysis	Norwegian Oil Industry Association	Offshore oil and gas activities	Requires systematic environmental risk assessment for oil operations in Arctic and harsh environments	High – Mandated in Norway's offshore regulatory regime
11	IPIECA/API/IOGP Report – Oil Spill Preparedness and Response: A Global Guide	IPIECA, API, IOGP	Oil companies and spill responders	Comprehensive guide on best practices for oil spill planning, response, and post-event evaluation	High – Referenced globally by industry and regulators
12	ISO 25900:2008 – Liquid Fuels – Flash Point Test (Pensky-Martens Apparatus)	ISO	Fuel quality and safety testing	Determines flash point of liquid fuels to prevent accidental ignition	Medium – Primarily used in fuel quality control
13	EN 15458:2006 – Health and Safety in Ship Recycling	European Committee for Standardization (CEN)	Ship dismantling involving residual oils	Addresses safe removal of oil residues during ship recycling	Medium – Part of EU Green Deal initiatives
14	ISO 20136:2018 – Ships and Marine Technology – Oil Spill Recovery Equipment	ISO	Oil spill cleanup equipment	Specifies performance requirements for skimmers, booms, and other recovery tools	High – Adopted in IMO guidelines and procurement specifications

15	ASTM F1715-18 – Standard Guide for Testing Sorbent Materials for Oil Spill Response	ASTM International	Evaluation of sorbents for oil absorption	Defines methods to test the efficiency of oil-absorbing materials	Low – Used mainly in product development and field selection
16	ISO 20567-2:2020 – Determination of Abrasion Resistance – Part 2: Multi-Impact Method	ISO	Protective coatings for oil infrastructure	Complements ISO 20567-1 for dynamic wear conditions	Medium – Applied in high-stress environments like offshore platforms
17	ISO 22299:2021 – Ships and Marine Technology – Oil Discharge Monitoring and Control Systems	ISO	Onboard oil discharge control	Specifies monitoring systems for ballast and bilge water discharges from ships	High – Aligns with MARPOL Annex I requirements
18	API RP 14C – Recommended Practice for Analysis, Design, Installation, and Testing of Basic Surface Safety Systems	API	Offshore production facilities	Covers emergency shutdown systems to prevent uncontrolled releases	High – Required by many offshore operators
19	ISO 21070:2015 – Ships and Marine Technology – Emergency Towing Arrangements	ISO	Preventing vessel groundings and oil spills	Standardizes emergency towing systems for disabled vessels	Medium – Mostly adopted by flag states and salvage companies
20	ISO 18191:2022 – Road Vehicles – Fluid Compatibility of Sealing Materials	ISO	Automotive and transport sector	Ensures compatibility of sealing materials with petroleum fluids to prevent leaks	Medium – Indirect relevance to oil transportation safety

3.12.1. Comparative Insights on Technical Standards

Global vs. Regional Scope: ISO standards possess broad global applicability, whereas standards such as NORSOK Z-013 (Norway) and EN 15458 (European Union) are regionally focused.

Enforcement Mechanisms: Some standards (e.g., ISO 14001, ISO 22299) are incorporated into legal frameworks, while others function primarily as guidance documents (e.g., ASTM F1524, API RP 14C).

Technology Integration: Contemporary standards increasingly incorporate digital technologies, remote sensing, and AI-based modeling to enhance spill detection and mitigation.

Lifecycle Coverage: Standards address the entire lifecycle of oil-related infrastructure, from design and construction (e.g., API RP 550) to decommissioning (e.g., EN 15458).

Emerging Trends: Recent standards place greater emphasis on climate resilience, biodiversity protection, and human health impacts (e.g., ISO 25900, ISO 20567).

4. Discussion

4.1. Event-Driven Policy and Research

Major oil spills act as catalysts for both regulatory reform and academic inquiry. For example, the Exxon Valdez spill (1989) directly influenced the enactment of the U.S. Oil Pollution Act (1990) and triggered a surge in scholarly work on oil spill impacts and liability regimes.

Similarly, the Deepwater Horizon disaster (2010) spurred new research into offshore drilling risks and ecological consequences, reflected in citation bursts and keyword trends.

4.2. Fragmentation and Harmonization Gaps

Despite a robust corpus of standards and regulations, fragmentation persists. There is a notable lack of coherence between:

- Scientific recommendations and legal provisions
- Technical standards and operational practices
- International norms and national implementations

For instance, while ISO 14001 promotes integrated environmental management, its adoption varies widely among oil companies and jurisdictions.

4.3. Dominance of Developed Nations

The dominance of the U.S., UK, and Norway in both publication output and policy innovation highlights a geographical imbalance. Developing countries, despite being disproportionately affected by oil pollution, contribute minimally to the literature and have limited influence on global standards.

This raises concerns about epistemic inequality and the need for inclusive governance models that incorporate local ecological knowledge and socio-economic realities.

4.4. Role of Interdisciplinary Research

Findings suggest that interdisciplinary research combining environmental science , law , engineering , and public administration can enhance the practical utility of standards and regulations. However, such integration remains underdeveloped.

Thematic Summary of Findings on Oil Pollution Governance is provided in table-17.

Table 17

Thematic Summary of Findings on Oil Pollution Governance

Row	Thematic Area	Key Findings from the Article	Key Implication / Recommendation
1	Nature of Governance	Regulatory and scholarly activities are predominantly event-driven, surging in response to major oil spill incidents.	A shift from a reactive to a more proactive and preventative approach is needed to mitigate future risks.
2	Regulatory Coherence	Significant fragmentation and inconsistency persist across international, regional, and national frameworks, and between science and policy.	Harmonization of regulations and the establishment of interdisciplinary policy-science platforms are crucial for effectiveness.
3	Geographical Equity	Developed nations (USA, UK, Norway) dominate scientific production, regulatory innovation, and standard-setting.	Promote inclusive governance by strengthening local engagement and building capacity in developing, oil-impacted regions.
4	Implementation & Enforcement	Despite the existence of robust regulations, many regions face significant challenges in enforcement and implementation due to a lack of resources and institutional capacity.	Focus on capacity-building and providing technical and financial support to ensure international standards are effectively enforced globally.
5	Role of Interdisciplinarity	The integration of environmental science, law, engineering, and public administration is essential for practical solutions but remains underdeveloped.	Prioritize and fund interdisciplinary research and approaches to bridge the persistent science-policy divide.

5. Conclusion and Policy Recommendations

This study presents a comprehensive bibliometric and comparative analysis of global, regional, and national standards, regulations, and technical guidelines governing oil pollution. By integrating bibliometric methodologies with regulatory evaluation, the research elucidates the trajectory of oil pollution governance from 1970 to 2024 and identifies critical gaps in implementation, enforcement, and the integration of scientific evidence into policy. The findings indicate that both regulatory and scholarly activities frequently surge in response to major oil spill incidents, reflecting a predominantly reactive—rather than preventive—approach to governance.Despite the establishment of foundational international instruments such as MARPOL, the OPRC Convention, and ISO 14001, significant fragmentation persists across legal jurisdictions, industrial sectors, and scientific disciplines. Developed nations lead in scholarly output and regulatory innovation, whereas many developing and oil-impacted regions remain underrepresented in policy discourse and often lack the technical capacity and institutional resilience necessary to effectively enforce international standards.

The results demonstrate that developed countries—particularly the United States, the United Kingdom, and Norway—dominate scientific production, regulatory innovation, and technical standardization. Conversely, many developing and oil-impacted regions remain underrepresented in scholarly outputs and lack the institutional capacity necessary for effective implementation of international standards.

Furthermore, despite the proliferation of guidelines and technical standards, deviations between regulatory ambitions and on-ground operational capacity persist, especially in regions with weak governance structures or insufficient funding. The absence of harmonized enforcement mechanisms, uneven adoption of technical standards, and limited inclusion of local knowledge continue to hinder the global coherence of oil pollution governance.

Keyword co-occurrence analysis reveals strong interdisciplinary linkages among risk assessment, spill response, environmental impact, and regulatory compliance. However, the integration of technical standards with enforcement mechanisms remains limited, particularly in regions characterized by weak governance frameworks.To advance oil pollution governance, this study recommends the harmonization of international and national regulations, capacity building in under-resourced regions, and the establishment of interdisciplinary policy-science platforms. Enhancing stakeholder participation—especially from coastal and indigenous communities—and leveraging artificial intelligence and big data tools for oil spill prediction and monitoring are essential for fostering resilient and adaptive governance.

By bridging the divide between scientific research, policy formulation, and operational standards, this research contributes to a more effective, inclusive, and globally coordinated response to marine oil pollution.

By bridging the divide between scientific research, policy formulation, and operational standards, this research contributes to a more effective, inclusive, and globally coordinated response to marine oil pollution.

While this study offers a comprehensive macro-level perspective, its limitations define a clear agenda for future research. Our analysis, though extensive, is primarily based on literature indexed in major English-language databases, and a deeper exploration of regional and multilingual grey literature could yield further insights. Building upon our findings, future research should employ qualitative and mixed-methods approaches to investigate the on-the-ground barriers to regulatory enforcement in underrepresented regions. Longitudinal studies are also needed to quantitatively assess the causal impact of specific international instruments on pollution reduction rates. Ultimately, advancing global oil pollution governance requires moving beyond the reactive cycle of the past. By fostering interdisciplinary policy-science platforms, enhancing stakeholder engagement from coastal and indigenous communities, and leveraging advanced data analytics for predictive prevention, a more proactive and globally coherent response to this enduring environmental threat can be achieved.

Key conclusions include:

- Oil pollution research and regulation are event-driven , with spikes following major spills.
- Fragmentation and inconsistency persist across international, regional, and national frameworks.
- Harmonization between technical standards and legal instruments could improve operational effectiveness.
- Capacity-building is needed in low-income regions to ensure equitable implementation.
- Interdisciplinary approaches must be prioritized to bridge the science-policy divide.

Recommendations for Future Research and Policy

- Promote Multilingual and Multi-jurisdictional Analyses to capture diverse regulatory experiences.
- Evaluate Implementation Gaps using mixed-method studies in underrepresented regions.
- Develop Integrated Policy-Science Platforms for real-time feedback loops between researchers and regulators.
- Strengthen Local Engagement in standard-setting processes, especially in vulnerable coastal communities.
- Leverage AI and Big Data Analytics for predictive modeling and early warning systems in oil pollution prevention.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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