Oil Spills- Where We Were, Where We Are, And Where We Will Be? A Bibliometric and Content Analysis Discourse

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Abstract. More frequently and in more ways than one might think, oil spills are a very common phenomenon. There were three major (>700 tonnes; Asia and Africa) and four minor oil spills only in 2022 (between 7 and 700 tonnes; North America, Asia, and Africa). Oil spills have been known to cause numerous negative ecological, societal, economic, and public health impacts. Not only this but oil spills require rapid response to contain and mitigate multidimensional damages caused. A SCOPUS search of the keyword 'Oil Spills' in ''Article title, Abstracts, and Keywords' and 'Article title' results in 30529 and 9851 (as of March 4th, 2023) documents (Journal articles, Conference proceedings, Books, Book series, Trade journals, and Reports). In the year 2023 alone, the SCOPUS database had 297 documents at the time of writing. Such a massive database requires a retrospection of underlying and emerging themes for readers to understand the extant literature and to uncover future research agendas. This study is an attempt to conduct a bibliometric analysis of select 'Oil spill' publications. This investigation will involve performance analysis (performance of research constituents such as publication and citation evolution, leading authors, publications, affiliations, sources, and countries) and science mapping (relationship between research constituents by analyzing conceptual, intellectual, and social structures). VOSviewer and Biblioshiny The study will conclude future research trends by the content analysis of the fifteen most recent and cited documents.

1 Introduction

Any accidental or intentional discharge of a liquid petroleum hydrocarbon into the environment is known as an oil spill. These spills, which could occur on land or in bodies of water like rivers, lakes, or oceans, can be very harmful to the environment, animals, and people's health. Since biological productivity is greater in shorelines or coasts and oil stranded on shorelines may stay for a long time, the issue is made worse if spilled oil reaches these shorelines or coast[6].

In line with ITOPF, three major spills (more than 700 tonnes) and four moderate accidents (between 7 and 700 tonnes) were reported during the year 2022. One spill in Africa and two major spills in Asia. The medium spills occurred in North America, Asia, and Africa. With this, the decade average now stands to over 6 spills (>7 tonnes) annually. This is equivalent to the 2010s average. In 2022, the total amount of oil lost to the environment due to tanker spills was roughly 15,000 tonnes. The three significant incidents are responsible for almost 14,000 tonnes of oil spills thereby polluting the environment. Oil may also pollute soil and groundwater, making agricultural production or other uses problematic. Preventing spills is therefore the best course of action. The size of the worldwide market for oil spill management is expected to increase at a compound annual growth rate (CAGR) of 3.5% between 2023 and 2030, with current estimates of USD125.6 billion. Over the next nine years, the worldwide market is anticipated to be driven by increased safety concerns as well as an increase in the number of oil spill occurrences throughout the world in recent years. Despite best attempts, however, oil spills continue to occur, emphasizing the need for ongoing studies and developments in this area. Through bibliometric analysis, this research critically investigates the pattern of publications on the subject of oil spills that are published by the most highly cited and prominent authors as well as the contribution of developed and developing nations and their associated institutions and thematic evolution. The article also provides a thorough analysis of several control and monitoring methods for avoiding oil spills and remedies for them. A keyword search of 'Oil Spills' in the 'Article Title' option of SCOPUS alone results in 9935 publications (April 15, 2023). Along with 17,143 total publications (and 9996 only WOS publications) extracted from WOS (April 15, 2023), this extraordinarily large dataset is far beyond the limits of systematic reviews and other review techniques. Since bibliometric analysis can handle

extraordinarily large datasets as compared to systematic reviews, this bibliometric research approach could help researchers, students, and practitioners all over the world to assimilate the past and present of 'Oil spills' research along with exploration of future avenues of research in this area. Moreover, as in bibliometric investigations, the central stage is taken up by bibliometric data which is highly objective and is blended with the authors' logical subjectivity, bibliometric investigation was preferred over systematic reviews which are more subjective and hence sometimes believed to be suffering from authors' bias. A search of "Bibliometric analysis" and "Oil Spills" in the "Article Title" search option of SCOPUS and WoS resulted in seven publications. Two of these seven publications namely "Bibliometric Analysis of Accidental Oil Spills in Ice-Infested Waters"[54] and "Bibliometric Analysis of Research Hotspots Related to Marine Oil Spill Accidents in the Environmental Field"[119] specifically were found to focus on bibliometric research inquiries on "Accidental Oil Spills". The third publication titled "Oil spill detection and Mapping: A 50-year bibliometric analysis"[109] focused on 'Oil spill detection and mapping'. Two publications titled "Bioremediation of Diesel Contaminated Marine Water by Bacteria: A Review and Bibliometric Analysis"[56] and "Bibliometric Analysis of Hydrocarbon Bioremediation in Cold Regions and a Review on Enhanced Soil Bioremediation"[123] were found very specifically covering aspects of 'Bioremediation'. The remaining two publications; 'A Review and Bibliometric Analysis on Applications of Microbial Degradation of Hydrocarbon Contaminants in Arctic Marine Environment at Metagenomic and Enzymatic Levels'[111] and 'Bibliometric Analysis of Research on Diesel Pollution in Antarctica and a Review on Remediation Techniques'[63] were region specific (arctic and Antarctica). Bibliometric investigations help uncover the performance of and relationship between research constituents on a broad level[29]. Research areas specific to any topic are usually addressed using either systematic literature reviews or are made part of a set of research questions under bibliometric investigations. This research, therefore, differentiates itself from existing systematic literature reviews and bibliometric investigations by providing a holistic and objective retrospection of the literature on 'Oil Spills'. This bibliometric investigation, therefore, tries to address the undermentioned broad research questions pertaining to Oil Spills literature:

RQ1. To determine the performance of research constituents (performance analysis) in the 'Oil Spills' literature
RQ2. To determine the relationship between research constituents (science mapping) in the 'Oil Spills' literature
Further, all seven existing bibliometric investigations employed only bibliometric techniques to cover various aspects of oil spills. This bibliometric investigation on the other hand tries to perform a content analysis of the most recent (2020 onward) but highly cited publications to address research question three;
RQ3: To explore the contemporary and sustainable oil spill clean-up techniques
This study also tries to conduct content analysis (scope for future studies and limitation sections of recent and highly cited articles) to triangulate the results of thematic mapping to explore future research agendas, thereby adding to the robustness of this research investigation.
RQ4. To unearth the 'hot spots' for future research investigations

2 EXPERIMENTAL

2.1 Materials and Methods

This study deployed the use of bibliometric analysis to accomplish the stated research questions. Since Bibliometrix empowers researchers to do scientific descriptive analysis, beginning with bibliographic databases, it has attracted the attention of scholars from a plethora of fields [99,134]. This helps to unveil the "hidden patterns" that define the field, as well as enables exploring vistas for future research. This section focuses on the methodology employed to accomplish the stated research questions.

2.2 Database Curation

To accomplish the foregoing goals of the study, a bibliometric analysis of academic works published between 1973 and 2023 was conducted. SCOPUS and WOS (Web of Sciences) were chosen to compile bibliometric data because of their extensive database, an advisory council that assures only the best quality publications are indexed, and continual evaluation and upgrade of quality control mechanisms.

2.3 Keyword Identification

Keywords used to find relevant literature on 'Oil Spills' were chosen using a two-way strategy. The authors began by reviewing fifteen open-access publications (Five each from SCOPUS and WOS). In the next stage, ten professors with relevant experience were shown the list of keywords that had been compiled in the previous phase. Academics were briefed on the study's research questions and asked to evaluate the preliminary list of keywords.

2.4 Procurement of Articles for Bibliometric Analysis

SCOPUS and WOS were used to retrieve 9935 and 9996 publications by searching for specific keywords and their combinations in the database's article title, and relevant keywords search options. VOSviewer and the R-based tool Biblioshiny were used to perform bibliometric analysis. Because of the study's emphasis on conducting performance analysis, science mapping, exploration of contemporary and sustainable oil spill treatment techniques, it was essential to select only relevant publications that could help achieve stated outcomes, articles were selected using the Preferred Reporting Items for the Systematic Review template[71]. Figure 1 presents an adapted schema of the PRISMA process utilized for publications selection and a snapshot of the methodology:

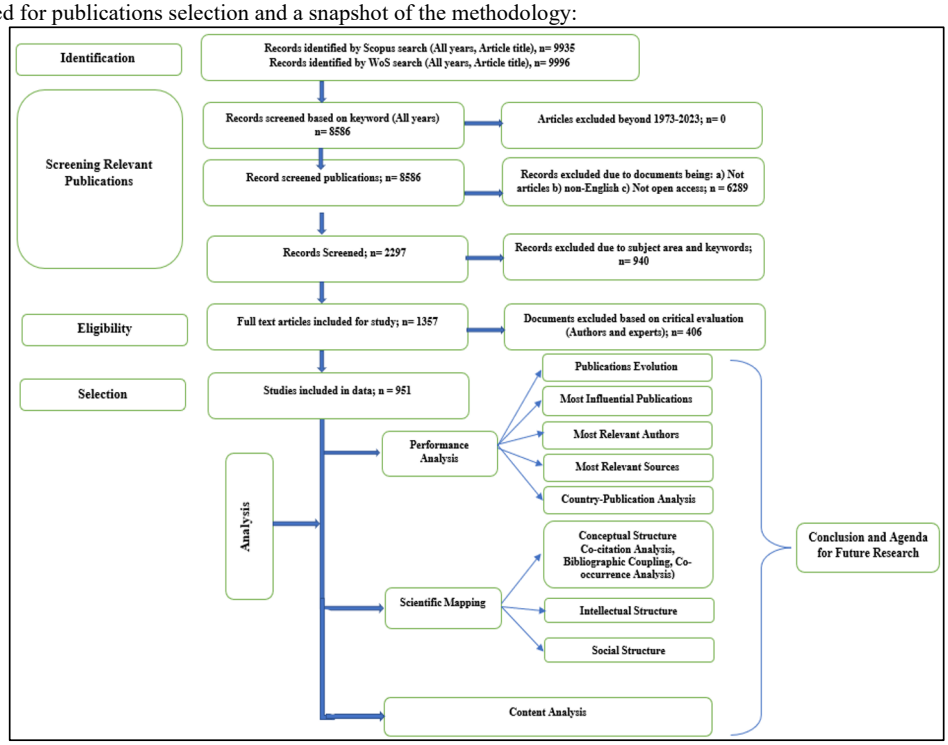


Fig. 1 Preferred reporting items for systematic review and methodology

By the end of the process, bibliometric analysis was employed on 951 publications that were chosen for further investigation after having been analyzed to meet the goals of this investigation. Two primary methods, performance analysis, and scientific mapping proposed by Noyons et al. (1999) were employed for these outcomes as discussed below:

2.4.1 Performance analysis

Performance analysis[23,91] gazes at how individual publications, researchers, and institutions have impacted a certain topic. Various metrics are used for performance analysis, with most of them having to do with tracking the performance of research constituents[69] such as publication and citation overview, most cited publications, authors, sources, and countries.

2.4.2 Scientific Mapping

Through the use of science mapping, one can gain acquaintance with the emerging themes in the intellectual, social, and conceptual frameworks of a knowledge corpus and its progressive changes over time[24].
In this investigation, the major conceptual frameworks pertaining to oil spills were captured by keyword co-occurrence analysis. Mainstream literature (past but significant knowledge body) with its theoretical underpinnings was determined using co-citation analysis, current areas of research were mined using bibliographic coupling of documents, and underlying themes and potential areas for future research were unearthed using a thematic map, which is displayed by exhibiting clusters in a bi-dimensional grid with density and centrality as two axes. Future research

hot spots identified using thematic map were supplemented with a content analysis of recent and highly cited research publications (2020-2023). A co-authorship analysis was also performed to understand the intellectual structure (the author collaborations)[85]. The social structure of oil spill literature was determined by country collaboration analysis.

3 Analysis and discussion of results

This section builds upon the performance analysis and science mapping coupled with content analysis to accomplish RQ3 (exploring contemporary and sustainable oil spill clean-up techniques) and to supplement the results of RQ4 (identification of Hot spots for future research).

3.1 Performance Analysis

3.1.1 Publication and Citation Overview over Time

Figure 2 demonstrates the publication and citation evolution from 1973 to 2023. A publication titled "The impact of impact studies"[44] marked the beginning of the publication trajectory highlighting the environmental impacts of oil spills. The publication focused on how the Santa Barbara oil spill of January 1969 led to the emergence of the National Environmental Protection law from just an act in the United States. With somewhat slow growth in the number of publications till 2005, the publications covering various aspects of oil spills; from 'damage' to 'damage control' have witnessed a sharp increase from 2006 onwards.

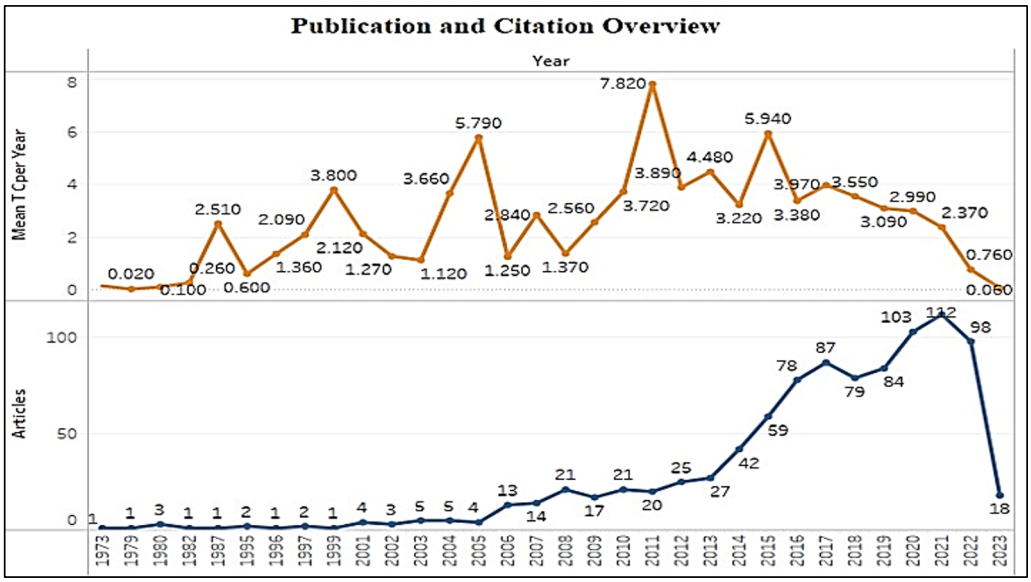


Fig. 2 Publication and citation evolution from 1973 to 2023

The publication overview clearly shows four peaks; 2006 (TP=13, MCA=110), 2008 (TP=21, MCA=21.95), 2017 (TP=87, MCA=27.78) and 2021 (TP=112, MCA=7.12). The major focus of publications in 2006 (first peak) was to determine the impact of salinity on the dispersion of oil spills[19], concentrations of polycyclic aromatic hydrocarbons (PAH) in the wild mussels (Mytilus galloprovincialis), and their fluctuation over time due to oil spills[76] to name a few.

The focus shifted to themes such as Oil weathering at a marine seep using GCxGC and Petroleum biodegradation[115], classification of alkanes, hopanes, and polycyclic aromatic hydrocarbons[20,] and oil exploration's destructive effects on Nigeria's, efforts to preserve the region's unique ecology[106] in the year 2008 (second peak).

The third peak in the year 2017 witnessed publications focusing on deepwater oil spills[22] and areas such as deepwater oil spill response and clean-Up[61], Hazards, Extenuation Priorities, and State Reporting Requirements for unconventional oil spills[81], and bioremediation to name a few[14].

Peak four (2021) was populated by publications trying to detect marine oil spills using methods such as Synthetic Aperture Radar over the Indian Ocean[73], sensors, image transformation methods, and mapping[131]

3.1.2 Most Influential Publications

Since the impact of a publication can be directly measured by the number of citations it receives, the most influential publications in the dataset that influenced the writers working on 'Oil Spills' globally were identified and extracted accordingly. Table 1 illustrates the most cited publications in the dataset:

Table. 1 Most Influential Publications

Rank	Title	Authors	Year	TC
1	"Oil biodegradation and bioremediation: A tale of the two worst spills in U.S. history"	Atlas R.M., Hazen T.C.	2011	579
2	"Aryl hydrocarbon receptor-independent toxicity of weathered crude oil during fish development"	Incardona J.P., Carls M.G., Teraoka H., Sloan C.A., Collier T.K., Scholz N.L.	2005	282
3	"Impact of the deepwater horizon oil spill on bioavailable polycyclic aromatic hydrocarbons in Gulf of Mexico coastal waters"	Allan S.E., Smith B.W., Anderson K.A.	2012	280
4	"Multitissue molecular, genomic, and developmental effects of the deepwater horizon oil spill on resident Gulf killifish (Fundulus grandis)"	Dubansky B., Whitehead A., Miller J.T., Rice C.D., Galvez F.	2013	244
5	"Global Gray Water Footprint and Water Pollution Levels Related to Anthropogenic Nitrogen Loads to Fresh Water"	Mekonnen M.M., Hoekstra A.Y.	2015	238
6	"Coastal and environmental remote sensing from unmanned aerial vehicles: An overview"	Klemas V.V.	2015	236
7	"Restoration and repair of Earth's damaged ecosystems"	Jones H.P., Jones P.C., Barbier E.B., Blackburn R.C., Rey Benayas J.M., Holl K.D., McCrackin M., Meli P., Montoya D., Mateos D.M.	2018	165
8	"Next-generation sequencing of microbial communities in the Athabasca River and its tributaries in relation to oil sands mining activities"	Yergeau E., Lawrence J.R., Sanschagrin S., Waiser M.J., Korber D.R., Greer C.W.	2012	162
9	"Polycyclic aromatic hydrocarbon (PAHs) and hopanes in stranded tar-balls on the coasts of Peninsular Malaysia: Applications of biomarkers for identifying sources of oil pollution"	Zakaria M.P., Okuda T., Takada H.	2001	145
10	"Analysis of eight oil spill dispersants using rapid, in vitro tests for endocrine and other biological activity"	Judson R.S., Martin M.T., Reif D.M., Houck K.A., Knudsen T.B., Rotroff D.M., Xia M., Sakamuru S., Huang R., Shinn P., Austin C.P., Kavlock R.J., Dix D.J.	2010	143

***Source**: Biblioshiny and Authors' Compilation, **Note**: TC- Total Citations*

With 579 citations (TC=579), "Oil biodegradation and bioremediation: A tale of the two worst spills in U.S. history", authored by Atlas and Hazen (2011) was the most influential publication in the dataset. Focusing on the upsetting ecological impacts of the Exxon Valdez spill (1989) and the BP Deepwater Horizon spill (2010), this publication suggested employing the biological pathways inside microbes or plants engaged in the bioremediation of oil spills as an effective method to treat oil spills. "Aryl hydrocarbon receptor-independent toxicity of weathered crude oil during fish development" (TC=282) authored by Incardona, Carls, Teraoka, Sloan, Collier., and Scholz (2005) was the second most influential publication. This study employed antisense morpholino oligonucleotides to inhibit components of the AhR (aryl hydrocarbon receptor) pathway, and the results demonstrated that low-molecular-weight tricyclic PAHs were mainly accountable for the major defects in development caused by exposure to weathered crude oil. The results of this study thus suggested many implications to assess the impact of Polycyclic aromatic hydrocarbons (PAHs) on coastal habitats.
The detailed analysis of the ten most influential publications has been tabulated below in Table 2.

Table. 2 Research Questions and Outcomes of Top Ten Most Influential Publications

RANK	PUBLICATION	RESEARCH QUESTION	OUTCOMES
1	"Oil biodegradation and bioremediation: A tale of the two worst spills in U.S. history"	Assessing the Efficacy and Safety of Bioremediation	Native oil-degrading microbes were crucial in mitigating the devastating effects of the Exxon Valdez and BP Deepwater Horizon oil spills on the ecosystem.
2	"Aryl hydrocarbon receptor-independent toxicity of weathered crude oil during fish development"	An assessment of Polycyclic aromatic hydrocarbons (PAHs) impacts coastal habitats.	By blocking AhR pathway components using antisense morpholino oligonucleotides, this study found that low-molecular-weight tricyclic PAHs were responsible for the major developmental abnormalities generated by exposure to weathered crude oil, acting independently of AhR to impair cardiovascular health and morphogenesis.
3	"Impact of the deepwater horizon oil spill on bioavailable polycyclic aromatic hydrocarbons in Gulf of Mexico coastal waters"	To evaluate the levels of bioavailable polycyclic aromatic hydrocarbons (PAHs) in the Gulf of Mexico off the coastlines of four states affected by the oil spills	As shown by chemical forensic modelling, increased PAH concentrations have been linked to unique chemical profiles.
4	'Multitissue molecular, genomic, and developmental effects of the deepwater horizon oil spill on resident Gulf killifish (Fundulus grandis)"	To study the molecular, genetic, and developmental implications of the Deepwater Horizon oil spill on Gulf Killifish.	The expression of genes linked to stress response, metabolism, and development were all found to be altered by the oil spill. Fish had other morphological abnormalities, like shrunken bodies and altered liver and gill structures.
5	"Global Gray Water Footprint and Water Pollution Levels Related to Anthropogenic Nitrogen Loads to Fresh Water"	To learn more about the worldwide connection between greywater footprint, water pollution, and anthropogenic nitrogen loads to freshwater sources.	The study found that a considerable proportion of the nitrogen load was not appropriately processed and discharged into the environment, as indicated by the high correlation between the greywater footprint and nitrogen pollution levels discovered by the researchers.
6	"Coastal and environmental remote sensing from unmanned aerial vehicles: An overview"	The purpose of the research was to examine how UAVs can be used for ecological monitoring and management in diverse contexts, such as detecting coastal erosion, tracking biodiversity, detecting changes in land use and land cover, and checking water quality.	The study participants believed that UAVs' high spatial resolution, adaptability, and low cost were significant benefits over more conventional remote sensing methods.

7	"Restoration and repair of Earth's damaged ecosystems"	The aim of this article was to give readers an overview of the present state of ecosystem restoration activities.	The participation of local people and stakeholders, as well as the establishment of effective monitoring and assessment mechanisms, are essential for successful ecosystem restoration and reconstruction initiatives. Insufficient resources, a lack of political will, and a lack of understanding of ecological processes are all hindrances to restoration and rehabilitation efforts.
8	"Next-generation sequencing of microbial communities in the Athabasca River and its tributaries in relation to oil sands mining activities"	The purpose of this study was to determine the diversity and quantity of microorganisms in the Athabasca River and its tributaries and to investigate the effects of oil and mining on these communities.	Oil sand mining has the potential to negatively affect microbial communities, however, this study found multiple microbial species with the potential to break down hydrocarbons, suggesting that bioremediation may be an effective technique for reducing these negative effects.
9	"Polycyclic aromatic hydrocarbon (PAHs) and hopanes in stranded tar-balls on the coasts of Peninsular Malaysia: Applications of biomarkers for identifying sources of oil pollution"	Using biomarkers such as polycyclic aromatic hydrocarbons (PAHs) and hopanes, researchers hope to pinpoint the origins of oil pollution off Peninsular Malaysia's coasts.	This research showed how biomarkers like polycyclic aromatic hydrocarbons (PAHs) and hopanes might be used to trace oil pollution back to its origins and better direct management and prevention strategies.
10	"Analysis of eight oil spill dispersants using rapid, in vitro tests for endocrine and other biological activity"	The purpose of this study was to evaluate the eight dispersants for their impact on biological pathways like oxidative stress and cytotoxicity, as well as the function of estrogen, androgen, and glucocorticoid receptors.	There may be consequences for human and ecological health from using oil spill dispersants due to the possibility of unanticipated effects on endocrine and other biological mechanisms.

***Source**: SCOPUS database and Author's Compilation*

3.2 Most Relevant Authors

The relevance of authors can be determined based on productivity and impact. While the productivity of authors is measured by the number of papers they produced in a specified time frame, the impact of authors can be measured using the number of citations that publications contributed by them receive over a period of time. Working in the same direction, the most relevant authors in the dataset were identified and have been presented below in Tables 3a and 3b:

Table 3a: Most Productive Authors

Rank	Element	h_index	g_index	m_index	TC	NP	PY_start	AF
1	Li Y	7	13	0.412	171	13	2007	3.08
2	Wang C	10	15	0.909	323	15	2013	2.70
3	Le Floch S	10	16	0.769	412	16	2011	2.26
4	Reddy CM	11	12	0.647	618	12	2007	2.12
5	Brakstad OG	6	8	1	127	8	2011	1.90
6	Engel LS	8	13	1.143	239	13	2017	1.63
7	Murawski SA	7	8	0.778	149	8	2015	1.51
8	Kwok RK	8	12	0.889	249	12	2015	1.46
9	Sandler DP	7	11	0.778	225	11	2015	1.38
10	Rouhani S	8	8	1	319	8	2016	1.24

Table 3b: Most Impactful Authors

Rank	Element	h_index	g_index	m_index	TC	NP	PY_start
1	Hazen TC	5	5	0.385	847	5	2011

2	Valentine Dl	4	4	0.25	838	4	2008
3	Liu Z	5	5	0.333	835	5	2009
4	Li H	3	3	0.333	712	3	2015
5	Lu Y	1	2	0.111	706	2	2015
6	Ferrier RC	1	1	0.111	705	1	2015
7	Jenkins A	1	1	0.111	705	1	2015
8	Luo W	1	1	0.111	705	1	2015
9	Meng J	1	1	0.111	705	1	2015
10	Song S	1	1	0.111	705	1	2015

***Source**: SCOPUS database and Authors' Compilation*
***Note**: TC= Total Citations, NP= Number of Publications, AF = Article Fractionalized*

Table 3a shows the most productive authors. As many authors contributed an equal number of publications (e.g., Engel L.S and Li Y; NP=13) in the field, this necessitated ranking the authors based on the article fractionalized score (the fractionalized frequency distribution of articles) rather than just the total number of publications.
As evident in Table 3a, Li Y (NP=13, AF=3.08) was found to be the most productive author in the dataset. Use of a novel hydrophobic magnetic biochar to treat oil spills (2018), modulating the spatial discretization used in oil spill simulations along coastlines (2007) and distribution scheme, risk evaluation, and reasons for petroleum hydrocarbons in the Yellow River estuary and nearby coastal area in China (2017) were some of the influential works contributed by Li Y.

Wang C, (NP=15, AF=2.70) was found to be the second most productive author. Sedimentary petroleum, aliphatic, and polycyclic aromatic hydrocarbon concentrations and sourcing in Bohai Bay and the nearby river (2015), weathering and fingerprinting of crude oils following China's Dalian oil spill (2013), The ability of a recently identified strain to remove polycyclic aromatic hydrocarbons (PAHs) from oilfield generated water (2017) and use of indigenous bacterial consortia for marine oil spill clean-up in China's Penglai 19-3 oil spill (2018) were major influential areas of contribution by Wang C.

Le Floch S was found to be the third most productive author (NP=16, AF=2.26). Evaluating the role of treated and untreated oil on fish's capacity to adapt to its environment (2013), evaluating the role of dispersants on the environment and nearshore habitats (2011), and contrasting the cost-benefit analysis of the use of dispersants in treating oil spills (2011) were some of the most influential works by Le Floch.

Reddy CM (NP=12, AF=2.12, Rank=4) on the list of most productive authors worked on characterizing the biological breakdown of long-lasting saturated hydrocarbons in Deepwater Horizon oil samples (2014) followed by Brakstad OG (NP=8, AF=1.90, Rank=5) who worked on surfactants' use to clean up oil spills break down in frigid water. The major contribution of Engel LS. (NP=13, AF=1.63, Rank=6) was evaluating the impacts of deepwater horizon Oil Spills. Murawski SA (NP=8, AF=1.51), Kwok RK (NP=12, AF=1.46)., Sandler DP (NP=11, AF=1.38), and Rouhani S (NP=8, AF=1.24) ranked 7,8, 9 and 10 on the list of most productive authors. Surprisingly, none of the authors on the list of the most productive authors were found to be on the list of the top 10 most impactful authors as evidenced by Table 3b. Hazen TC with 847 citations was found to be the most impactful author. His mainstream work revolved around employing the biological pathways inside microbes or plants engaged in the bioremediation of oil spills as an effective method to treat oil spills (2011). Valentine Dl (TC=838) was the second most influential author whose major work revolved around evaluating the fate of dispersants used to treat deepwater horizon oil spills (2011). Liu Z with 835 citations was the third most impactful author who worked on exploring the environmental and food safety issues in China due to oil spills and soil pollution. Li H was found to be the fourth most impactful author (TC=712) who contributed to simulating the toxicity of metal mixtures and hydrocarbons leading to environmental and health risks in China.

Lu Y (TC=706, Rank=5), Ferrier RC (TC=705, Rank=6), Jenkins A (TC=705, Rank=7), Luo W (TC=705, Rank=8), Meng J (TC=705, Rank=9), and Song S. (TC=705, Rank=10) on the list of most impactful authors had one paper in a collaboration that was one of the most impactful publications (Impacts of soil and water pollution on food safety and health risks in China) in the dataset (except Lu Y who had an additional publication with one citation).

3.3 Most Relevant Sources

The dataset consists of 187 journals that have published articles covering oil spills' environmental impact. This domain has been progressive over the years (Figure 2). To demonstrate the impact of journals, Tables 3a and 3b list the ten most relevant journals. In this analysis, the total number of publications and the total number of citations were used to categorize the most productive and most impactful sources respectively.

Table. 4a Top Ten Most Productive Journals

Source	h_index	g_index	m_index	TC	NP	PY_start
Marine Pollution Bulletin	31	47	1.069	2817	118	1995
Science of the Total Environment	22	35	1	1407	61	2002
Environmental Science and Technology	28	41	1.647	3945	41	2007
Ecotoxicology and Environmental Safety	13	19	1.083	402	30	2012
International Journal of Environmental Research and Public Health	13	22	1.3	489	29	2014
Environmental Pollution	17	27	1	749	27	2007
Chemosphere	13	24	0.481	621	27	1997
Frontiers in Marine Science	10	16	1.25	274	27	2016
Journal of Marine Science and Engineering	7	9	0.778	117	25	2015
Applied and Environmental Microbiology	17	21	0.459	1207	21	1987

Table 4b: Top Ten Most Impactful Journals

Source	h_index	g_index	m_index	TC	NP	PY_start
Environmental Science and Technology	28	41	1.647	3945	41	2007
Marine Pollution Bulletin	31	47	1.069	2817	118	1995
Science of the Total Environment	22	35	1	1407	61	2002
Applied and Environmental Microbiology	17	21	0.459	1207	21	1987
Environment International	11	15	0.25	929	15	1980
Environmental Health Perspectives	11	16	0.579	865	16	2005
Environmental Pollution	17	27	1	749	27	2007
Chemosphere	13	24	0.481	621	27	1997
Marine Ecology Progress Series	15	17	0.6	531	17	1999
Journal of Hazardous Materials	9	14	0.6	526	14	2009

***Source**: SCOPUS and Author's Compilations; **Note:** TC= Total Citations, TP= Total Publications, PY_start= Publication Year Start*

With 118 publications in the dataset, "Marine Pollution Bulletin" was the most productive source followed by "Science of the Total Environment" (TP=61), "Environmental Science and Technology" (TP=41), "Ecotoxicology and Environmental Safety" (TP=30), "International Journal of Environmental Research and Public Health" (TP=29), "Environmental Pollution" (TP=27), "Chemosphere" (TP=27), "Frontiers in Marine Science" (TP=27), "Journal of Marine Science and Engineering" (TP=25), and "Applied and Environmental Microbiology" (TP=21).

However only the third most productive journal (TP=41) with 3945 total citations, "Environmental Science and Technology" was found to be the most impactful source in the dataset. Interestingly, while not in the top ten productive sources list, sources like "Environment International", "Environmental Health Perspectives", "Marine Ecology Progress Series", and "Journal of Hazardous Materials" made their place in the list of the top ten most impactful sources with 929, 865, 531, and 526 citations respectively.

3.4 Country Publication Analysis

53 nations contributed to the publication of the 951 publications in the dataset under consideration. Table 5 shows the ten most productive countries to publish on oil spills.

Table. 5 Country Publication Analysis

Rank	Country	TP
1	USA	273
2	CHINA	95
3	NORWAY	46
4	CANADA	45
5	UNITED KINGDOM	45
6	SPAIN	44
7	FRANCE	35
8	BRAZIL	30
9	GERMANY	20
10	FINLAND	18

***Source**: SCOPUS database and Author's Compilation; **Note**: TP-Total Publications*

The top ten most productive countries contributed 651 (68.45%) publications in the dataset. As clear from Table 5, the USA was found to be the most productive country to publish on oil spills in the dataset (NP=273) followed by China (NP=95), Norway (NP=46), Canada (NP=45), the United Kingdom (NP=45), Spain (NP=44), France (NP=35), Brazil (NP=30), Germany (NP=20) and Finland (NP=18). Only two developing countries i.e., China (Rank-2, NP=95) and Brazil (Rank-8, NP=30) made it to the list of the top ten most productive nations to publish on oil spills while the rest all places belonging to developed countries indicating a very skewed publication productivity trend.

3.5 Science Mapping

3.5.1 Co-Citation analysis

Co-citation helps determine the subject similarity of two research documents. When two research documents are cited together in a third document, they are said to be co-cited. The number of identical cited items defines the strength of co-citation between two documents. CO-citation strength can be measured as the degree of relationship or association between documents as perceived by the group of citing authors[103]. The co-citation analysis of cited authors is presented in Figure 3. The minimum no. of citation was kept at 7, only 21 authors met this criterion. The network formed was based on 5 clusters. Cluster 1 and Cluster 2 were the largest clusters with 5 documents each. Cluster 1 highlights key research areas like post impact of deepwater horizon disaster [3,16], biodegradation at the deepwater horizon[16], and long-term ecosystem response to the oil spill[86]. Cluster 2 as represented in green color in Figure 3 corresponds to research areas like oil biodegradation and bioremediation[7], genetic damage to aquatic animals, and marine toxicity[18,74,92]. Cluster 3 with 4 documents is represented by blue color in Figure 3 corresponds to research areas like the effect of dispersed crude oil on copepods and polycyclic aromatic hydrocarbon uptake by fishes[100,5,42] and environmental effects of the deepwater horizon oil spill[11]. Cluster 4 with 4 documents is represented in yellow color in Figure 3 corresponds to research areas like microbial degradation of petroleum hydrocarbons[108,60,43] and data collection method for ecotoxicity due to dispersed oil[77]. Cluster 5 with 4 documents is represented with purple color in Figure 3 corresponds to the distribution and concentrations of petroleum hydrocarbons [98], the impact of polycyclic aromatic hydrocarbon on fish embryos[17], and the environmental effects of the deepwater horizon oil spill[11].

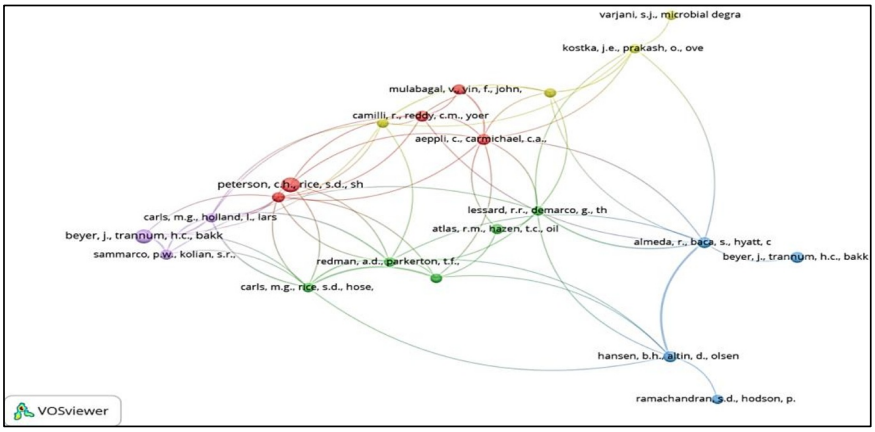


Fig.3 Co-citation Analysis, VOSviewer

3.5.2 Co-Occurrence Analysis

Co-word analysis helps in identifying an intrinsic relationship when two or more keywords from a particular research area appear in the same article. The intensity of this relationship is represented by how many times these words have co-occurred in articles considered for the bibliometric analysis[122]. For conducting Co-word analysis, a bibliometric tool i.e., VOSviewer is used. Figure 4 represents keyword co-occurrence output from VOSviewer with those keywords that have a minimum occurrence of 50. Out of the total keywords i.e., 10641 only 77 keywords met the threshold. The analysis resulted in 3 main clusters.

The largest cluster with 26 keywords (represented in red color in Figure 4) was populated with prominent keywords like environmental monitoring[32,87,107], environmental impact[59,114], risk assessment[97,102,31], ecosystem restoration[93] and oil spill response[61,40,52]. This cluster highlighted the importance of quality assurance/quality control and different methods to ensure consistency and comparability of data collected from marine information systems for environmental monitoring[32,87,107]. Another highly emergent research area in the cluster was found to be health risk assessment caused due to a variety of factors arising from oil spills like seafood contamination[97], cancer caused due to polycyclic aromatic hydrocarbons[102] and health risk caused by exposure to benzene[31].

Cluster 2 is highlighted in green color in Figure 4 and is anchored with keywords like bioremediation[7,95,14,90] biodegradation[7,43,39], metabolism[25,110,36] and microbial community[47,112,94]. As highlighted in cluster 2 of the co-citation analysis shown in Figure 1 this cluster also highlights the use of bioremediation and biodegradation for reducing the impact of oil spills on the environment[7,43]. Another interesting theme highlighted in the cluster corresponds to changes in metabolic scope indicating changes in fishes' ability to face environmental contingencies[25,110,36] and microbial community dynamics that lead to oil degradation[47,112].

Cluster 3 is shown with blue color in Figure 4 and corresponds to marine toxicity and its impact on aquatic life. The cluster is manifested with keywords like polycyclic aromatic hydrocarbon[4,82,112] toxicity[49,68,83] and Gulf of Mexico[4,98]. It was worth noting that most of the studies related to polycyclic aromatic hydrocarbon exposure to aquatic life relate to deep water horizon blowouts in the Gulf of Mexico.

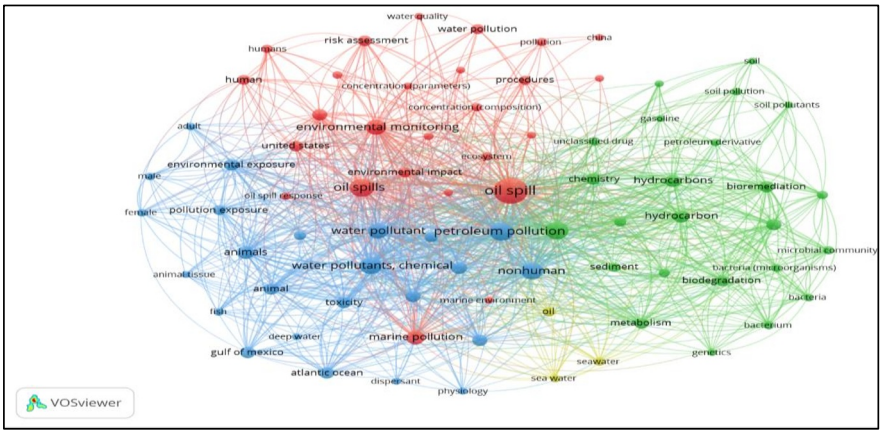


Fig.4 Keyword Co-occurrence

3.5.3 Bibliographic coupling

Based on the idea that works that share a large number of references are likely to have similar subject matter[117], the bibliographic coupling is a method for science mapping. The analysis is most effective when applied to a narrow window of time and is focused on organizing publications into theme clusters based on shared references[130]. Bibliographic coupling (as opposed to co-citation analysis) helps bring attention to newer and more specialized publications by grouping them depending on their citing publications. That's why bibliographic coupling works well for business researchers who are interested in learning about the latest advancements across a wide range of topics. Since this is a current snapshot, the analysis can serve as an illustration of the current state of the field.

Figure 3 represents bibliographic coupling output from VOSviewer with those documents that are published between 2020 to 2023 and with a minimum of 20 citations. Out of 300 total documents, only 15 met the threshold forming 5 clusters.

Cluster 1: The key areas of research that appeared from this cluster were, the impact of integrated application of biochar, rhamnolipid (RL) biosurfactant, and nitrogen (N) on petroleum hydrocarbon remediation on soil microbial community[116]. Activated charcoal enrichment strategies for facilitating bioremediation of anoxic oil-contaminated sediments and soils[12]. Application of this cold-tolerant strain in the bioremediation of diesel-contaminated soil[2], crude oil degradation bacteria[126], and phytoremediation[65].

Cluster 2: The key areas of research in this cluster are volatile organic compounds[89], Bacillus licheniformis[57], Transformation of soil microbial community under oil pollution stress[48] and polyaromatic hydrocarbons and saturated hydrocarbons degradation method[41].

Cluster 3: Documents in this cluster relate to areas like environmental monitoring[27,67] changing environment on marginal coral reefs[104] and Polycyclic aromatic compounds in marine bird species[88].

Cluster 4: This cluster highlighted areas such as probabilistic risk assessment of oil spills [45], polycarbonate and activated charcoal for emphatic oil–water separation[38] and impact of oil spills on marine mammals with polar cod responses[34].

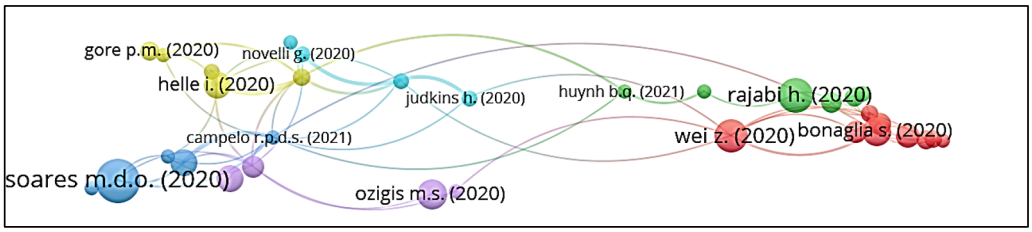


Fig. 5 Bibliographic Coupling, VOSviewer

3.5.4 Intellectual Structure- Co-authorship Analysis

Co-authorship analysis helps in examining the areas of research collaborations among authors. Figure 6 represents the co-author network with authors having a minimum of 50 citations and 6 documents. The network resulted in 4 key clusters.

Cluster I consisted of 4 authors, i.e., Hazen T.C., Greer C.W., Brakstad O.G., and Lee K where Lee K., is a liaising author between clusters 1,3, and 4. The key research area in this cluster was the biodegradation of oil spills at lower temperatures[37,94]. Cluster 2 consisted of 4 authors i.e., Li J., Li Y., Wang X., and Zhang H. where Zhang H. and Li Y were liaising authors. The common interest area of these authors was hydrophobic and oil sorbent based on jute fiber. Cluster 3 was populated by 3 authors i.e., Guo J., Li X., and Wang C. who collaborated on research in areas like remediation of crude oil-polluted soil by the bacterial rhizosphere community[126], effects of diesel oil spill on microbenthic assemblages at the intertidal zone[129], oil spill detection algorithm[128] and biodegradation using aboriginal bacterial consortium[123]. Cluster 4 consisted of only 2 authors i.e., Lui X. and Wang Y. The common research area of these two authors are environmental impact and recovery post-oil spills[114] and public attitudes toward funding oil pollution clean-up[64].

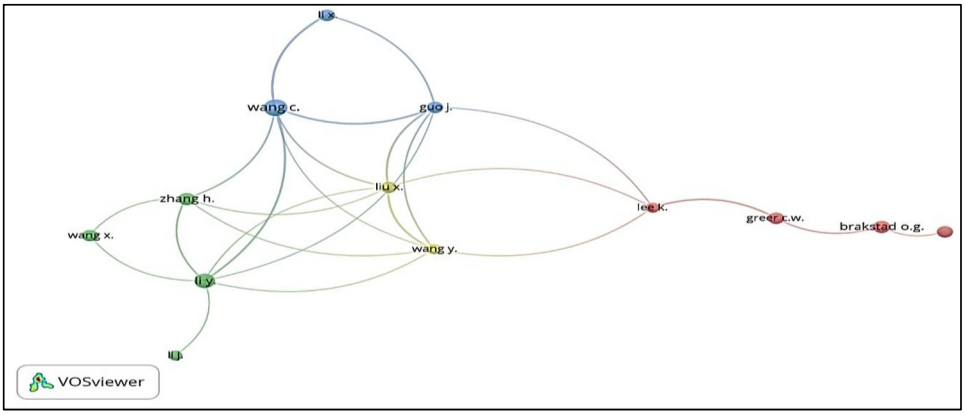


Fig. 6 Co-authorship Analysis, Biblioshiny

3.5.5 Social Structure

Based on works that have been collaboratively published, the social structure analyses the connections (the degrees of scientific collaboration) between players operating at various levels (authors, institutions, and nations). This section tries to decipher the social structure amongst collaborating nations. Because there were only 37 single-authored publications in the dataset, collaboration and teamwork (914 publications written in collaboration) were found to be crucial factors for writers exploring various aspects of Oil spills.

Table. 6 Country Collaboration Analysis

Rank	Country	SCP	MCP	Freq	MCP_Ratio
1	USA	227	46	0.287	0.168
2	China	68	27	0.1	0.284
3	Norway	25	21	0.048	0.457
4	Canada	36	9	0.047	0.2
5	United Kingdom	25	20	0.047	0.444
6	Spain	30	14	0.046	0.318
7	France	24	11	0.037	0.314
8	Brazil	19	11	0.032	0.367
9	Germany	8	12	0.021	0.6
10	Finland	11	7	0.019	0.389

***Source**: SCOPUS database and Author's Compilation*
***Note**: SCP- Single Country Collaboration, MCP- Multi-Country Collaboration, MCP_Ratio- Multi-Country Collaboration Ratio*

Table 6, Illustrates country publication analysis, where SCP is single-country publications (articles authored by writers from a single nation) and MCP is multi-country publications (articles authored by writers from several nations).
When considering the multi-country publications ratio, Germany was found most open to global collaborations (MCP_Ratio=0.6) followed by Norway (MCP_Ratio=0.457), the United Kingdom (MCP_Ratio=0.444), Finland (MCP_Ratio=0.389), Brazil (MCP_Ratio=0.367), Spain (MCP_Ratio=0.318), France (MCP_Ratio=0.314), China (MCP_Ratio=0.284), Canada (MCP_Ratio=0.2), and USA (MCP_Ratio=0.168). The United States despite being the most productive nation was found to have the least global collaborations.

3.6 The Contemporary and Sustainable Oil Spill Clean-up Techniques

This section focuses on a bibliometric investigation to explore contemporary and sustainable oil spill clean-up techniques employed by researchers in their studies. As per the dataset (N=951), a number of methods could be used for oil spill clean-ups. These include mechanical containment and recovery, using chemical dispersants, in-situ burning, sorbents, and bioremediation[116,64]. This study employed the procedure of content analysis on selected documents to identify environmentally sustainable and recent oil clean-up techniques. Content analysis is described as a process of analyzing and communicating in a methodical and quantitative manner with the aim of identifying the hidden dimensions of the given research area[55]. The most recent highly cited publications were reviewed thoroughly to identify contemporary and sustainable oil spill techniques. The result of the content analysis highlighted “Bioremediation” as one of the techniques of oil spill recovery. Bioremediation is a method for treating water polluted with petroleum hydrocarbons. The use of microorganisms that can break down the pollution to supplement the current system (bioaugmentation), stimulate natural biodegradation processes, and monitor and confirm those processes (natural attenuation) are all examples of bioremediation procedures. Compared to other methods of mitigating oil spills, bioremediation is one of the most environmentally friendly methods since it enables microorganisms to break down harmful hydrocarbons into simple chemicals that don't harm the environment[10]. Further, there are numerous techniques where the spills have been treated with enhanced bioremediation procedures. Some of the contemporary oil spill techniques discussed in the data set (N=951) were:

3.6.1 Nano-Remediation

One of the studies titled “Nano-enhanced Bioremediation for Oil Spills: A Review” authored by[84] discussed nano-enhanced bioremediation for cleaning oil spills which is the combination of bioremediation and nano-remediation where nanoparticles have primarily been used as magnetic sorbents and can also function as emulsifiers, increasing the bioavailability of the oil by providing microbes with a surface to attach to and encourage proliferation.

3.6.2 Bioaugmentation

Biological augmentation is an enhanced technique of using bacterial cultures required to speed up the rate of degradation of hydrocarbon pollutants. The most recent study titled “Bioaugmentation enhance the bioremediation of marine crude oil pollution: Microbial communities and metabolic pathways” authored by Gao et al., (2023) discussed bioaugmentation, an effective technique that speeds up the process of bioremediation for oil spills by using highly efficient petroleum degrading bacterium. Another study authored by[13] also discussed the usage of native microorganisms having a better capacity for surviving in the natural environment while eliminating unforeseen ecological effects linked to the introduction of non-native species to boost the efficacy of bioremediation.

3.6.3 Phytoremediation

Phytoremediation is the process of using plants and other soil microbes to remove, disintegrate, stabilize, mineralize, or degrade the toxicity of the hydrocarbons from the contaminated area[75]. The author also concluded that phytoremediation along with the combination of *Jatropha Curcas* (JC) reduces hydrocarbon levels in the contaminated area.

3.7 Hydrophobic and Oil Sorbent Based on Jute Fiber

Natural fiber is less likely to cause pollution than other modified materials, has adequate buoyancy, is biodegradable by microorganisms, and is environmentally benign. The modified fiber has a water contact angle (CA) of 136.2° in comparison to the hydrophilic raw fiber, indicating that the substance possesses good

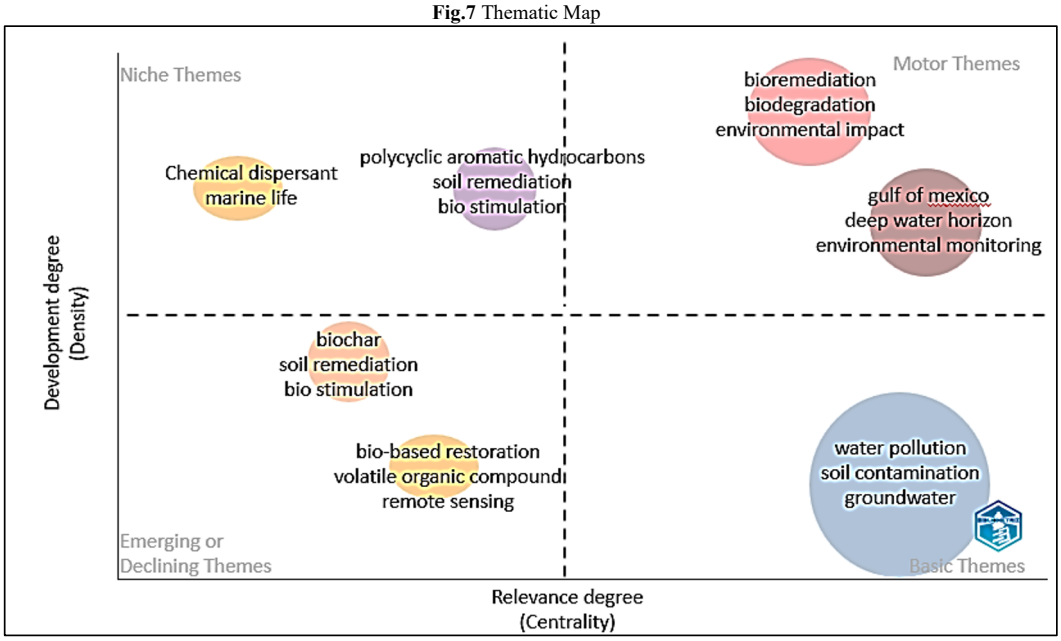
hydrophobicity. After the jute fiber was modified, the capacity to adsorb water fell from 8.53 0.03 g/g to 0.92 0.02 g/g. The thermodynamic parameters prove that the adsorption of diesel onto modified jute is a spontaneous and favorable process[132]. It was found that the maximum adsorption capacity of the modified fiber is higher than most of the inorganic adsorbents. Although some adsorbents had better adsorption capacity than modified jute, they are expensive and difficult to biodegrade. So, on the basis of cost and biodegradability, modified jute fiber has better prospects[132].

3.8 Hot Spots for Future Research- Thematic Maps

A thematic map helps understand the conceptual structure of a research area. It uses a network map of keywords occurrence to identify four themes i.e., motor theme, basic theme, niche theme, and emerging/declining themes[28]. Figure 6 shows the thematic map created with the help of a Biblioshiny tool with 500 words with a high occurrence and minimum cluster frequency of 5 per thousand keywords. As shown in the lower left quadrant of Figure 7 the key emerging/declining areas are the use of biochar, biosurfactant, and nitrogen for restoring affected areas due to oil spills pollutants[116,105] biostimulation for biodegradation of contaminated soil[101], volatile organic compound emissions[89,12146], remote sensing of marine oil spills[105,79] and oil-saltwater separation with different permeable membranes[118,72,33.]

Whereas the upper lefthand quadrant shows themes that are of high density but low centrality and represent niche themes. The key niche themes highlighted in this quadrant are the impact of chemical dispersants on marine life[21,5] nanoparticle-based dispersants for marine oil spill[96], the effect of polycyclic aromatic hydrocarbon on marine life like cardiovascular function and fish development[39], Liver antioxidant and plasma immune responses in juvenile golden grey mullet to polycyclic aromatic hydrocarbons and human health risk assessment due to polycyclic aromatic hydrocarbon[105].

Fig.7 Thematic Map



Source: *Thematic Maps, Biblioshiny*

3.9 Hot Spots for Future Research- Content Analysis

To supplement the results of the thematic map, a content analysis of recent and highly cited publications published between 2020 to 2023 was performed. The four most cited publications from each year were reviewed with a special focus on the 'Scope for future research' section to decipher the future hot spots in the Oil Spills research domain. Since the year 2023 had only one publication with one citation, rest three publications from the year 2023 were selected based on the impact factor of the journals. The details are mentioned as follows in Table 7:

Table 7: Hot Spots for Future Research

AUTHORS	TITLE	YEAR	TC	FUTURE RESEARCH AGENDA
SOARES ET AL.	"Oil spill in South Atlantic (Brazil): Environmental and governmental disaster"	2020	91	Evaluating the oil spill's long-term ecological and socio-economic effects on the regions that were affected. Establishing effective oversight and reaction strategies, as well as enhancing cooperation and disclosure of government actions. Assessing the efficacy of various oil disaster clean-up techniques and investigating the possibility of employing natural and bio-based restoration and preventative measures.
RAJABI ET AL.	"Emissions of volatile organic compounds from crude oil processing – Global emission inventory and environmental release"	2020	54	Enhancing the precision and exhaustiveness of global VOC emissions inventories Determining the distribution of volatile organic compounds (VOCs) in the ecosystem and evaluating the health and ecological effects of VOC exposure Creating sophisticated monitoring and modeling tools for VOC emissions and transportation Exploring the possible benefits of innovative mitigation methods and the causal connection between emissions of volatile organic compounds and climate change.
WEI ET AL.	"Remediation of crude oil-contaminated coastal marsh soil: Integrated effect of biochar, rhamnolipid biosurfactant, and nitrogen application"	2020	51	Optimization of biochar, biosurfactant, and nitrogen application rates for optimal efficacy of crude oil-polluted coastal marshland restoration Assessing the long-term impacts of restoration solutions on soil health and biodiversity Considering the financial viability of massive clean-up initiatives. Examining the possibility of other organic and bio-based remediation procedures, such as phytoremediation and microbial remediation, and the application of nanotechnology for oil spill clean-ups.
OZIGIS ET AL.	"Detection of oil pollution impacts on vegetation using multifrequency SAR, multispectral images with fuzzy forest, and random forest methods"	2020	42	Investigating methods for increasing the reliability and precision of remote sensing data for oil spill identification and categorization Combining remote sensing with other tracking methods, such as in situ measurements and UAVs, and investigating the possibility of novel technologies such as Light Detection and Ranging and hyperspectral imaging
MAGALHÃES ET AL.	"Oil Spill + COVID-19: A disastrous year for Brazilian seagrass conservation"	2021	35	Exploring the possibility of deploying citizen science and collaborative methods for tracking the environment and disaster response Investigating the role of cultural and social variables in influencing attitudes and behaviors regarding environmental hazards, and devising multidisciplinary models to tackle complex environmental problems.
NAZ ET AL.	"Marine oil spill detection using Synthetic Aperture Radar over the Indian Ocean"	2021	33	Examining the feasibility of SAR data for oil disaster risk evaluation and emergency preparation Investigating the use of SAR data for tracking other marine contaminants as well as creating international standards for oil disaster identification and response utilizing SAR data.
YU ET AL.	"Environmental threats induced heavy ecological burdens on the coastal zone of the Bohai Sea, China"	2021	26	Evaluating the collective effects of several stressors, such as oil pollution, heavy metal pollution, and nutrient enhancement, on seaside ecosystems in the Bohai Sea, China

Balogun et al.	"Oil spill trajectory modeling and environmental vulnerability mapping using GNOME model and GIS"	2021	23	Improving the models used to foretell the path and ultimate outcome of oil spills and their effects on the ecosystem.
Lim et al.	"Impacts of Fishing Vessels on the Heavy Metal Contamination in Sediments: A Case Study of Qianzhen Fishing Port in Southern Taiwan"	2022	12	Assessing the long-term consequences of heavy metal pollution on the marine environment and the hazards to human health from eating polluted seafood.
Faksness et al.	"Offshore field experiments with in-situ burning of oil: Emissions and burn efficiency"	2022	11	Assessing the potential for enhancing the efficacy of in-situ burning strategies to reduce air pollution and lessen the effects of oil spills
Zengel et al.	"Meta-analysis of salt marsh vegetation impacts and recovery: a synthesis following the Deepwater Horizon oil spill"	2022	9	Improvement of salt marsh and other coastal ecosystem restoration methods after oil spills.
de Moura et al.	"Deep-water oil-spill monitoring and recurrence analysis in the Brazilian territory using Sentinel-1 time series and deep learning"	2022	8	Developing more sophisticated and precise remote sensing techniques in order to track and forecast the likelihood and effect of oil accidents in deep-water habitats.
Brown et al.	"Assessing risks from fuel contamination in Antarctica: Dynamics of diesel ageing in soil and toxicity to an endemic nematode"	2023	1	Exploring the knowledge of the possible dangers to human activity in Antarctica and the long-term impacts of fuel pollution on ecosystems there.
Iriartet al.	"Snow-Dependent Biogeochemical Cycling of Polycyclic Aromatic Hydrocarbons at Coastal Antarctica"	2023	0	Determining how climate change can affect the movement and ultimate destination of Polycyclic Aromatic Hydrocarbons in icy and snowy landscapes.
Xin et al.	"The effect of temperature on hydrocarbon profiles and the microbial community composition in North Saskatchewan River water during mesoscale tank tests of diluted bitumen spills"	2023	0	Figuring out how different remediation procedures perform and what kind of long-term effects oil spills could have on river ecosystems.
Abdelhamid et al.	"Recent progress on electrospun nanofibrous polymer membranes for water and air purification: A review"	2023	0	Exploring the possibility of creating nanofibrous polymer membranes for improving water and air purification processes

Source: SCOPUS Database and Authors; Compilation; **Note**: TC- Total Citations

4 Conclusion and discussion

This bibliometric investigation was an attempt to conduct performance analysis and science mapping of research constituents in oil spill literature. This investigation also tried to unearth contemporary yet sustainable oil clean-up techniques using content analysis. At last, the bibliometric investigation tried to conclude hot spots for future research using a research triangulation (bibliometric thematic maps and content analysis). This section concludes and builds a discussion on the findings of this study.

Increased research vigor in specific years causing peaks in the number of publications could be attributed to oil spills that shook the world for environmental detrimental effects on flora and fauna including local communities. The first peak (2006) was the result of instances where nearly 2.1 million liters (approximately 555,000 gallons) of bunker fuel were spilled when the oil tanker M/T Solar 1, chartered by Petron Corporation, collapsed off the coast of Guimaras, in the Philippines, on August 11, 2006. This oil leak, till today, is remembered as the most catastrophic in Philippine history. Further, roughly 5,054 barrels of crude oil were accidentally released on the

North Slope in Alaska by BP Alaska in March 2006. Similarly, the Montara oil spill (August 21, 2008, Australia), the Hebei Spirit oil spill (December 7, 200, South Korea), and the Bonga oil spill (December 20, 2008, Nigeria) caused a publication spike in 2008. The Agia Zoni II oil spill (September 10, 2017, Saronic Gulf, Greece), the Keystone Pipeline leak (November 16, 2017, South Dakota), and the Sea Rose FPSO spill (November 16, 2017, Canada) caused a sharp peak in 2017. The last peak in the year 2021 could be attributed to oil spills such as the MV X-Press Pearl disaster (May 20, 2021, Shri Lanka), the Israel-Lebanon oil spill (February 2021, Eastern Mediterranean Sea) and the Sunken Vessel offshore California spill (October 2021, Southern California).

Working towards unearthing the most cited publication, "Oil biodegradation and bioremediation: A tale of the two worst spills in U.S. history", authored by Atlas and Hazen (2011) was found to be the most influential publication in the dataset. The most probable reason for being the most cited publication apart from it being an old publication could be the future forward approach in this publication that suggested employing the biological pathways inside microbes or plants engaged in the bioremediation of oil spills as an effective method to treat oil spills.

Li Y (NP=13, AF=3.08) and Wang C, (NP=15, AF=2.70) were found to be the two of the most productive authors (Table 3a). The reason behind authors of Chinese origin taking leadership positions as most productive authors could be attributed to the fact that China has been a victim of numerous blowouts and pipeline failures and that some of the biggest oil spill incidents in the past few years include the Xingang Port spill in China thereby creating an obvious research motivation. The same reasons could be extended to the results of most cited authors where Chinese authors (60%) made up the list of most cited authors (Table 3b). Hazen TC with 847 citations was found to be the most impactful author. The reason behind his work being one of the most cited works could be his contribution to employing the biological pathways inside microbes or plants engaged in the bioremediation of oil spills as an effective method to treat oil spills; an area that gained a lot of traction since 2011 onward.
With 118 publications in the dataset, the "Marine Pollution Bulletin" was the most productive source while with 3945 total citations, "Environmental Science and Technology" was found to be the most impactful source in the dataset. Because both journals strive to disseminate high-quality research on marine pollution and its impacts and help promote the creation of remedies to this pressing ecological issue, they serve as a natural fit to the emerging field of 'Oil spills'.

With 273 publications USA and with 95 publications China, were the two most productive nations to publish on oil spills. Not only that the USA is a major producer and consumer of oil, but it has also witnessed some of the most disastrous and publicized oil spills in history. Therefore, the nation has a longstanding stake in investigating and creating oil spill prevention, response, and mitigation. Moreover, through bodies such as the "National Oceanic and Atmospheric Administration (NOAA)", the "Environmental Protection Agency (EPA)", and the "National Science Foundation (NSF)", the US government contributes significant funding and support to oil spill-related research.

Highly Co-cited publications represent key concepts that can be used to map the relationship between these key concepts. Co-citation analysis in this investigation, therefore, enabled identifying foundational themes. The explosion of the Deepwater Horizon oil drilling rig in the Gulf of Mexico on April 20, 2010, resulted in the release of an estimated 5.3 × 108 kg of oil and 1.7 × 108 kg of gas from the Macondo well (MW), (1-3) making it the largest marine spill in US history. This cluster highlights the Deepwater Horizon oil spill due to its highly publicized environmental, economic, and social impacts.

The results of the co-citation analysis were supplemented by keyword occurrence analysis. The largest cluster in Figure 4 is represented in red and consists of 26 keywords. Prominent keywords in this cluster include environmental monitoring, environmental impact, risk assessment, ecosystem restoration, and oil spill response. The results are in tandem with an increased worldwide focus on seeking not only tracking and prevention of oil spills but also post-oil spill treatment techniques in the wake of increasing oil spill cases.

Bibliographic coupling groups newer and specialized publications based on their citing publications, highlighting the latest advancements across a wide range of topics. This method works well for business researchers and provides a current snapshot of the field. Biochar enrichment strategies for facilitating bioremediation, cold-tolerant strains for bioremediation of soil, crude oil degradation bacteria, and phytoremediation were some of the topics brought to light by the main cluster with the impact of integrated application of biochar, rhamnolipid biosurfactant, and nitrogen on remediation of petroleum hydrocarbons.

Hazen T.C., Greer C.W., Brakstad O.G., and Lee K were found to have maximum documents co-authored together. These authors were found to have an overlap in their areas of research interest. In co-authored documents

and as well as in independent documents, the authors worked on the biodegradation of oil spills in cold temperatures.

With an MCP_Ratio of 0.66, Germany was the only country to have more multi-country collaborations than single-country collaborations, making Germany the most open for international collaborations in oil spill research. This could be due to the fact that both nations have a strong commitment to accomplishing SDG Goals (Life Below Water, Climate Action, and Life on Land) and are situated in the North Sea region, which has a long history of oil and gas extraction and transport.

To explore the contemporary yet sustainable methods for oil clean-up, a content analysis of recent publications working on oil clean-up and remediation was conducted. Bioremediation along with other related techniques like Nano-Remediation[84], Bioaugmentation[133], and Phytoremediation[75] emerged as the most prominent sustainable oil clean-up technique having the most potential to be employed on a large scale. Yet another emergent sustainable oil clean-up technique was hydrophobic and oil sorbents based on jute fibers. This is because natural fiber like jute with appropriate adjustments is less likely to cause pollution than other modified materials, has adequate buoyancy, is biodegradable by microorganisms, and is environmentally benign.

One major contribution of this bibliometric and content analysis discourse was to unearth hot spots for future research areas. Establishing effective oversight and reaction strategies, assessing the efficacy of various oil disaster clean-up techniques, improving global VOC emissions inventories, studying the distribution and health effects of VOC exposure, exploring innovative mitigation methods, and exploring organic and bio-based remediation procedures were some of the hot spot areas of future research. A few publications advise evaluating remote sensing for oil spill identification and monitoring and assessing the combined effects of many stressors on maritime ecosystems. Other research future research areas include the long-term effects of heavy metal pollution, in-situ burning strategies, salt marsh and coastal ecosystem restoration, and fuel pollution in Antarctica.

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