International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 38 العدد
Part 2 المجلد

المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ

http://www.doi.org/10.62341/istj-vol38-2-ad29

Received	**2026/05/10**	**تم استلام الورقة العلمية في**
Accepted	**2026/05/29**	**تم قبول الورقة العلمية في**
Published	**2026/05/30**	**تم نشر الورقة العلمية في**

Impact of Oil Spills on Humans and the Environment in Libya

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Abstract
Oil spills in Libya represent one of the most pressing contemporary environmental and public health crises, given their far-reaching consequences for ecosystems and human well-being. This systematic review aims to assess the environmental and health impacts of oil spills in Libya, analyze the challenges impeding risk management, and ultimately present practical and actionable solutions. Libya holds the largest proven oil reserves in Africa (48.4 billion barrels), with the oil sector contributing over 90% of government revenues, rendering the national economy almost entirely dependent on this industry. However, aging infrastructure—largely constructed between the 1960s and 1980s with no systematic modernization—coupled with recurring armed conflicts since 2011, has led to repeated oil spills in both terrestrial and marine environments. The most recent incident, the January 2026 grounding of the Russian-flagged tanker Mikhail Odintsov off the coast of Al-Khums, starkly exposed the fragility of Libya's maritime emergency response capabilities.

Environmental impacts include the destruction of sensitive marine ecosystems such as seagrass meadows, contamination of soil and groundwater, and air quality deterioration resulting from volatile organic compound emissions. At the health level, risks are unevenly concentrated among communities adjacent to oil fields, refineries, and export terminals, where elevated rates of chronic respiratory

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diseases, dermatological conditions, and malignancies have been documented. The researcher identifies a critical knowledge gap characterized by the rarity of longitudinal epidemiological studies, population-based cancer registries, and biomonitoring programs capable of measuring hydrocarbon metabolites in exposed populations.
The researcher concludes that the challenges are fundamentally institutional and political, not merely technical. Immediate recommendations include: prepositioning containment equipment at three strategic ports, adopting a ready-made contingency plan template, conducting a focused field survey of five priority sites, and establishing a monthly inter-agency coordination mechanism. Strategic recommendations include: rebuilding human capacity through regional training partnerships, creating a deterrent penalty system, launching a pilot biomonitoring study in Brega, decentralizing response authority to three regional entities, and activating meaningful participation in the Barcelona Convention. The researcher estimates the cost of immediate recommendations at 3-5 million USD, while the cost of in action exceeds 500 million over two decades.
Keywords: Oil spills, Libya, environmental impacts, health impacts, risk management, knowledge gap, emergency response, Russian tanker, systematic review.

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http://www.doi.org/10.62341/istj-vol38-2-ad29

تأثير التسربات النفطية على الإنسان والبيئة في ليبيا

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الملخص

تُعد التسربات النفطية في ليبيا واحدة من أخطر القضايا البيئية والصحية المعاصرة، بالنظر إلى ما تخلّفه من آثار بعيدة المدى على النظم الإيكولوجية وصحة الإنسان. تهدف هذه المراجعة المنهجية إلى تقييم التأثيرات البيئية والصحية للتسربات النفطية في ليبيا، وتحليل التحديات التي تعوق إدارة المخاطر، وصولاً إلى تقديم حلول عملية قابلة للتنفيذ. تمتلك ليبيا أكبر احتياطي نفطي مؤكد في أفريقيا (48.4 مليار برميل)، ويعتمد اقتصادها بشكل شبه كامل على هذا القطاع الذي يسهم بأكثر من 90% من الإيرادات الحكومية. بيد أن تقادم البنية التحتية—التي شُيدت بين ستينيات وثمانينيات القرن الماضي دون تحديث يذكر—إلى جانب النزاعات المسلحة المتعاقبة منذ عام 2011، أدى إلى تسربات نفطية متكررة في البيئات البرية والبحرية. وكان آخر هذه الحوادث جنوح الناقلة الروسية "ميخائيل أودينتسوف" قبالة سواحل مدينة الخمس في يناير 2026، وهو الحادث الذي كشف هشاشة قدرات الاستجابة للطوارئ البحرية.

تتمثل التأثيرات البيئية في تدمير النظم البحرية الحساسة كالأعشاب المرجانية، وتلوث التربة والمياه الجوفية، وتدهور جودة الهواء بانبعاث المركبات العضوية المتطايرة. وعلى المستوى الصحي، تتركز المخاطر في المجتمعات المجاورة للحقول النفطية والمصافي والموانئ، حيث ترتفع معدلات الإصابة بأمراض الجهاز التنفسي المزمنة والآفات الجلدية والأمراض السرطانية. ويكشف الباحث عن فجوة معرفية خطيرة تتمثل في ندرة الدراسات الوبائية الطولية وسجلات السرطان السكانية وبرامج الرصد البيولوجي.

يخلص الباحث إلى أن التحديات ليست تقنية بل مؤسسية وسياسية بطبيعتها. يوصي بإجراءات فورية: توزيع معدات الاحتواء في ثلاثة موانئ، اعتماد خطة طوارئ جاهزة، مسح خمسة مواقع ملوثة، وإنشاء آلية تنسيق شهرية. كما يوصي بحلول استراتيجية: إعادة

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بناء القدرات البشرية عبر الشراكات الإقليمية، إنشاء نظام غرامات رادع، إطلاق دراسة رصد بيولوجي في البريقة، لا مركزية سلطة الاستجابة، وتفعيل اتفاقية برشلونة. يقدر الباحث تكلفة التوصيات الفورية بـ3–5 ملايين دولار، بينما تتجاوز تكلفة الجمود نصف مليار دولار على مدى عقدين.
الكلمات المفتاحية: التسربات النفطية، ليبيا، التأثيرات البيئية، التأثيرات الصحية، إدارة المخاطر، الفجوة المعرفية، الاستجابة للطوارئ، الناقلة الروسية، المراجعة المنهجية.

Introduction

Oil spills represent one of the most severe forms of environmental pollution globally, given their far-reaching impacts on ecosystems and human health. Crude oil contains a complex mixture of pollutants, including polycyclic aromatic hydrocarbons (PAHs) with carcinogenic and bioaccumulative properties, necessitating systematic in-depth investigation (Laffon *et al*., 2016). This study derives its significance from addressing this phenomenon within the Libyan context, where oil constitutes the backbone of the national economy. Libya holds the largest proven oil reserves in Africa (48.4 billion barrels), with the oil sector contributing over 90% of government revenues (OPEC, 2024; World Bank, 2023). Since the commercial discovery of oil at the Zelten field in 1959, Libya has undergone a profound structural transformation from a traditional economy to a rentier system heavily dependent on oil exports, with production peaking at approximately 3.3 million barrels per day by 1970 (Vandewalle, 2012). The nationalization of the industry led to the establishment of the National Oil Corporation (NOC), which continues to oversee exploration, production, and export activities. However, aging infrastructure—largely developed between the 1960s and 1980s without systematic modernization—combined with inadequate maintenance and armed conflicts since 2011, has led to recurrent oil spills in terrestrial and marine environments, resulting in cumulative environmental degradation that remains insufficiently documented (UNEP, 2021). Operational spills have been driven by pipeline failures, corrosion, and loading operations, particularly along the Gulf of Sirte, most notably the 1980 Ras Lanuf spill which polluted approximately 150 km of coastline

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(IMO, 1981). The post-2011 period represents a critical turning point, as armed conflict directly targeted oil infrastructure, leading to some of the largest and most environmentally destructive spills in Libya's history. The 2011 Sarir field incident exemplifie this trend, with an estimated loss of 2.5 million barrels of crude oil and the formation of extensive oil lakes covering hundreds of hectares (UNEP, 2012). Subsequent instability, including sabotage of key export terminals such as Es Sider and Ras Lanuf, further exacerbated marine pollution, while disruptions in major onshore fields—particularly Sharara—resulted in significant desert contamination (Human Rights Watch, 2016; NOC, 2019). Marine incidents have also contributed to this pattern, including the 2006 grounding of the "Port Said" tanker. The persistence of these risks was further underscored in January 2026, when the Russian-flagged vessel *Mikhail Odintsov* ran aground off the coast of Al-Khums, carrying an estimated 800 tons of heavy fuel oil and 200 tons of marine fuel oil. Although the subsequent offloading operation was successfully completed without a large-scale spill, the incident highlighted the fragility of Libya's maritime emergency response capabilities, revealing the absence of updated national contingency plans for dealing with distressed vessels (IMSA, 2026; UNEP, 2026).

A review of the scientific literature on oil pollution impacts reveals two main streams of research. The vast majority of studies confirm that oil spills cause serious and undeniable environmental and health damage, including destruction of marine ecosystems, contamination of soil and groundwater, air quality deterioration, respiratory diseases, dermatological conditions, and malignancies (Boudouresque *et al*., 2012; Laffon *et al*., 2016; Johnston *et al*., 2019; Neff, 2002; Saadoun & Al-Ghzawi, 2005). A second stream of literature argues that the severity of impacts depends significantly on contextual factors such as oil type, spill volume, environmental conditions, and local response capacities, with some studies suggesting that impacts in certain contexts may be less severe due to rapid natural degradation (Zenetos *et al*., 2002). Furthermore, a study of fuel station workers in Benghazi found no statistically significant hematological abnormalities compared to the control

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group, which contradicts international literature confirming such abnormalities (Bengleil *et al*., 2020). From the researcher's perspective, after an in-depth analysis of the available literature and the specific Libyan context, several positions are taken. First, the researcher strongly agrees that oil spills cause indisputable environmental and health damage, as the scientific evidence for this is robust and consistent across decades of research worldwide. Second, the researcher rejects the uncritical generalization of the second stream's findings to the Libyan context, because Libya's unique conditions—aging infrastructure, lack of maintenance, armed conflicts, and weak oversight—would likely increase, not decrease, the severity of impacts compared to contexts that may experience faster recovery. Third, regarding the Benghazi study's findings, the researcher's personal assessment is that this result does not negate the existence of risk but rather reflects the study's limitations in terms of sample size, cross-sectional design, and possibly insufficient exposure duration to produce measurable hematological changes; this does not mean workers are not at risk, but that methodological tools failed to capture this risk, underscoring the need for more rigorous, long-term studies. Fourth, the researcher is fully convinced that the knowledge gap in the Libyan context—characterized by the absence of longitudinal epidemiological studies, population-based cancer registries linked to environmental exposure data, and biomonitoring programs assessing hydrocarbon metabolites in exposed populations—is not merely an academic deficiency but a major obstacle to public health protection, preventing accurate determination of the problem's magnitude and development of evidence-based preventive interventions.

Accordingly, this study aims to achieve four main objectives: first, to present a systematic review of the environmental impacts of oil spills in Libya focusing on marine and terrestrial systems and air quality, while incorporating the researcher's personal analysis within the Libyan context; second, to analyze the acute and chronic health effects of oil spills on Libyan communities, identifying the most vulnerable populations and analyzing the existing knowledge gap; third, to identify and analyze the main challenges facing

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environmental response and risk management efforts in Libya with emphasis on technical, institutional, and political challenges; and fourth, to formulate a set of implementable recommendations classified according to temporal priority aimed at improving environmental response and protecting public health. The primary research question this study seeks to answer is: How can the environmental and health impacts of oil spills in Libya be assessed and addressed, given the absence of systematic local data, weak infrastructure, and political instability? The following table summarizes the most significant documented oil spill incidents in Libya, including both historical events and the recent *Mikhail Odintsov* grounding. The paper then proceeds to examine environmental impacts, human health impacts, challenges in environmental response and risk management, and finally recommendations and proposed solutions.

Table 1. Major Documented Oil Spill Incidents in Libya and Their Environmental Impacts (1980–2026)

Year	Location	Type of Spill	Main Impact
1980	Ras Lanuf Port, Gulf of Sirte	Tanker loading accident	~10,000 tons spilled, 150 km coastline polluted
2006	Off Tripoli coast	Tanker grounding ("Port Said")	Marine pollution (undocumented extent)
2011	Sarir oil field	Armed attack/fire	2.5 million barrels spilled, oil lakes (~500 ha)
2014	Ras Lanuf Port	Sabotage/shutdowns	Limited coastal contamination
2015	Es Sider & Ras Lanuf	Armed clashes	Oil leakage into Mediterranean
2019	Sharara pipeline	Sabotage	Large-scale desert contamination
2020	Brega Port	Operational incidents	Localized environmental damage
2026	Off Al-Khums coast	Vessel grounding (*Mikhail Odintsov*)	1,000 tons of fuel at risk; successful offloading without major spill; exposed emergency response gaps

Source: Compiled by the author based on IMO (1981, 2006), UNEP (2012, 2021, 2026), NOC (2015, 2019, 2020), Human Rights Watch (2016), and IMSA (2026).

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2. Environmental Impacts on Marine, Terrestrial, and Air Systems

Building upon the preceding introduction and the documented historical spill incidents, environmental impacts emerge as a direct extension of these structural and operational disruptions. From the researcher's perspective, oil spills constitute one of the most severe threats to marine and terrestrial ecosystems and air quality in Libya, yet the true magnitude of these impacts remains largely unquantified due to the absence of systematic monitoring. The magnitude of these impacts varies depending on environmental characteristics, oil properties, spill volume, and exposure duration, but the researcher argues that in the Libyan context, the severity is amplified by unique aggravating factors.

Marine and coastal ecosystems are particularly vulnerable, given the concentration of oil infrastructure along Libya's Mediterranean coastline, especially in the Gulf of Sidra, Brega, Ras Lanuf, Benghazi, and Misrata. In the researcher's assessment, the impacts are not limited to acute spill events but also include chronic pollution—the cumulative effect of decades of operational leaks—which leads to long-term contaminant accumulation that has never been properly mapped. Seagrass meadows, particularly *Posidonia oceanica*, are highly sensitive to oil contamination, as oil films inhibit photosynthesis and damage root systems, resulting in biodiversity loss (Boudouresque *et al.*, 2012). Coral reefs are similarly affected through tissue damage and impaired reproductive capacity due to hydrocarbon exposure (Loya & Rinkevich, 1980). The researcher notes that these ecosystems, once degraded, may take decades or even centuries to recover, yet no restoration efforts have been documented in Libya. Marine fauna are impacted across trophic levels; fish experience respiratory dysfunction and organ damage, alongside bioaccumulation and biomagnification of polycyclic aromatic hydrocarbons (PAHs), increasing ecological and human health risks (Neff, 2002). Sea turtles and marine mammals, including dolphins, are affected through inhalation, ingestion, and immune suppression pathways (Lutcavage *et al.*, 1997; Schwacke *et al.*, 2010). Coastal contamination further degrades shoreline ecosystems and undermines economic activities

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such as fisheries and tourism, while imposing high remediation costs under resource-constrained conditions (FAO, 2018). From the researcher's perspective, the economic impact on local fishing communities—who have no alternative livelihoods—is among the most pressing yet overlooked consequences.
In terrestrial environments, desert soils in production areas suffer long-term contamination from pipeline leaks, oil lakes, and improper disposal of produced water. Due to low microbial activity and organic content, natural attenuation processes are limited, allowing pollutants to persist for decades (Saadoun & Al-Ghzawi, 2005). The researcher observes that the Sarir oil lakes, formed in 2011, remain largely untreated, releasing volatile organic compounds continuously for over a decade. This leads to vegetation loss, desertification, and habitat degradation. Groundwater resources, the primary water supply in Libya, are at significant risk due to the infiltration of soluble hydrocarbons such as benzene and PAHs, posing long-term threats to drinking water safety (Fetter, 1999). The researcher considers this the most dangerous long-term impact, as groundwater contamination is virtually irreversible and would affect millions of Libyans.
Air quality is also severely affected by emissions of volatile organic compounds (VOCs), including benzene, toluene, and xylene, particularly from oil lakes and flaring activities. These emissions, combined with nitrogen and sulfur oxides and particulate matter, contribute to significant air quality deterioration and associated health risks (WHO, 2021). In the researcher's view, the absence of air quality monitoring stations near oil fields means that residents have been breathing unknown levels of carcinogens for decades without any public health intervention. Additionally, regional environmental characteristics—such as arid conditions and oligotrophic marine systems—reduce ecosystem resilience, resulting in long-lasting and cumulative environmental impacts (Zenetos *et al.*, 2002). The researcher concludes that addressing these environmental impacts requires not only technical solutions but also a fundamental shift in how environmental data is collected and shared in Libya.

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3. Human Health Impacts (Acute and Chronic)

Building upon the previously discussed environmental impacts, the public health dimension emerges as a direct and consequential extension of these effects. Hydrocarbon pollutants are transmitted through multiple environmental pathways, ultimately affecting human populations and generating a complex and long-term health burden. Despite the significance of this issue, a critical review of the available literature reveals a substantial knowledge gap in the Libyan context.

3.1 Detailed Analysis of the Knowledge Gap (Researcher's Perspective)

What is the knowledge gap exactly? The Libyan context suffers from the complete absence of three essential components of environmental health research: (1) longitudinal epidemiological studies that track exposed populations over time; (2) population-based cancer registries linked to environmental exposure data; and (3) biomonitoring programs that measure hydrocarbon metabolites in exposed populations, such as urinary PAH metabolites or blood benzene levels. This is not a partial gap but a total void.
Why is this gap dangerous? From the researcher's perspective, the absence of this data means that public health authorities cannot answer basic questions: Are cancer rates higher near oil fields? Do children in Brega have lower lung function than children in non-oil regions? Are miscarriages more common among women living near refineries? Without answers to these questions, evidence-based interventions are impossible. The researcher argues that this gap likely conceals a severe but invisible public health crisis, where diseases are being attributed to other causes or simply going unrecorded.
How does this gap affect future research and policymaking? The researcher identifies three critical consequences. First, international organizations and donors cannot justify funding for health interventions without baseline data. Second, affected communities cannot claim compensation or demand relocation without scientific evidence linking their illnesses to oil pollution. Third, Libyan

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researchers lack a foundation upon which to build further studies, perpetuating the cycle of ignorance.

The researcher's vision for bridging this gap: Addressing this requires a three-step national strategy: (1) establish a pilot biomonitoring study in a high-exposure community such as Brega or Ras Lanuf to measure PAH metabolites and establish baseline exposure levels; (2) create a national environmental health registry that links health records with residential proximity to oil facilities; (3) train Libyan researchers in environmental epidemiology through partnerships with international universities. Without these steps, the researcher asserts that the knowledge gap will persist for another generation, and the true health cost of Libya's oil wealth will remain unknown.

3.2 Exposure Pathways and Health Risks

In the absence of robust local data, this analysis draws upon high-quality international evidence—including cohort studies and meta-analyses—and cautiously applies these findings to the Libyan context (Laffon *et al*., 2016). Evidence indicates that health risks are unevenly distributed, disproportionately affecting populations residing near oil fields, refineries, and export terminals. Field data from Brega, for instance, report high prevalence rates of respiratory (58%) and dermatological (61.5%) symptoms among residents, albeit based on self-reported measures (Gadalla *et al*., 2022). From the researcher's perspective, even self-reported data at this magnitude signals a genuine public health emergency that warrants immediate investigation. Additional high-risk groups include oil industry workers and coastal communities, particularly artisanal fishermen exposed through both environmental contact and consumption of contaminated seafood.

Health risks are strongly influenced by primary exposure pathways: inhalation, dermal contact, and ingestion. Inhalation represents the most critical route due to the widespread presence of volatile organic compounds (VOCs) such as benzene, toluene, and xylene, which are rapidly absorbed through the respiratory system and distributed systemically (Rajabi *et al*., 2020). Dermal exposure occurs through direct contact with contaminated soil or water, leading to dermatological conditions, while ingestion—particularly

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via contaminated seafood—poses significant risks due to bioaccumulation and biomagnification within the food chain.

3.3 Acute and Chronic Health Effects

Acute health effects are well-documented and include respiratory symptoms such as coughing and dyspnea, exacerbation of pre-existing conditions like asthma, dermatological irritation, and transient neurological symptoms including headaches and dizziness (Abereton *et al*., 2023). These outcomes are primarily driven by oxidative stress and inflammatory responses at the cellular level.

Chronic health effects, however, represent the most serious public health concern. Petroleum hydrocarbons, particularly benzene and polycyclic aromatic hydrocarbons (PAHs), are associated with well-established carcinogenic risks, including leukemia and cancers of the lung and skin (Falcão *et al*., 2025). Long-term exposure is also linked to chronic respiratory diseases, hepatic and renal dysfunction, and adverse reproductive outcomes such as miscarriage, preterm birth, and congenital anomalies (Ghobakhloo *et al*., 2024).

Beyond physiological impacts, oil spills exert profound psychological and socio-economic effects. Affected populations often experience chronic stress, anxiety, and depression, compounded by economic disruption, particularly in communities dependent on fisheries and coastal resources. These factors contribute to a cycle of vulnerability that exacerbates both health and socio-economic instability. The researcher concludes that the Libyan population faces significant health risks that are likely amplified by weak regulatory frameworks and limited healthcare infrastructure. Bridging the knowledge gap is not merely an academic exercise but a moral imperative to protect public health.

The following figure presents an integrated overview of the interconnected environmental and human health impacts of oil pollution in Libya. It illustrates how oil spills affect marine, terrestrial, and air systems, while exposing human populations through multiple pathways such as inhalation, dermal contact, and ingestion. The figure highlights the vulnerability of coastal ecosystems, groundwater resources, and local communities, particularly in oil-producing regions such as the Gulf of Sidra, Brega, and Ras Lanuf. It also emphasizes the long-term risks

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associated with chronic pollution, including biodiversity loss, groundwater contamination, respiratory diseases, and carcinogenic effects linked to hydrocarbon exposure. Furthermore, the figure underscores the significant knowledge gap in Libya resulting from the absence of systematic environmental monitoring, epidemiological studies, and biomonitoring programs, stressing the urgent need for integrated environmental and public health strategies.

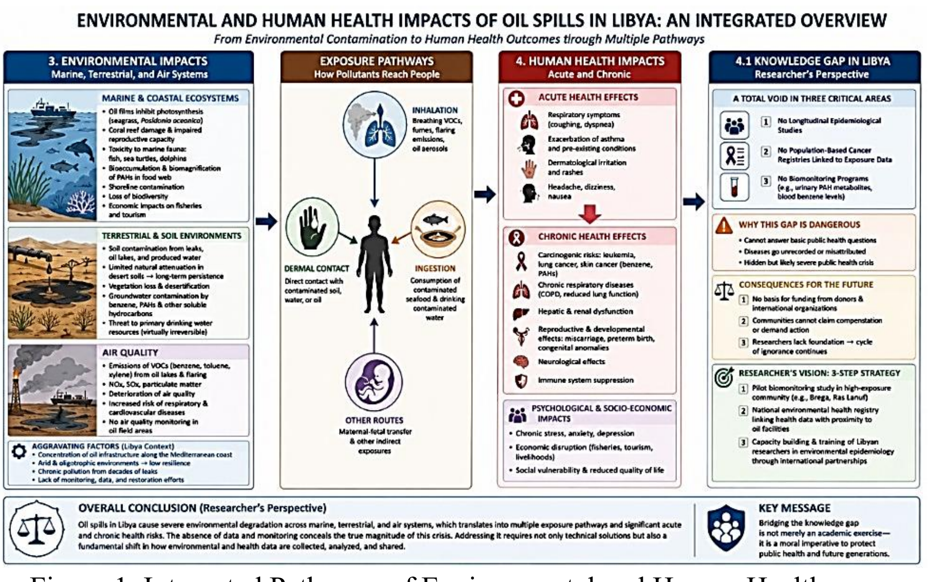

Figure 1. Integrated Pathways of Environmental and Human Health Impacts of Oil Pollution in Libya. Source: Prepared by the Researcher Based on the Reviewed Literature.

4. Challenges in Environmental Response and Risk Management

Based on this analysis, the researcher identifies seven fundamental challenges facing environmental response and risk management efforts in Libya. These challenges span technical deficiencies, institutional fragmentation, and political instability. The researcher concludes that these obstacles are fundamentally institutional and political, not merely technical. The Mikhail Odintsov incident (2026) validated this assessment, exposing critical maritime response gaps. ***(A detailed structural mapping of these challenges***

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and their independent solutions is integrated within the final framework in Section 5).

5. Recommendations and Proposed Solutions

This systematic review underscores that the oil spill crisis in Libya is fundamentally an institutional and political dilemma rather than a purely technical failure. While aging infrastructure and armed conflicts since 2011 have driven environmental degradation across marine and terrestrial ecosystems, the chronic absence of systematic monitoring and environmental health registries conceals a severe public health crisis. To bridge the dangerous knowledge gap and strengthen Libya's emergency response capabilities, the strategic recommendations must directly neutralize the identified institutional challenges.

To provide a transparent, metrics-driven path forward, the table below maps each critical challenge identified in this study to its independent, actionable solution, categorized by temporal priority and estimated financial resource requirements:

Immediate Priorities (0–12 Months)

- **Resolving Challenge 1 (No Response Equipment): Prepositioning Containment Equipment** To address the total lack of containment booms, skimmers, or specialized pumps at Libyan ports, the state must immediately procure and deploy rapid-response equipment at three strategic ports: Tripoli, Ras Lanuf, and Benghazi. This requires an estimated budget of $2 to $3 million, which can be requested through technical assistance from the International Maritime Organization (IMO) and the United Nations Environment Programme (UNEP).
- **Resolving Challenge 2 (No Functional Contingency Plan): Adopting Global Templates** To replace current national protocols that exist only on paper and remain untested—as exposed by the 2026 *Mikhail Odintsov* incident —Libya must complete a direct adaptation of the standard IMO contingency plan template within 6 months. This solution relies on a low-cost, technical assistance framework rather than inventing a plan from scratch.

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- **Resolving Challenge 3 (Institutional Fragmentation): Establishing an Inter-Agency Working Group** To overcome the fragmented governance and shared authority among the National Oil Corporation (NOC), Environment Authority, Ministry of Health, and Ministry of Water, a formalized monthly coordination working group must be established. This administrative mechanism unifies data sharing and response command structures without requiring any additional budget.
- **Resolving Challenge 4 (No Environmental Data): Executing Targeted Priority Surveys** To remedy the total void in baseline environmental data and air quality monitoring near oil fields, the state must bypass comprehensive, long-term mapping initially and focus on immediate field surveys across 5 high-risk sites: the Sarir oil lakes, Gulf of Sidra, Sharara, Brega, and Al-Khums. The costs will be absorbed into the initial environmental response framework.

Strategic Priorities (1–5 Years)

- **Resolving Challenge 5 (Critical Knowledge Gap): Launching a Pilot Biomonitoring Project** To bridge the dangerous total void in longitudinal epidemiological data and baseline exposure metrics, Libya must launch its first human biomonitoring study in a high-exposure community like Brega. The project will track polycyclic aromatic hydrocarbon (PAH) metabolites in a cohort of 200 residents, requiring a strategic budget of $150,000 to $250,000.
- **Resolving Challenge 6 (No Legal Enforcement): Implementing a Deterrent Penalty System** To activate Environmental Law No. 15, which has historically been ignored in favor of unverified self-reported data, a strict legal enforcement mechanism must be created. This system will impose escalating public financial penalties indexed directly to the volume of spilled crude oil, with all violations and penalty records published transparently online to generate state revenue and deter corporate negligence.
- **Resolving Challenge 7 (No Trained Personnel): Initiating Regional Capacity Building** To reverse the severe erosion of technical training and institutional knowledge that has persisted

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http://www.doi.org/10.62341/istj-vol38-2-ad29

since 2011, Libya must establish strategic training partnerships with regional neighbors including Turkey, Egypt, and Tunisia. This institutional funding and regional grant framework will sponsor the annual training of 10 to 20 Libyan experts, with each expert required to train 5 additional personnel upon their return.

In summary, choosing political and institutional inaction threatens a cumulative economic and environmental toll exceeding $500 million over the next two decades. Conversely, implementing these independent, structured solutions proves that acting small on immediate targets can successfully safeguard Libya's public health and rescue its vital coastal and desert ecosystems.

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