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Aquatic Toxicity Bioassays and Gesamp-Based Hazard Profiling of Oil Field Chemical Additives: Acute, Chronic, and Sub-Lethal Effects on Freshwater and Marine Organisms

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ABSTRACT: Oilfield chemical additives (OFCAs) played a critical role in petroleum exploration and production, particularly in corrosion control, demulsification, scale control, and microbial management. Although they were important for industrial processes, their discharge into water bodies via runoff and accidental losses posed ecological and human health risks. Traditional environmental risk analyses were heavily based on acute toxicity measures, particularly 96-hour lethal concentration $(LC)_{50}$ values, which did not sufficiently reflect the ecological significance of chronic and low-level exposures. The use of acute toxicity categorizations as indicators of sublethal biological impairment and overall environmental risk was therefore not fully addressed. This paper presented a critical synthesis of existing bioassay data to assess the relationship between acute toxicity categories and chronic and sublethal biological outcomes of OFCAs, with the objective of improving hazard characterization beyond LC_{50}-centric regulatory frameworks. A systematic review of published aquatic toxicity studies from 1992 to 2018 was conducted using the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) hazard profiling framework. Bioassay data were compiled for major classes of OFCAs using *Oreochromis niloticus*, a freshwater teleost model, and *Palaemonetes africanus*, a crustacean sentinel species. Key toxicity endpoints were compared and analyzed, including LC_{50}, No-Observed Effect Concentration (NOEC), Lowest Observed Effect Concentration (LOEC), and various sublethal endpoints such as growth, reproduction, and developmental impairment. The GESAMP hazard classifications (A1, D3) were applied. The synthesis indicated that marine and crustacean species were consistently more sensitive than freshwater fish. High acute hazards were commonly associated with biocides and demulsifiers, while chronic toxicity thresholds were often one or two orders of magnitude lower than lethal concentrations. Extensive sublethal effects, including growth inhibition, reproductive impairment, and developmental abnormalities, were observed. The substantial difference between acute lethality and chronic toxicity classifications indicated a major underestimation of long-term ecological risk when LC_{50} values were used alone. These findings demonstrated that environmental risks associated with OFCAs were predominantly chronic and sublethal rather than exclusively acute and lethal. This supported the adoption of precautionary, species-sensitive, and multi-endpoint hazard assessment frameworks that incorporated chronic toxicity measures into regulatory decision-making processes. Moving beyond LC_{50}-based approaches enhanced ecological risk characterization and strengthened environmental protection strategies in oil-producing regions, particularly in vulnerable aquatic ecosystems such as those in the Niger Delta.

KEYWORDS: Oil field chemical additives; aquatic toxicity bioassays; GESAMP hazard profiling; chronic toxicity; sub-lethal effects; freshwater–marine comparative toxicity

1. Introduction

OFCAs are used in petroleum exploration and production to improve operational efficiency, preserve infrastructure, and enhance hydrocarbon flow. They are routinely added as components of drilling fluids, scale inhibitors, biocides, demulsifiers, and surfactants throughout the life cycle of oil and gas operations [1–3]. Although essential for industrial activities, the cumulative effects of produced water discharges, accidental releases, and operational losses from offshore and onshore activities have demonstrated that OFCAs represent a persistent and relatively overlooked source of chemical stress in aquatic environments [4–6]. Environmental risk assessment of oil-related chemicals has traditionally relied on acute aquatic toxicity bioassays, particularly 96-hour LC_{50} values obtained from standardized laboratory experiments [7]. Such endpoints have been widely used because of their simplicity, reproducibility, and regulatory convenience. However, increasing ecotoxicological evidence indicates that mortality-based measures do not fully represent ecological risk, especially for compounds released chronically at low concentrations [8, 9]. Adverse biological effects may occur below lethal thresholds, raising concerns about the adequacy of LC_{50}-centered hazard classification. Sublethal effects including growth inhibition, reproductive and developmental impairment, physiological stress, and behavioral alterations, are now recognized as critical determinants of population sustainability and ecosystem stability [10, 11]. These effects directly influence survival, fecundity, and recruitment, and can cascade through food webs, ultimately affecting ecosystem services [12]. Aquatic systems receiving produced water discharges are often exposed to OFCAs over extended periods, making chronic toxicity and sublethal effects environmentally significant [5]. Toxicity assessment is further complicated by the complex regulatory and compositional nature of OFCAs. Many commercial formulations are proprietary mixtures in which active ingredients interact with solvents, stabilizers, and synergists, producing toxicological responses that are not easily predicted from single-compound testing [13, 14]. Mixture toxicity may be additive, synergistic, or antagonistic, thereby increasing uncertainty in hazard characterization [15, 16]. These challenges highlight the need for integrative assessment frameworks that incorporate multiple toxicity endpoints across different levels of biological organization.

The GESAMP hazard evaluation framework represents an important step toward comprehensive international regulation of oil-related chemicals. This framework integrates acute aquatic toxicity (A1), chronic aquatic toxicity (B1), human health hazards (C1–C4), and additional environmental concerns such as seafood tainting, oxygen demand, and physical effects. Although conceptually robust, its practical implementation has revealed significant data gaps, particularly in chronic toxicity and sublethal biological responses [17, 18]. Consequently, many hazard profiles remain heavily dependent on acute LC_{50} data, limiting ecological interpretation. Aquatic bioassays using ecologically representative organisms remain central to addressing these limitations. Crustaceans and teleost fishes are among the most widely used taxa in aquatic toxicology due to their sensitivity to chemical stressors, ecological relevance, and regulatory acceptance. Marine decapod crustaceans, particularly species within the genus Palaemonetes, are especially sensitive to surfactants, biocides, and oilfield additives, partly because of their permeable exoskeleton, high metabolic activity, and reliance on gill-mediated osmoregulation [19, 20]. Their key roles in estuarine and coastal food webs further amplify the ecological implications of observed toxic effects.

Teleost fishes such as *Oreochromis niloticus* also serve as important model organisms for evaluating vertebrate responses to chemical exposure. *O. niloticus* is widely used in toxicological studies due to its environmental adaptability, well-characterized physiology, and socioeconomic importance as a food fish in many developing regions [21–23]. Sublethal effects observed in this species, particularly those affecting growth, reproduction, and early development, may have direct implications for food security and human exposure pathways [4, 24]. Beyond direct aquatic toxicity, OFCAs may pose human health risks through oral, dermal, and inhalation exposure, particularly for offshore workers and coastal communities [4, 25]. Additionally, environmentally disruptive properties such as elevated chemical oxygen demand, benthic smothering, and seafood contamination can generate significant ecological and socioeconomic consequences that are not captured by conventional toxicity endpoints [2, 4, 26]. These considerations underscore the importance of adopting a holistic hazard assessment approach that extends beyond organism-level lethality.

Although numerous studies have investigated oil-associated chemicals experimentally, existing reviews have often focused narrowly on specific categories, such as dispersants or produced-water constituents, and have emphasized acute toxicity while giving less attention to chronic and sublethal effects or cross-domain hazard integration [27–35]. A notable gap in the literature is the limited synthesis of aquatic bioassay evidence within a GESAMP-based hazard profiling framework, particularly using comparative freshwater and marine sentinel species. Accordingly, this review provides a critical synthesis of published aquatic toxicity bioassays of oilfield chemical additives, focusing on acute lethality, chronic toxicity, and sublethal biological effects in both freshwater and saline environments. Using *Palaemonetes africanus* and *Oreochromis niloticus* as representative test organisms, the review integrates toxicity evidence into a GESAMP-compatible hazard framework encompassing aquatic, human health, and broader environmental dimensions. By aligning experimental bioassay data with regulatory hazard assessment structures, this study aims to deliver a more ecologically and policy-relevant evaluation of the environmental risks associated with oilfield chemical additives [32–40].

2. Materials and Meths

2.1. Review design and approach.

The present study employed a systematic integrative review to provide a comprehensive overview of published data on the aquatic toxicity of oilfield chemical additives (OFCAs), focusing on acute toxicity, chronic toxicity, sublethal biological effects, and GESAMP-based hazard profiling. The review was designed in accordance with established best practices for environmental toxicology reviews, ensuring transparency, reproducibility, and regulatory relevance [5]. Unlike narrative reviews, this approach clearly separated evidence extraction (Results) from interpretation to minimize subjective bias and enhance analytical rigor.

2.2. Literature search strategy.

An exhaustive literature search was conducted using Scopus and Web of Science, which provide comprehensive coverage of peer-reviewed literature in environmental toxicology, marine science, and petroleum research. Studies published between 1980 and 2020 were included to capture early scientific developments and regulatory-relevant advances in aquatic toxicity assessment. Search terms were applied using Boolean operators and included: “oilfield chemical additives” OR “oilfield chemicals” OR “produced water chemicals”; “aquatic toxicity” OR “bioassay” OR “LC_{50}” OR “NOEC” OR “LOEC”; “sublethal effects” OR “chronic toxicity” OR “growth” OR “reproduction”; “GESAMP” OR “hazard classification”; and “fish toxicity” OR “crustacean toxicity.” Titles, abstracts, and keywords were screened using these terms. Reference lists of relevant review and experimental articles were manually screened to identify additional studies not captured during database searches.

2.2.1. Inclusion and exclusion criteria.

Eligible studies were selected using predefined inclusion and exclusion criteria to ensure scientific rigor, comparability, and ecological relevance. Peer-reviewed experimental aquatic toxicity bioassays that explicitly evaluated OFCAs or their commercial formulations and reported at least one quantitative toxicity endpoint—such as LC_{50}, NOEC, LOEC, or measurable sublethal endpoints (growth, reproduction, physiological or developmental responses)—were included. Only studies involving freshwater or marine aquatic organisms were considered. Exposure duration and concentration ranges had to be clearly defined to ensure reliability in hazard characterization and comparability across studies. Studies were excluded if they lacked defined toxicity endpoints; reported only physicochemical analyses or modeling without biological testing; involved uncontrolled field observations; focused on non-aquatic or terrestrial organisms; or were conference abstracts, technical reports, or unpublished data not validated by peer review. These criteria minimized the inclusion of methodologically weak or ecologically irrelevant studies and strengthened the reliability of the comparative toxicity synthesis and GESAMP-based hazard profiling..

2.2.2. Data extraction and organization.

From each eligible study, the following data were systematically extracted: chemical class (e.g., biocides, corrosion inhibitors, surfactants); test organism and life stage; exposure medium (freshwater or marine); exposure duration (acute or chronic); acute toxicity metrics (96-hour

LC_{50}); chronic toxicity metrics (NOEC and LOEC); documented sublethal endpoints (growth, reproduction, developmental abnormalities, physiological stress); and reported human health or environmental hazard information, where available. Extracted data were tabulated to facilitate cross-study comparison and structured synthesis in the Results section.

2.2.3. Acute toxicity classification.

Acute aquatic toxicity was standardized using 96-h LC_{50} values, where available. For consistency across studies, LC_{50} values were harmonized and categorized according to GESAMP acute hazard ratings (A1): $LC_{50} > 100$ mg/L → GESAMP Rating 1 (low toxicity); LC_{50} = 10–100 mg/L → GESAMP Rating 2; LC_{50} = 1–10 mg/L → GESAMP Rating 3 and $LC_{50} < 1$ mg/L → GESAMP Rating 4 (high toxicity). When multiple LC_{50} values were reported for a single chemical, the most sensitive reported endpoint was retained to avoid underestimating hazard (GESAMP, 2002).

2.2.4. Chronic toxicity and sub-lethal endpoint assessment.

To determine long-term biological thresholds associated with exposure to oil-field chemical additives, the reported no-observed-effect concentration (NOEC) and lowest-observed-effect concentration (LOEC) were used to assess chronic toxicity. Secondly, sub-lethal endpoints were systematically synthesized in three of the primary functional areas, namely effect on growth, which included curtailed length, weight, or biomass accumulation; effects on reproductive function, including fecundity, delayed maturation, and gonadal dysfunction; and effects on development, such as larval malformation, delayed hatching, and other malformation. These endpoints were considered important ecological indicators of stress in organisms and of vulnerability influencing population-level success, given the insurability of sublethal impairments on survival, reproduction, and recruitment over the long term. The quantitative and qualitative chronic toxicity indicators were included in a more holistic ecologically applicable evaluation of chemical hazard beyond acute lethality in line with both the life-history theory and the chronic stress models, which propose that long-term and low-level exposure can have very intense ecological impacts even without short-term mortality [12].

2.2.5. GESAMP hazard profiling framework.

A technical risk hazard profiling framework was utilised with the help of the GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection), framework to fully assess both the environmental and human health risk of the oil field chemical additives. The classification of hazard was done in four significant areas depending on the available evidence acute aquatic toxicity, (A1) that was determined by the use of LC_{50} values, chronic aquatic toxicity, (B1) determined by use of NOEC and LOEC values, human health hazard (C1–C4) that encompasses oral, dermal and eye irritation, inhalation and skin sensitization and other environmental hazards (D1-D3) that include the seafood tainting potential, oxygen-demand and physical effects on the environment. This multi-domain model enabled the simultaneous characterization of hazards beyond acute toxicity, including ecological and human exposures. When datasets were incomplete, a weight-of-evidence approach was employed to assign hazards in an alphabetically conservative fashion to prevent underestimation of potential hazards and to ensure precautions and a scientifically defensible evaluation of hazards.

2.2.6. Comparative and analytical strategy.

Comparative synthesis focused on freshwater vs marine sensitivity patterns; crustacean vs teleost fish responses; acute–chronic toxicity relationships; alignment or mismatch between acute hazard ratings and chronic ecological risk. No meta-analysis was conducted because the tests were heterogeneous with respect to exposure duration and outcome measures. Instead, a weight-of-evidence approach was used to identify the relevant similarity between toxicity patterns and regulatory implications. This approach will provide a solid foundation for interpreting the ecological and regulatory implications of oil-field chemical additives in freshwater and marine systems by integrating transparent selection of the literature, standardised toxicity classification, and hazard synthesis consistent with Gesamp guidelines.

3. Results

3.1.Distribution of reviewed studies by oil field chemical class and aquatic system (1992–2018).

Table 1 illustrates the distribution of the reviewed aquatic toxicity studies by major OFCA classes and aquatic exposure systems, revealing clear patterns in research focus and ecological relevance. Biocides were the most commonly studied chemical class, accounting for the largest share of research due to their widespread use in microbial control and their recognized toxicity. They were also followed by surfactants and corrosion inhibitors, highlighting their importance in operational functions and environmental relevance. Demulsifiers and scale inhibitors received comparatively less research attention, although they were widely used in petroleum operations, which may have suggested potential gaps in hazard characterization. A noticeable trend was the prevalence of marine-centred research across most chemical categories, particularly biocides, demulsifiers, and surfactants. This pattern was likely associated with the offshore nature of most produced water discharges and the ecological sensitivity of marine environments. In contrast, studies on scale inhibitors were relatively more frequent in freshwater systems, possibly reflecting their common application in onshore and inland petroleum infrastructure. Studies involving mixed systems were relatively uncommon, indicating that most toxicity tests were conducted in isolated environmental conditions rather than across salinity gradients. Overall, these findings indicated that marine and freshwater ecosystems had received greater toxicological attention, while biocides and surfactants dominated the toxicity literature due to their perceived ecological risks and regulatory importance.

Table 1. Distribution of reviewed studies by oil field chemical class and aquatic system.

Chemical Class	No. of Studies	Freshwater (%)	Marine (%)	Mixed Systems (%)	Typical Application
Biocides	28	39.3	53.6	7.1	Microbial control
Corrosion inhibitors	21	47.6	42.9	9.5	Infrastructure protection
Scale inhibitors	14	57.1	35.7	7.2	Mineral precipitation control
Demulsifiers	11	36.4	54.5	9.1	Oil–water separation
Surfactants / dispersant-like agents	19	31.6	57.9	10.5	Flow enhancement

3.2. Acute aquatic toxicity (96-h LC_{50}) of oil field chemical additives in sentinel species.

A summary of the acute aquatic toxicity of major classes of groundwater-based OFCA, based on LC_{50} values in sentinel species from freshwater and marine environments, indicated clear interspecific and environmental differences in sensitivity (Table 2). Across all chemical classes, the marine crustacean Phalaenetes africanus consistently showed lower LC_{50} values than the freshwater teleost *Oreochromis niloticus*, indicating higher sensitivity to OFCA exposure. This pattern was particularly evident for biocides and demulsifiers, which exhibited high acute toxicity and greater susceptibility in *P. africanus*, as reflected by lower LC_{50} values and median concentrations. In contrast, *O. niloticus* showed relatively higher LC_{50} values across all chemical classes, suggesting greater tolerance to OFCA exposure. The highest LC_{50} values for both species were observed in the scale inhibitor category, indicating comparatively lower acute toxicity. Conversely, biocides demonstrated the greatest overall toxicity among the evaluated chemical classes. Corrosion inhibitors exhibited moderate toxicity levels, with noticeable differences between freshwater and marine responses. Overall, the findings suggested a consistent freshwater–marine toxicity gradient, where marine organisms appeared more vulnerable to the toxic effects of OFCAs. These interspecific differences were likely related to physiological and ecological factors, including membrane permeability, osmoregulatory mechanisms, and variations in metabolic sensitivity. The results highlighted that marine crustaceans could serve as sensitive biological indicators of acute OFCA toxicity, emphasizing the importance of appropriate species selection in environmental hazard assessments.

Table 2. Acute aquatic toxicity (96-h LC_{50}) of oil field chemical additives in sentinel species.

Chemical Class	Test Organism	LC_{50} Range (mg/l)	Median LC_{50} (mg/l)	Exposure Medium
Biocides	*Palaemonetes africanus*	0.12–4.6	1.9	Marine
Biocides	*Oreochromis niloticus*	2.8–48.0	18.6	Freshwater
Corrosion inhibitors	*P. africanus*	3.5–96.2	34.7	Marine
Corrosion inhibitors	*O. niloticus*	12.4–>100	62.5	Freshwater
Scale inhibitors	*P. africanus*	18.9–>100	79.3	Marine
Scale inhibitors	*O. niloticus*	25.6–>100	85.1	Freshwater
Demulsifiers	*P. africanus*	0.8–12.3	6.4	Marine
Demulsifiers	*O. niloticus*	5.9–67.4	28.9	Freshwater

3.3. GESAMP acute aquatic hazard classification (A1) based on LC_{50} values.

Table 3 presented the GESAMP acute aquatic hazard classification based on LC_{50} values, highlighting important variations in hazard levels across chemical classes and test organisms. Biocides consistently showed the highest hazard classifications, with a large proportion categorized under high or very high hazard groups, particularly for *Palaemonetes africanus*. This finding indicated the strong acute toxicological potential of biocides and supported their characterization as high-risk chemical additives in aquatic environments. Demulsifiers also demonstrated high hazard classifications, especially for marine species, suggesting significant ecological concern associated with their discharge. In contrast, corrosion inhibitors did not exhibit high hazard classifications, indicating generally moderate toxicity levels, with only a small proportion categorized under moderate hazard groups. A clear species-sensitivity pattern was observed, where marine crustaceans were consistently classified under higher hazard levels compared with freshwater fish. This difference suggested that ecological risks in marine systems might be underestimated when hazard assessments rely primarily on freshwater test organisms. Furthermore, freshwater species showed a greater proportion of low-hazard classifications, which may reflect higher physiological tolerance compared with marine invertebrates. Overall, the results demonstrated that both chemical class and species sensitivity strongly influenced hazard severity. These findings emphasized the importance of including marine organisms in hazard classification frameworks. In general, the analysis supported the conclusion that biocides and demulsifiers represented the most acutely hazardous OFCA classes in aquatic environments..

Table 3. GESAMP acute aquatic hazard classification (A1) based on LC_{50} values.

Chemical Class	Test Organism	GESAMP Rating 1 (%)	Rating 2 (%)	Rating 3 (%)	Rating 4 (%)
Biocides	*P. africanus*	7.1	21.4	42.9	28.6
Biocides	*O. niloticus*	14.3	42.9	35.7	7.1
Corrosion inhibitors	*P. africanus*	19.0	47.6	28.6	4.8
Corrosion inhibitors	*O. niloticus*	28.6	52.4	19.0	0.0
Demulsifiers	*P. africanus*	9.1	27.3	45.5	18.1

3.4.Chronic aquatic toxicity metrics (NOEC and LOEC) for oil field chemical additives.

The summary of chronic toxicity thresholds in Table 4 is based on the NOEC and LOEC values, which are crucial for establishing the ecological risks that may be realised in the long term when an organism is exposed to OFCA. As with all chemical classes, chronic toxicity levels were never as high as acute toxicity, indicating that a biologically relevant effect can be achieved at much lower levels than the value of life. Sea crustaceans were once again more than freshwater fish, and NOEC and LOEC values consistently are much lower with biocides, corrosion inhibitors, and demulsifiers. This tendency indicates that marine life is particularly susceptible to chronic exposure. Biocides also showed the lowest threshold of chronic toxicity, which proves their inclusion into the list of high-risk chemicals both in acute and chronic settings. There was also considerable potential for chronic toxicity from demulsifiers, particularly in marine systems. Corrosion inhibitors demonstrated moderate long-term toxicity, yet they had severe biological effects at normal environmental levels. The ecological risk was also emphasised by the duration of exposure: the longer the exposure, the lower the effect threshold, as the ecological damage had already occurred. Such findings show that chronic toxicity is a prevailing ecological risk pathway and that long-term ecological impacts could be underestimated with reliance on acute toxicity only in marine ecology.

Table 4. Chronic aquatic toxicity metrics (NOEC and LOEC) for oil field chemical additives.

Chemical Class	Test Organism	NOEC Range (mg/l)	LOEC Range (mg/l)	Exposure Duration
Biocides	*P. africanus*	0.01–0.25	0.05–0.9	14–28 days
Biocides	*O. niloticus*	0.08–1.2	0.4–3.6	21–60 days
Corrosion inhibitors	*P. africanus*	0.2–2.6	0.9–8.4	14–28 days
Corrosion inhibitors	*O. niloticus*	0.6–4.8	2.3–12.5	28–90 days
Demulsifiers	*P. africanus*	0.03–0.7	0.2–2.4	10–21 days

3.5. Sub-lethal biological endpoints reported across reviewed studies.

Table 5 presents the prevalence and distribution of sublethal biological effects in the reviewed studies and indicates early signs of ecological impairment. The most commonly reported sublethal effect was growth inhibition, especially in freshwater fish, suggesting that energy distribution and metabolic processes are highly sensitive to OFCA exposure. Reproductive impairment, such as diminished fecundity and gonadal damage, was also predominantly observed, suggesting it may have severe consequences for population sustainability.

Crustaceans living in the sea exhibited more developmental defects and behavioural changes, indicating greater susceptibility during early life. Physiological responses to stress, such as enzyme inhibition, were observed across all groups and species, indicating that biochemical toxicity mechanisms are conserved. These results display significant freshwater-marine disparities whereby freshwater fish were extremely susceptible of growth and reproductive impacts, and marine crustaceans were highly sensitive to developmental and behavioural deficiencies. The divisions indicate species-dependent life-history traits and physiological delicacy. The prevalence of sublethal effects is high, indicating that ecological damage occurs even in the absence of mortality and justifying the inclusion of sublethal endpoints in hazard assessment.

Table 5. Sub-lethal biological endpoints reported across reviewed studies.

Endpoint Category	Specific Effect	% of Studies Reporting	Dominant Test Organism
Growth inhibition	Reduced length/weight gain	62.4	*O. niloticus*
Reproductive impairment	Reduced fecundity	41.9	*O. niloticus*
Reproductive impairment	Gonadal histopathology	29.0	*O. niloticus*
Developmental abnormalities	Larval deformities	37.6	*P. africanus*
Behavioral alterations	Reduced feeding activity	26.9	*P. africanus*
Physiological stress	Enzyme inhibition	48.4	Both

3.6. GESAMP chronic aquatic hazard classification (B1) based on NOEC/LOEC data.

The recommended chronic hazard was based on the NOEC and LOEC, and Table 6 indicates a significant long-term ecological threat across various classes of the OFCA. The highest percentage of high chronic hazard ratings was observed among biocides, particularly for marine crustaceans, indicating their pronounced ecological effects over long-term exposure. Demulsifiers were other substances with high potential for chronic hazards, which signifies their chronic toxicity, where acute toxicity occurs prior to the exposure. Corrosion inhibitors showed mostly moderate levels of hazard classification yet significant ecological risk was evident. The same trend of higher chronic sensitivity in marine versus freshwater species was observed, reinforcing prior findings of higher acute toxicity. This contrast between freshwater and marine ecosystems indicates the disproportionate susceptibility of marine ecosystems to foreignness, defined as the extent to which a marine organism is exposed to a foreign substance (OFCA). It has been noted that chronic hazard classifications tended to be higher than the acute hazard classifications of the same chemical classes that showed significant acute-chronic discrepancies. These results demonstrate the importance of chronic toxicity in identifying ecological hazards and the inadequacy of acute toxicity alone in examining hazards holistically.

Table 6. GESAMP chronic aquatic hazard classification (B1) based on NOEC/LOEC data.

Chemical Class	Test Organism	Low Chronic Hazard (%)	Moderate (%)	High (%)
Biocides	*P. africanus*	11.1	33.3	55.6
Biocides	*O. niloticus*	22.2	44.4	33.4
Corrosion inhibitors	*P. africanus*	28.6	47.6	23.8
Demulsifiers	*P. africanus*	18.2	36.4	45.4

3.7.Human health hazard endpoints (GESAMP C1–C4) associated with oil field chemical additives.

Table 7 presents a summary of human health hazard endpoints for OFCAs and shows that these vary considerably across chemical classes. Irritation of the skin and the eyes was the most frequently reported risk, especially in corrosion inhibitors, due to the reactive nature of these atoms. Oral toxicity was another important factor, particularly for biocides and surfactants, and this implies that there is a potential hazard via or through ingestive routes. Volatile demulsifiers were mostly linked with inhalation toxicity, which outlines the issues of occupational exposure. Skin sensitization was less common but still reported, particularly among biocides. The results have shown that OFCAs pose multidimensional hazards to ecological and human health systems. Notably, aquatic toxicity patterns do not necessarily parallel human health hazard patterns, underscoring the importance of integrated hazard assessment frameworks.

Table 7. Human health hazard endpoints (GESAMP C1–C4) associated with oil field chemical additives.

Endpoint	% of Chemicals Flagged	Dominant Chemical Classes
C1: Oral toxicity (LD_{50})	34.4	Biocides, surfactants
C2: Skin/eye irritation	51.6	Corrosion inhibitors
C3: Inhalation toxicity	27.9	Volatile demulsifiers
C4: Skin sensitization	18.3	Biocides

3.8. Environmental hazards (GESAMP D1–D3).

Table 8 presents additional environmental hazards beyond organism-level toxicity, emphasising effects at the ecosystem level. The most commonly reported hazard was effects on oxygen demand, which would indicate the possibility of hypoxia and ecosystem disturbance. There was also significant seafood contamination, a risk of bioaccumulation, and transfer to food chains. The physical environmental impact, which encompassed sediment smothering, was also infrequent but ecologically significant. These results indicate that the risks posed by OFCA are not necessarily direct toxicity but encompass broader-scale ecosystem disturbance processes.

Table 8. Other environmental hazards (GESAMP D1–D3).

Hazard Category	% of Chemicals Affected	Primary Concern
D1: Seafood tainting	29.0	Bioaccumulation
D2: Oxygen demand (COD/BOD)	46.2	Hypoxia risk
D3: Physical effects	21.5	Smothering/insolubility

3.9. Integrated GESAMP hazard profile summary.

Table 9 presents an integrated hazard profile of the acute, chronic, human health, and environmental hazards associated with the chemical classes. The hazard profile of biocides was the most elaborate and posed a high risk in various areas. Demulsifiers also had a high potential for hazard, particularly due to discrepancies between acute and chronic toxicity. Corrosion inhibitors exhibited moderate and persistent hazard profiles, whereas scale inhibitors had relatively lower toxicity and still caused harmful environmental effects. These findings affirm that the profiles used to assess the hazards of OFCA are multidimensional and should be evaluated using a combined approach.

Table 9. Integrated GESAMP hazard profile summary.

Chemical Class	A1 Acute	B1 Chronic	C1–C4 Human	D1–D3 Environmental	Hazard Pattern
Biocides	High	High	Moderate–High	Moderate	Multi-domain risk
Corrosion inhibitors	Moderate	Moderate	Moderate	Low–Moderate	Chronic-dominant
Demulsifiers	High	High	Low–Moderate	Moderate	Acute–chronic mismatch
Scale inhibitors	Low	Low–Moderate	Low	Moderate	Non-toxic stressor

4. Discussion

4.1.Acute toxicity patterns and differential species sensitivity.

These acute toxicity results, presented in Tables 2 and 3, indicate a consistent, ecologically relevant pattern of greater sensitivity in the marine crustacean *Palaemonetes africanus* relative to the freshwater teleost *Oreochromis niloticus* for most oil field chemical additives (OFCAs). This trend is powerful for biocides and demulsifiers, for which LC_{50} values for *P. africanus* often fall within GESAMP hazard Ratings 34, whereas those for *O. niloticus* fall within Ratings 23. This is not a random incident but rather a divergence between crustaceans and teleost fishes, characterized by physiological and morphological differences. The exoskeleton of crustaceans is fairly permeable and is mainly associated more with ion exchange carried out by the branches rather than through membrane exchange, making them highly susceptible to the action of surfactants and membrane-degrading components often found in the OFCAs. Similar power hierarchies have been reported in other vulnerable marine species exposed to oil-related chemicals, such as amphipods and copepods, supporting the generalizability of this observation across taxa. From a comparative perspective, the profile of acute toxicity shows a systematic bias in testing systems dominated by fish, which can underestimate risks in marine environments. In contrast, invertebrate groups are both the most sensitive and the ecologically dominant. Although acute LC_{50} testing cannot replace baseline hazard screening, the apparent interspecific variability highlights the shortcomings of projecting hazard classification on a small taxonomic foundation. Notably, several corrosion and scale inhibitors classified as low acute hazard in *O. niloticus* are still used with moderate toxicity in *P. africanus*, indicating that chemical categories typically developed as operationally benign may be toxic to non-target marine organisms. These results are consistent with centuries of criticism of single-species acute tests for failing to reflect ecosystem-level vulnerability. Accordingly, it can be argued that these acute toxicity consequences are neutral, conditional on judgments that go either way about whether regulatory selection is indeed a neutral methodological position or a determinant of regulatory outcome; however, purely insofar as GESAMP-based hazard models continue to bake their LC_{50} thresholds tomorrow.

4.2.Chronic toxicity and the dominance of long-term ecological risk.

Table 4 and Table 6 present chronic toxicity patterns that reflect the most important ecological risk pathway of the OFCAs, often occurring at levels one to two orders of magnitude below acute mortality thresholds. In chemical classes, NOECs and LOECs consistently indicate biologically meaningful effects at levels many times below GESAMP's acute hazard limits, suggesting a sharp threshold between short-term mortality and long-term ecological fitness. This acute chronic disjunction is one of the main principles of a modern ecotoxicological theory, which indicates that cumulative stress, the execution of delayed physiological damage, and alteration of energy distribution occur with repeated exposure regimes. Compared with marine systems, marine systems are again more susceptible, with *P. africanus* exhibiting lower chronic thresholds across most classes of *O. niloticus*. This trend is in line with the chronic stress theory that suggests that organisms having a low level of detoxification, as well as having high levels of metabolism, which are common attributes of most crustaceans, are overrepresented in the effects of rampant exposure to chemicals. Conversely, the chronological impact could be obscured by the loose temporal resolution of *O. niloticus* at higher concentrations, leading to false-negative risk inferences without direct examination of chronological endpoints. Adjusted chronically sensitive gradients of the exact nature have also been observed in experiments on constituents of produced water and industrial surfactants, which further supports the overall applicability of the described trends. Regulatory concerns regarding the prevalence of chronic toxicity highlight the need to assess the adequacy of LC_{50}-based approval procedures for chemicals intended for chronic discharge. The data used to synthesise here indicate that using acute hazard classifications may underestimate ecological risk in a systematic account, particularly in receiving environments with low dilution and extended exposure. This result directly contradicts traditional regulatory assumptions and indicates the need to make chronic toxicity information mandatory in hazard evaluation systems, particularly for OFCAs used in offshore and nearshore environments.

4.3.Sub-lethal endpoints as early-warning indicators of population decline.

The strong upward trend in the sublethal biological endpoints of the studies reviewed (Table 5) indicates that ecologically significant impairment levels are achieved well before visible mortality occurs. Inhibition of growth, reproductive dysfunction, developmental abnormalities, and behavioural changes are mechanisms by which chemical exposure can produce population-level effects through mechanistic pathways. The most commonly reported endpoints in *Oreochromis niloticus* were growth suppression and reproductive impairment, as is expected by bioenergetic theory (which suggests that detoxification and stress-response mechanisms shift energy away from the growth of somatic tissues, as well as in the gonadal development of the organism). In the long term, these trade-offs reduce fecundity, delay maturation, and decrease recruitment success, thereby exerting downward pressure on population stability. However, *Palaemonetes africanus* exhibited a higher frequency of developmental anomalies and behavioural disturbances, most notably in early life stages. This finding is consistent with the life-stage sensitivity theory, which posits that embryos and larvae are disproportionately exposed due to incomplete organogenesis and low physiological buffering capacity. Comparative analyses of marine invertebrates in the context of oil release and surfactants indicate similar patterns, suggesting that sublethal developmental impairment is a widespread response to oil-related chemical emergencies. More importantly, sublethal effects provide an early warning of persistent changes, as evidenced by shifts in abundance or biomass. They are consequently of such great ecological importance that they appear more subtle than they are. Nevertheless, sublethal endpoints remain underrepresented in regulatory hazard profiling, in part because of methodological complexity and a historical focus on mortality-based measures. The evidence summarized in this review supports the argument that ignoring sublethal effects in hazard assessment reduces the predictive capability of risk assessment, especially in ecosystems where exposure is chronic and at low chemical concentrations.

4.4.Acute–chronic mismatches and regulatory blind spots.

Among the most significant insights to emerge from this review is the systematic difference between the shapes of acute and chronic hazards, especially for demulsifiers and specific corrosion inhibitors (Tables 3, 4, and 6). Moderate acute hazard chemicals were often characterised by high chronic hazard potential, as commonly observed in analyses of pesticides, antifoulants, and industrial surfactants. This discrepancy aligns with the fundamental shortcomings of LC_{50}-based screening, which captures only brief survival outcomes and does not account for cumulative physiological disturbance. Such acute-chronic disconnection was more extreme in marine systems, complementing the central alarm that the contemporary regulatory paradigms might not take sufficient care of marine life against long-term chemical stress. The continuity of such discrepancies both within chemical classes and between taxa implies that there is a structural problem and no single anomaly. Theoretically, such a trend can be associated with stress ecology models, in which biological responses to chemical exposure are time- and nonlinear. The use of acute toxicity as a proxy of long-term safety is therefore a central blind spot, especially in the case of ORFSAs that are used continuously and discharged. The results of this review support the argument that acute toxicity should be used as a screening tool rather than as a determinant of environmental acceptability. It has been argued that the use of chronic thresholds and sublethal endpoints in hazard assessment would not only make hazard assessment more ecologically relevant but also provide precautionary protections by introducing sublethal endpoints, which are predominantly invertebrate-dominated in sensitive marine habitats.

4.5.Cross-domain hazard integration and GESAMP framework implications.

Combining data on aquatic toxicity with human health (C1-C4) and other environmental hazard groups (D1-D3) indicates that the environmental risk of OFCAs is necessarily multidimensional. As represented in Tables 7, 8, and 9, aquatic toxicity is not necessarily associated with the potential of the chemical in question to cause the depletion of human health, as it is possible to have chemicals that are of low occupational or environmental hazard, but of high risk to the occupational or population well-being. This dissociation underscores the need for cross-domain hazard profiling, particularly in offshore environments, where human exposure and ecological pathways intersect. In parallel, the discovery of non-toxic environmental risk factors, including oxygen requirements and seafood contamination, also identifies stress pathways that are independent of direct toxicity. These impacts can induce ecological degradation and socioeconomic losses despite the absence of central organism-level toxicity, as reported in oil-polluted coastal ecosystems. Their inclusion in the GESAMP framework is a conceptual strength; however, in practice, they are constrained by data availability and inconsistent reporting. Overall, this review shows that GESAMP hazard profiling is most effectively conducted using multi-endpoint-informed evidence rather than acute toxicity data. Through triangulation of the acute, chronic, sub-lethal, human health, and ancillary environmental hazards, the current synthesis demonstrates that the framework can be a promising decision-support model. Nonetheless, exploiting this possibility will require the systematic expansion of chronic and sublethal tests, greater transparency of chemical formulations, and greater attention to vulnerable marine life in hazard evaluation.

5. Conclusions

This integrative review and synthesis of aquatic toxicity bioassays of oil-field chemical additives illustrates that ecological risk is primarily driven by non-lethal, chronic, and sub-lethal biological impacts rather than by lethal effects. Comparing chemical classes and test organisms, sharp differences between LC_{50}-based hazard classification and long-term biological outcomes were observed, indicating inherent weaknesses in mortality-based assessment systems. Marine crustaceans have always been the most vulnerable kind of taxa, and the significance of species choice in hazard assessment needs to be emphasised. The prevalence of sublethal outcomes such as growth effects, reproductive impairment, developmental abnormalities, and behavioural disruption supports the conclusion that effects on populations-at-large can occur at exposure levels conventionally considered safe for the environment. The review by placing these findings in a GESAMP-consistent hazard profiling framework has shown that acute aquatic toxicity (A1), chronic toxicity (B1), human health hazards (C1–C4), and other environmental stressors (D1-D3) tend to increase rather than overlap, and hence the multi-domain hazard integration needs to be undertaken. Significantly, the chemicals that showed low acute toxicity often had high chronic or ancillary environmental risks, refuting the notion that short-term lethality is a reliable proxy for ecological safety. In a comparative study of freshwater and marine systems, the present study highlights the increased vulnerability of marine habitats to persistent exposure to low chemical concentrations and the disproportionate risk to invertebrate taxa. In all, the evidence in this synthesis suggests a paradigm shift in the environmental evaluation of chemical additives in oil fields, moving from acute, simplified screening to chronic and sublethal impact assessment grounded in ecological realism. This review of the literature provides a more precautionary and defensible basis for assessing the chemical risks of oil and gas processes by bridging experimental bioassay data with regulatory hazard classifications. This strategy is vital for protecting aquatic ecosystems, preserving human health, and ensuring the long-term sustainability of offshore and onshore petroleum operations.

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Author Contributions

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- Ubong Bernard Essien: Methodology development; Systematic literature review; Data extraction; GESAMP hazard classification; Formal analysis; Writing -original draught; Writing -review and editing; Corresponding scientific coordination.
- Ecotoxicological analysis, Comparative recognition of species sensitivity and Scientific validation, Manuscript review and editing.
- Adams Zainab Husain Hazard profiling framework support, Environmental risk assessment interpretation, Data interpretation, Manuscript review and technical editing.
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- Prince Micheal Uche: Data checking, Toxicity data compilation; Hazard categorization assistance, Sci-edit, standards control of the importance written down in the manuscript.
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Conflict of Interest Statement

The authors that they have no conflict of interest with regard to the publication of this manuscript.

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