Blue Waste, Green Future: Harnessing Fish By-products for Sustainable Oil Spill Response

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ABSTRACT

Marine oil spills represent one of the most catastrophic environmental disasters, devastating marine ecosystems and coastal communities worldwide. Traditional chemical dispersants, while effective at breaking down oil slicks, often introduce additional toxicity to already damaged marine environments, creating long-term ecological harm. The development of fish waste based biodegradable dispersants bridges the gap between marine pollution management and sustainable resource, these natural compounds effectively break down large oil slicks into smaller droplets, accelerating their natural degradation by marine microorganisms without introducing harmful toxins into the environment shows eco-friendly alternative that combine biodegradability, safety, and efficiency while minimizing ecological toxicity. This not only provides a sustainable solution to the environmental hazards of oil spills but also valorizes fishery by-products, aligning with the principles of circular bioeconomy and waste-to-wealth conversion.

INTRODUCTION

Oil is a complex mixture of hydrocarbons, derived from the fossil remains of marine organisms under high temperature and pressure over millions of years. Once released into the marine environment, oil contaminates the water, sediments and marine organisms causing toxic effects that can lead to the death of fish, marine mammals, other wildlife and destroy entire marine ecosystems. Oil spills are environmental disasters where petroleum or its refined products are accidentally released into the ocean or coastal waters. The global marine oil spill frequency annually averages around 6 to 7 spills of notable size (>7 tonnes) with a low total volume lost relative to past decades, reflecting improved risk management in marine oil transport and operations, this ongoing issue drives continual investment in oil spill management and response strategies worldwide.

These spills often result from human activities such as tanker accidents, offshore drilling rig failures, pipeline ruptures and operational discharges during oil transportation. They can also occur due to natural disasters like storms and earthquakes impacting offshore platforms. Both catastrophic large spills and frequent smaller chronic spills pose significant risks, long-term ecological imbalances, genetic mutations in marine species and reproductive impairments that affect biodiversity conservation. Coral reefs and coastal mangroves which serve as critical breeding grounds are highly vulnerable. Beyond ecosystems, human communities relying on fishing and tourism suffer economic losses and spill clean-up workers face health risks due to toxic exposure.

Climate change and global policies:

Climate change exacerbates these challenges by increasing the frequency of extreme weather events such as hurricanes, which elevate spill risks and complicate response efforts. Damaging coastal habitats, fisheries and affecting human health through seafood contamination. On the policy aspects, international cooperation is critical to confront the global dimension of oil spill threats. Organizations such as the International Maritime Organization (IMO) govern maritime safety and oil pollution prevention through treaties like the International Convention on Oil Pollution Preparedness, Response, and Cooperation (OPRC).

Food and Agriculture Organization (FAO) and World Health Organization (WHO) address marine oil spills through the lens of seafood safety, fisheries management, and public health, emphasizing risk assessment, monitoring, and appropriate response measures, FAO, along with the International Maritime Organization (IMO), developed detailed guidance on managing seafood safety during and after oil spills. Both FAO and WHO support integrated approaches to pollution management and restoration, emphasizing the close link between environmental health and food safety in marine contexts.

Dispersants are designed to break down oil slicks into smaller droplets, which facilitates dilution and biodegradation, while chemical dispersants remain a crucial tool in the oil spill response helping to quickly mitigate surface slicks and reduce coastal contamination. Current chemical dispersants used for marine oil spills have several limitations and face significant global challenges such as chemical dispersants themselves, as well as oil-dispersant mixtures, exhibit toxicity toward a range of marine organisms including fish, crustaceans, corals, molluscs and plankton. Suspended oil droplets treated with dispersants may be incorporated into marine snow and transported to the seabed, affecting benthic ecosystems where oil degrades more slowly.

Toxic components such as polycyclic aromatic hydrocarbons (PAHs) persist in the water and sediment, creating long-term sources of contamination that affect benthic habitats, coral reefs, mangroves and seagrass beds. Fish and other marine organisms absorb toxic oil compounds through gills, skin and ingestion of contaminated food or sediment. Oil and PAHs interfere with cellular functions and cholesterol biosynthesis, disrupting cardiac function, stress response, neuron signalling and calcium homeostasis in fish tissues. Contaminants bioaccumulate in fatty tissues and organs, sometimes transferring up the food web and even entering seafood consumed by humans.

Fish waste-based biodegradable dispersants represent a promising alternative to conventional chemical dispersants used in marine oil spill response, addressing many of the critical limitations associated with synthetic products. Unlike traditional dispersants, fish waste-derived dispersants are composed of natural, biodegradable compounds extracted from fish processing by-products.

Fish Waste as a Source of Bioactive Compounds

Global fisheries and aquaculture production reached about 223 million tonnes, about 15% of captured fish and seafood (roughly 23-27 million tonnes) are discarded or wasted annually. Fish processing by-products (waste) constitute approximately 30-50% of the fish mass, to the global fish production, fish waste may be roughly 70-110 million tonnes annually (FAO, 2025)

Fish processing wastes such as heads, skins, bones and viscera are discarded improperly, they contribute to significant organic pollution. These wastes decompose and release nutrients like nitrogen and phosphorus into water bodies, leading to eutrophication, harmful algal blooms, oxygen depletion and deterioration of aquatic ecosystems. Disposing of large quantities of fish waste requires costly handling, transport and treatment systems. This waste represents a large volume of valuable biomass containing proteins, oils and other bioactive compounds. Failure to utilize this waste results in lost opportunities for producing valuable products like fishmeal, biofertilizers, bioactive compounds, collagen, enzymes and biofuels, thus reducing the economic efficiency of fisheries and aquaculture sectors.

Component	Average Composition (%)
Head	10 - 15
Bones	10 - 15
Viscera	12 - 18
Skin & trimmings	~3.5
Scales	~2

Due to presence of biologically active molecules, proteins and peptides obtained by enzymatic hydrolysis exhibit strong emulsification properties, essential for breaking down oil slicks into microscopic droplets that disperse in seawater. Lipids and polysaccharides contribute surface activity and stability to the oil-water mix, improving dispersant efficiency. Enzymatic hydrolysis and microbial fermentation are the two main techniques used to extract these bioactive compounds. These methods are environmentally friendly, often carried out under mild conditions that preserve molecular functionality. The extracted compounds can be purified and formulated into dispersant mixtures tailored for specific oil types and spill conditions.

Dispersants formulated from fish waste bio-actives can achieve oil dispersion rates comparable to commercial synthetic dispersants. Importantly, toxicity assays using marine species like fish larvae and crustaceans indicate significantly reduced harmful effects, underscoring the safer ecological profile of these natural alternatives. The biodegradable nature of these compounds means they degrade naturally after performing their function, minimizing chemical accumulation in the marine environment.

Lipopeptides as Natural Biosurfactants

Biosurfactants help to clean up oil spills by breaking down large patches of oil into many tiny droplets, which become easier for natural bacteria to dissolve and eat. Biosurfactants are special molecules made by microbes, with one end that likes water and one end that likes oil. When these molecules mix with oil and water, they surround the oil, grabbing it with their oil-loving side and pointing their water-loving side outward, this breaks the oil into small droplets and keeps them from joining back together almost like how soap turns grease into small bits that rinse away when washing dishes. The small oil droplets have much more surface area, making it much easier for bacteria to reach, attack and break down the oil faster. By reducing oil to tiny droplets, biosurfactants make oil spills less harmful and help nature clean up the mess more quickly.

Fish waste is a promising source of bioactive lipopeptide compounds such as surfactin and iturin, which can act as potent biosurfactants with applications in environmental remediation, particularly for oil spill response in marine environments. Lipopeptides are amphiphilic molecules produced predominantly by *Bacillus* species, capable of reducing surface tension and forming stable emulsions, lipopeptide biosurfactants also show antimicrobial, antioxidant and emulsifying properties, contributing to shelf stability and multipurpose utility in biotechnology and food industry. Production involves microbial fermentation, optimizing hydrolysis conditions and careful selection of fish waste substrates, as fatty acid composition can influence biosurfactant yield and activity.

Processing of Waste for Dispersant Development

Fish waste is processed through steps like enzymatic hydrolysis and extraction to obtain peptides and oils used as substrates for biosurfactant production by microorganisms such as *Bacillus* species, the main steps include

Pre-treatment: Fish waste (skins, heads, viscera) is cleaned, ground, and homogenized to improve extraction efficiency (Zhu *et al*., 2020; Borges *et al*., 2023).

Enzymatic Hydrolysis: Proteolytic enzymes (papain, alcalase, trypsin, etc.) are added to digest the proteins, releasing peptides. The conditions like pH (7–9), temperature (40–60°C), enzyme concentration, and time (2–8 hours) are optimized for maximum yield (Nemati *et al*., 2024).

Separation: The hydrolysed mixture is filtered or centrifuged to separate soluble peptides from insoluble materials. The liquid fraction contains peptide-rich hydrolysates, which are collected for fermentation (Behera *et al*., 2022).

Peptide Purification: Additional purification steps (like ultrafiltration, precipitation or solvent extraction) can be used to concentrate bioactive peptides suited for biosurfactant production.

Fish Oil Extraction: Oil is separated from the hydrolysate using methods such as centrifugation, Soxhlet extraction, or microwave-assisted extraction, yielding ω-3 fatty acid-rich oil that can be further processed or used with co-substrates for biosurfactant synthesis (Pinela *et al*., 2022).

Fermentation for Biosurfactant Production: The peptide hydrolysate and extracted oil are used as carbon and nitrogen sources in fermentation media to culture biosurfactant-producing bacteria (Martins & Martins., 2017).

Recovery and Characterization: The biosurfactant is separated from the fermentation broth, purified, and characterized for emulsifying activity, surface tension reduction, and bioactivity using established chemical methods (Zhu *et al*., 2020).

Biosurfactants produced from fish waste peptones by *Bacillus subtilis* strains can significantly reduce the surface tension of water down to 27.9 mN/m with a critical micelle concentration as low as 0.18 g/L. These biosurfactants demonstrate excellent dispersion efficiency for crude oils (Zhu *et al*., 2020).

Opportunities and Applications

Fisheries can generate new profit streams by selling byproducts previously considered waste, with reduced disposal costs and possible government support for sustainable practices. Coastal communities benefit from job creation, cleaner natural environments, local entrepreneurship and diversified incomes that are less reliant on risky or overexploited fisheries. Biotechnological companies obtain inexpensive, renewable raw materials for biosurfactant production, making their operations more cost-effective, they can also attract premium markets interested in sustainability and access green incentives or funding.

CONCLUSION:

The conversion of fish-processing wastes into biodegradable dispersants offers a promising biotechnological solution for both waste valorization and marine oil spill remediation. Bioactive compounds such as lipopeptide biosurfactants produced by *Bacillus subtilis* can effectively reduce surface tension and disperse oil with high efficiency, while exhibiting biodegradability exceeding 60% within 28 days and substantially lower ecotoxicity than conventional petrochemical dispersants. Their amphiphilic molecular structure enables targeted oil emulsification without persistent bioaccumulation and synergistic formulations with small amounts of synthetic surfactants enhance efficacy on various crude oils. With continued rigorous scientific validation and regulatory support, these fish-waste-based dispersants could emerge as a key strategy in safeguarding oceans, turning waste into a resource that actively contributes to restoring marine health and resilience.

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