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Key trends in the development of sustainable marine lubricants for anti-fouling and reduced environmental impact

Part one of a two-part Lube-Tech by ***Dr. Raj Shah****, Director, Koehler Instrument Company,* ***Andrew Zhang*** *and* ***Mathew Roshan****, Chemical and Molecular Engineering Undergraduate Students, Stony Brook University, and Student Interns, Koehler Instrument Company, and* ***Beau Eng*** *and* ***Gavin Thomas****, Student Interns, Koehler Instrument Company,*

Marine lubricants play a crucial role in internal engine systems and external surfaces on marine vehicles, where they reduce friction, enhance performance, and protect against environmental wear and tear. In recent decades, increasing environmental regulations have pushed for greater sustainability, driving the marine transportation industry towards more eco-friendly lubrication practices. This is done in order to decrease the harsh ecological impacts caused by traditional formulations that harm marine organisms and aquatic ecosystems. Emerging innovations in nanotechnology and biolubricants have significantly advanced anti-fouling performance and engine efficiency while reducing toxicity and pollution. Nanostructured coating and additives, lubricant-infused surfaces, and biodegradable alternatives are leading to the transformation of marine lubricants. This review highlights the integrations of nanotechnology and biolubricants as the core strategies in the advancement of sustainable marine lubricants, emphasising their potential to meet rigorous environmental standards without compromising performance, offering an effective alternative to traditional production of lubricants.

Introduction

Lubricants are substances that decrease the friction between moving surfaces by acting as a slippery film, minimising the damage of moving parts, and enhancing the operational lifespan of mechanical systems [1]. In marine applications, lubricants are critical for ensuring engine efficiency and durability under harsh and variable oceanic conditions [2]. Due to their versatility, marine lubricants must be designed to possess a range of functional properties, including thermal stability, high viscosity retention, oxidation resistance, and biodegradability [2]. Beyond their use in engines, lubricants also play a vital role in anti-fouling technologies that prevent marine organisms from attaching themselves to the surface of ship hulls, which can increase drag, corrosion, and fuel consumption.

This review explores the latest trends in marine lubricants, beginning with the environmental and regulatory factors driving innovation and sustainability. It then examines the ecological impacts of traditional lubricants, the evolution of anti-fouling strategies, and the integration of emerging technologies like nanostructured coatings and slippery liquid-infused porous surfaces (SLIPS). The paper strongly emphasises biolubricants as sustainable alternatives and the application of nanotechnology to enhance lubrication performance. These developments collectively signal a shift toward cleaner, smarter, and more sustainable marine lubrication systems fit for modern environmental standards.

Environmental and regulatory drivers

Lubricants, while essential for reducing wear and ensuring efficient operation in marine engines, can pose a major threat to aquatic life and the marine ecosystems. Their leakage and improper disposal contribute to water pollution, which harms marine organisms and disrupts nearby ecosystems [3]. To solve this issue, an emerging field of tribology is the synthesis of green lubricants, lubricants formulated to minimally impact the ecology of their regions in which they are used. In response, there is an on-going push towards greener alternatives and sustainable lubricants that maintain high performance without compromising marine health.

Over the past few decades, international organisations have increasingly focused on promoting sustainability and reducing environmental impact. In 2012, the European Union passed the Biological Product Regulations (BPR), which governs the market use of biological products, including lubricants, their additives, and anti-fouling systems [4]. In the United States, the Environmental Protection Agency (EPA) implemented the 2013 Vessel General Permits, replacing the existing 2008 version. This updated permit imposes stricter control and mandates the use of Environmental Acceptable Lubricants (EALs), which must be "biodegradable", "minimally-toxic", and "not bioaccumulative" [5].

Internationally, the International Maritime Organization (IMO) adopted the International Convention for Prevention of Pollution from Ships, also known as MARPOL, in 1973 to address and regulate the various types of pollution from marine vehicles, such as oils spills, air emissions, and sewage, through the adoption of different annexes [6]. Under MARPOL Annex VI, a new global sulphur cap was introduced on January 1, 2020, which decreased the maximum allowable sulphur content in marine fuel from 3.50% to 0.50% [7]. Additionally, Annex VI capped nitrogen oxide (NOx) emissions and onboard waste incineration in an attempt to reduce greenhouse gases.

As environmental policies and standards become more rigorous, the marine industry faces greater pressure to adopt lubricants that meet operational demands while aligning with ecological goals. This shift underscores the urgent need for innovative, sustainable lubricants capable of delivering strong performance while minimising environmental harm to marine life and air quality. With the growing number of global policies that have been passed to further reduce pollution and promote sustainability, the adoption of biodegradable and non-toxic lubricants is essential. These developments clearly emphasise that the path for marine lubricants prioritises performance, compliance, and environmental responsibility for the future.

Impact of lubricants on marine ecosystems

While the drive to reduce airborne pollution is essential for curbing the ecological impact of large-scale shipping on the biosphere, marine leakage and spill off are far more significant when considering sustainable marine tribology. Lubricants can contribute to oil pollution in marine environments through leakage and spills from the ship engine, posing a serious threat to marine organisms [2]. The extent of this runoff is largely determined by key oil characteristics, mainly their viscosity, volatility, and toxicity [8]. Oil spills affect marine life, directly by physically smothering and poisoning animals due to the composition of the oil, and indirectly by destroying habitats and key species [9].

Marine organisms closest to the sea surface or coastline are the most vulnerable as they are more likely to come into contact with the oil. Seabirds, which often gather in flocks in water, are also at uniquely high risk of oil contamination-related illness or injury [9]. When oil adheres to their feathers, which also happens to other fur-bearing marine animals, it disrupts their insulation and buoyancy, which can lead to hypothermia, drowning, or starvation [9]. Marine mammals and reptiles, such as seals, dolphins, and sea turtles, are also endangered by floating oil, especially when surfacing to breathe [9]. Sea turtles can suffer from inflammation of the eyes, respiratory distress, and reproductive complications from ingesting oil or absorbing it through their mucous membrane, making it much harder to survive and reproduce [10, 11].

Mangroves, which serve as a critical nursery ground for many marine life including crabs, oysters, and fish, are highly sensitive to oil contamination. Their aerial roots, which are essential for oxygen exchange, can be blocked, causing mangroves to suffer from yellow leaves, deterioration, and eventually, death, within just a few weeks to months if oil exposure is prolonged [9, 12]. The loss of mangroves cascades through ecosystems, displacing countless organisms and diminishing biodiversity.

While lubricants are vital for ship operations, their high environmental risk emphasises the urgent need for greener alternatives. Even clean-up efforts, if poorly managed, can further damage the marine ecosystem. The use of heavy equipment and harsh chemical agents in spill remediation can destroy nesting sites, compact sediments, and kill delicate marine life [9]. Future advancements, therefore, must focus on creating biodegradable, non-toxic lubricants that minimise ecological harm while maintaining high-performance standards.

Trends in anti-fouling technologies

Recent trends in anti-fouling technologies reflect a growing emphasis on sustainability through the incorporation of lubricant-based coating, nanotechnology, innovative additives, improved maintenance protocols, and eco-friendly alternatives to traditional marine lubricant measures. These innovative developments aim to enhance performance while minimising environmental harm.

Biofouling is a persistent issue in marine operations, defined as the accumulation of organisms, such as barnacles and algae, that attach themselves to the hull surface, a schematic of which is shown in Figure 1 [13].

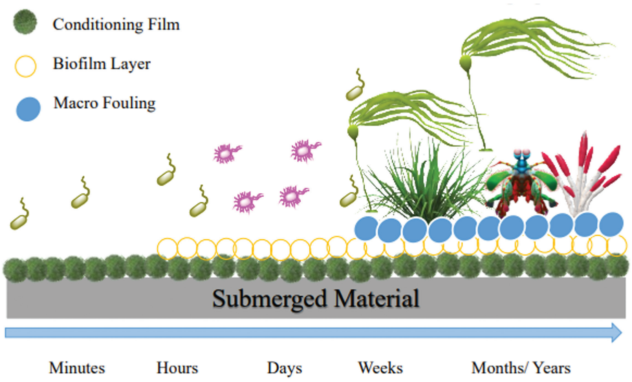

Figure 1: *Schematic of marine biofouling of submerged materials, such as boat hulls or rubber blades [11].*

This leads to a greater hydrodynamic drag force applied to the vehicle, resulting in higher fuel consumption, greater engine strain, and marine structure corrosion [13]. While anti-fouling coverings are applied to combat this problem, they can indirectly lead to an increase in greenhouse gas emissions by requiring more fuel as thick coatings can cause further drag [14]. Additionally, coatings can be economically disadvantageous, as it may repel organisms that are intended to be harvested for commercial purposes [13,15].

Since the 1960s, Tributyltin (TBT) has been a popular compound used in anti-fouling paints for its biocide properties. However, the International Maritime Organisation banned TBT-based products due to their significant and harmful toxicity to the marine environment in 2008 [16]. This shift led towards the adoption of less harmful compounds, mostly being copper and zinc in anti-fouling paints and biocides, which, although effective, continue to pose ecological risk and require frequent reapplication, usually 6 to 12 months, making them costly and unsustainable in the long term [13,17].

In response, current anti-fouling strategies are focused on nontoxic, biodegradable, and biologically inspired solutions. Advancements in surface-engineering combined with biolubricants, nanoparticle-infused coating, and stimuli-responsive materials, are paving the way for anti-fouling systems that are both environmentally friendly and economically viable.

Slippery liquid infused porous surfaces

To combat the issues of biofouling, a slippery liquid-infused porous surface (SLIPS) was created by Aizenberg's group [18] in 2011 at Wyss Institute for Biologically Inspired Engineering of Harvard University, embedding a liquid, usually a lubricant, into the substrate, enhancing anti-fouling properties and corrosion resistance [18]. This idea was inspired by Nepenthes pitcher plants, which trap prey with an infused slippery liquid on their microstructure surface. SLIPS technology can replicate this mechanism by locking lubricants in engineered surface textures to create a smooth, non-adhesive interface [18].

SLIPSs are composed of two key components: a substrate with appropriate surface energy and roughness, and a lubricating liquid held by capillary forces. The lubricant layer forms a slippery, dynamic barrier that effectively resists the adhesion of various marine organisms, from microorganisms such as algae to larger biofoulers like mussels [19].

The surface morphology of the substrate is critical to SLIPS performance. By introducing micro- or nanostructures, these surfaces can better retain the lubricants, minimising lubricant loss under shear stress, and enhancing anti-fouling efficacy [18]. Techniques such as lithography and etching are commonly used to fabricate structured surfaces, including nanopillars and nanosheets [20]. One-dimensional (1D) nanostructured materials can provide promising and supreme superhydrophobic self-cleaning surfaces because of their extremely high surface area and unparalleled morphology. Thus, the incorporation of 1D nanomaterial in non-toxic fouling release coatings is a strategic goal for fouling prevention.

Another equally important factor is the compatibility between the lubricant and the substrate [21]; the lubricant must also be chemically and physically stable within the surface of the substrate to achieve long-lasting, effective performance via high surface wettability, hydrophobicity, roughness and free energy [22, 23]. Common lubricants that are used are silicone oils, polydimethylsiloxane (PDMS), perfluoropolyether oils, long-chain alkanes, or paraffins. These selected lubricants have desirable properties such as thermal stability, long-lasting, low surface energy, and durability in marine environments [19]. This notion was confirmed after Selim et al. [22] synthesised a PDMS/SiO2-ZnO nanocomposite as a low cost nanofiller and discovered that it featured a stable, well-dispersed, uniform particle morphology. The nanofiller showed high potential for fouling release self-cleaning via a physical repelling mechanism, indicating the success of this nanocomposite as an efficient and environment-friendly self-cleaning coating of ship hulls and other marine applications.

Overall, SLIPSs represent an innovative and promising technology that continue to attract significant research interest. With the integration of rising nanotechnologies and biolubricants, SLIPS holds even greater potential to serve as a sustainable, eco-friendly alternative in marine applications, delivering effective anti-fouling performance while minimising environmental impact, and enhancing the applicability of marine lubricants in tandem with growing environmental regulatory demands.

This article will be continued in Lube Magazine, issue 190, December 2025.

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