Lube-Tech

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

Part two 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.

Nanotechnology in marine lubricants

Nanotechnology is widely used to improve anti-fouling properties. Whether through nanocomposites in lubricants or constructing the surface of the substrate down to the nanoscale, many studies have shown that the use of nanotechnology can drastically improve the anti-fouling properties [24]. The use of nanoporous structures further enhances the capillary retention and distribution of the lubricant across the surface. The nanoscale pores allow for stronger capillary forces, offering more effective lubricant storage and gradual release, which is crucial for maintaining a stable slipper layer under dynamic marine conditions [25].

The incorporation of nanoparticles into the substrate matrix enhances the hydrophobicity and fouling-release properties of nanocomposites [26]. These materials also exhibit high tensile strength and strong adhesion to underlying substrates, making them more resistant to mechanical wear under extreme marine conditions [26]. In a study by Haoyi Qiu et al. [27], nanocomposites composed of polythiourethane (PTU), PDMS, tetrapodal-shaped ZnO microparticles (PPZ) and ZnO with vinyl-functionalised silicone oil

(PPZO) were shown to significantly reduce algae adhesion. Qiu et al. submerged five substrates of slate into the Baltic Sea to gather algae fouling. As seen in Figure 2, reference materials of AlMg3, PTU and PPZ were shown to have the highest degree of fouling with both green and brown algae taking up most of the surface, whereas PDMS and PPZO had far fewer. Subsequent brush cleaning of AlMg3, PTU and PPZ revealed that most algae was able to come off with slight surface residue, but the PDMS and PPZO substrates witnessed a complete removal without any algae residue.

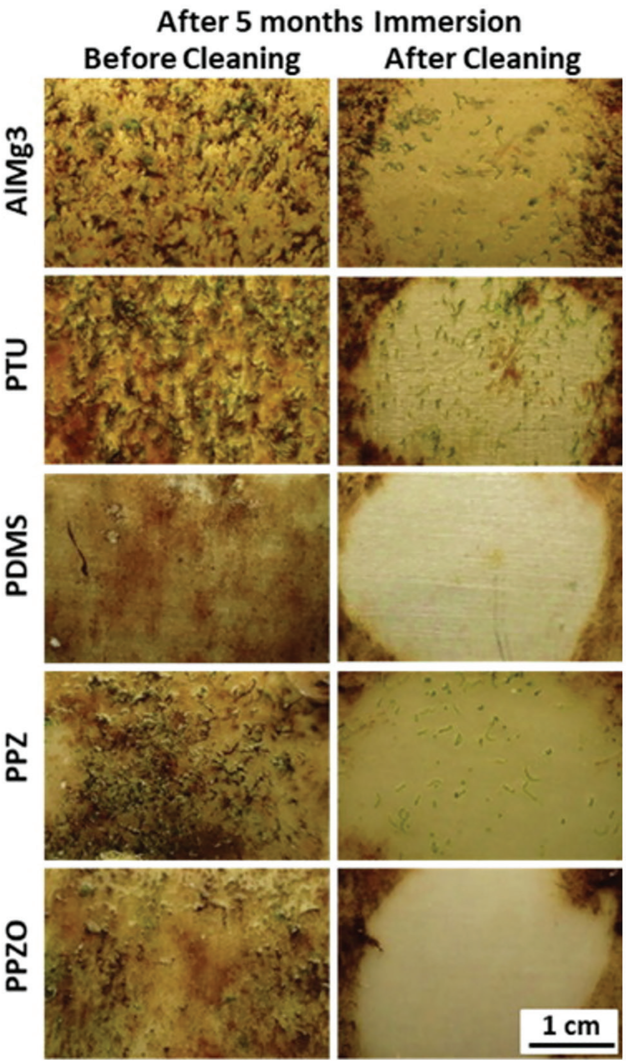

Figure 2: *Experimental nanocomposite substrates immersed in the Baltic Sea for 5 months before and after cleaning procedure [27].*

Additionally, the ZnO microparticles is a key component to address the limits of pure PDMS based coating as its incorporation improved the mechanical stability and adhesion strength to substrates [27]. The tensile strength of the nanocomposite was approximately 63 MPa, which is significantly higher than results reported in other studies. For example, Ba et al [28] reported tensile strength up to 200 times lower for their silicon-modified PDMS coating, and Zhang et al's [29] organogel-based anti-fouling layer exhibited tensile strength that was up to 400 times lower. These comparative findings underscore the crucial role that nanostructures play into developing high-performing, durable anti-fouling coatings that are able to address the mechanical weakness of traditional, standard materials.

This study also highlights the exceptional anti-biofouling performance of the PDMS and PPZO nanocomposites with great fouling-removal property, similar to the revelations found in the study by Selim et al. [20]. The PDMS phase contributed to low surface energy, while the silicone oil formed a lubricating interfacial layer that inhibited bio-adhesion. Additionally, Qiu used a low viscosity silicone oil in PDMS suggesting that less viscous lubricants could be retained better on target surfaces and help the release of algae settlements as compared to more viscous oils [23]. Overall, this work demonstrates the potential of lubricant-modified nanocomposites as effective, non-toxic additives in anti-fouling marine coatings.

In order for SLIPs to be effective in marine environments, the chemical and physical properties of surface morphology must be engineered and optimised to ensure that the surface structure is able to resist lubricant loss and provide long-lasting durability, while also maintaining anti-fouling performance underlying dynamic condition [17]. In 2020, Dr. Renzo A. Fenati [17] and his team at the School of Chemistry, University of Sydney, developed a slippery liquid-infused surface by infusing non-toxic silicone oil into microstructure

Teflon riblets inspired from Shark Skin. These riblets that are composed of parallel grooves can mimic the drag-reducing properties of shark dermal denticles. This design is able to constrain turbulent flow near the surface and thus, reduce the contact the fluid makes with the surface, minimising shear forces and decreasing drag force by approximately 13% [17, 30, 31]. The fabrication method for these riblets, known as direct contactless microfracture, was proposed to offer a much more cost-effective method for upscaling production, compared to the production of nanostructured Teflon wrinkles that, although were originally used in the creation of liquid infused surfaced, can't be applied on a large scale due to the requirements for specialised equipment and high cost [17].

In this study, these silicon oil-infused microstructured riblets exhibited high lubrication retention when exposed to shear flow conditions while presenting more slippery properties by preventing biofouling, inhibiting the attachment of Pseudoalteromonas spp. Additionally, modifying the geometry of the riblets, particularly the groove width and periodicity, did significantly influence the retention of the lubricant [17], demonstrating the significant importance of surface topography when designing robust and long-lasting SLIPSs. Although these riblets demonstrated lack of porous network or overhanging structures, features essential for effective lubricant retention, they still manage to retain a measure able amount of silicon oil which does offer potential for developing large-scale, low-cost production of anti-fouling solutions [17].

The integration of nanostructures can further enhance lubricant retention through the increased surface area and capillary effect, which can lead to an improvement in long-term anti-fouling performance. While nanostructures do offer superior performance, their high and specialised fabrication cost can present a tradeoff to future industry for large scale applications. Thus, future research should explore hybrid approach that combines microstructure ribets with nanoscale features, which present a balance between cost-effectiveness and anti-fouling efficacy.

The implementation of nanotechnology into novel anti-fouling innovations has demonstrated significant potential in enhancing lubricant retention and increasing corrosion resistance. These advancements align with the growing demand for sustainable and environmentally friendly approaches within the marine lubricant industry. Although there are challenges of high cost and limited scalability within nanofabrication techniques due to the specialised equipment and materials needed, nanotechnology remains as a promising and respected frontier for the future.
As environmental regulations continue to tighten, especially upon non-toxic and biodegradable solutions, nanotechnology offers a complementary pathway towards greener, high-performance marine lubricant systems that balance effect with sustainability.

Biolubricants: a greener alternative (SLIPS)

Biolubricants are another emerging approach in anti-fouling technology, offering further innovative ways towards greater sustainability and eco-friendly compatibility. Traditional slippery liquid infused porous surfaces (SLIPS) structures often use silicon or fluorinated-based lubricants, which, although generally non-toxic, may not fully be benign or biodegradable within the marine environment, as there still may be some drawbacks [32]. In contrast, biolubricants derived from fatty acids and natural oils are inherently non-toxic and often exhibit antibacterial properties, making them promising candidates for marine anti-fouling application [33].

In a study performed by Awad et al. [33], SLIPS were constructed by infusing vegetable oil into stainless steel surfaces, producing a coating that reduced biofilm formation and bacterial adherence of the Pseudomonas aeruginosa, a biofilm-forming bacterium that has the ability to adhere to surfaces and produce protective the biofilms that can be problematic in marine environments, especially in biofouling. This work illustrates the potential of safe plant-based biolubricants as effective, low-cost, and abundant anti-fouling agents. Their successful application allows for greater opportunities and further implementation within marine environments, where biolubricants can replace synthetic oils to create non-toxic, sustainable SLIPS systems with minimal ecological impact.

Furthermore, another study conducted by Basu et al. [34] explored the replacement of a synthetic lubricant in SLIPS with oleic acid and methyl oleate infused into polydimethylsiloxane (PDMS). The research revealed that the methyl oleate-infused UV-treated PDMS was the most stable liquid film and showed robust anti-fouling performance. Specifically, its ability to prevent the adhesion of muscle threads to the surface, which demonstrated anti-fouling capabilities comparable to those achieved with synthetic lubricants. The anti-fouling performance with biolubricants was equivalent to anti-fouling capabilities of that of other synthetic lubricants, indicating that biolubricants also possess the ability to be used in anti-fouling coating, providing a more effective approach towards further sustainability and eco-friendly measures [34]. This behaviour indicates that biolubricants, such as oleic acid and methyl oleate, offer a more sustainable alternative for creating effective SLIPS coating, combining eco-friendliness with performance on par with traditional synthetic oils.

Although SLIPS holds many benefits, such as a low Young's modulus and effective anti-fouling properties, one of its main issues is the loss of lubrication throughout anti-fouling applications [35]. One promising remedy was the creation of responsive SLIPS systems that would regulate lubricant release depending on the surrounding biofouling conditions. In a bioinspired approach, Tong et al. [35] designed a "smart SLIPS" coating modeled after the hagfish, which secretes mucus to evade predators. This system can dynamically adjust its lubricant release in response to environmental stimuli, visible light, or heating, as shown in Figure 3, allowing the surface to adapt its anti-fouling performance to real-time marine conditions. During high biofouling periods, usually during the daytime or hot season, the coating increases lubricant seepage to enhance slipperiness and deter fouling organisms. At cooler temperatures or nighttime, when biofouling is less prominent, lubricants release slowly, thereby conserving lubricants and extending the coating's functional lifespan. The self-regulating behaviour not only improves anti-fouling efficiency but also reduces excess lubricant leakage, making the system more efficient in conserving resources and benefiting the environment. This form of SLIPS also maintains an anti-fouling performance of 180 days, making it one of the longest-lasting anti-fouling coatings reported in real marine field conditions [35]. Pervious research cited in this study compared this result with other SLIPS materials that reported shorter anti-fouling durations, including the 150 days in Lorong Halus, Singapore [36], 148 days in Bohai Bay, China [37], 84 days in Bohai Sea, China [38] and 49 days in Watson Bay, Australia [39]. These findings show the significant advancements in durability and field performance achieved by new SLIPS formulation that reinforces its potential for long-term anti-fouling applications in harsh marine environments. This system demonstrates how bioinspired designs are reshaping marine lubricants, moving towards smart, greener solutions that balance high performance with sustainability.

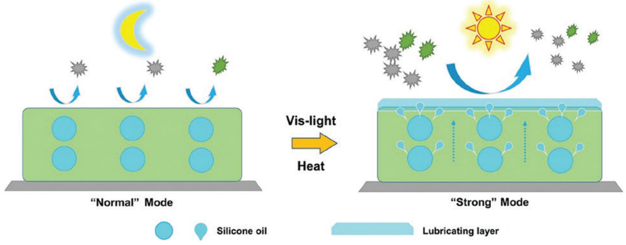

Figure 3: *A 2D diagram of the Hagfish-Inspired Smart SLIPS demonstrating the anti-fouling switching mechanism. The stimuli of UV light or heat cause the SLIPS to switch its mechanism and release a lubricating layer that provides greater anti-fouling efficacy. [35]*

Another recent study conducted by Tong et al. also involved a very similar mechanism of smart anti-fouling surface known as a slippery porous liquid infused porous surface (SPIPS), inspired by the poison dart frog, which secretes venomous mucus as a defense mechanism [40]. This SPIPS coating responds to UV exposure, switching between "offensive" and "defensive" states. This unique behaviour promotes anti-foulant release during periods of high biofouling activity while conserving materials and resources during low biofouling activity. This behaviour compensates for the gap period, a phase in which the anti-fouling SLIPS coating is weakened and thus reduces the anti-fouling efficacy, particularly due to increases biofouling pressures that can cause exhaustion of material, inefficient timing of release, or lack of adaptive releasing mechanism [40]. Usually, the coating would eventually have to be replaced however, this new innovative SLIPLS coating can fill in this gap as it introduced an on-demand anti-fouling release mechanism to reduce waste, extend the coating lifespan and provide continues defense across different environmental conditions. This SPIPS system shows excellent performance, demonstrating an anti-fouling effect for 360 days shown in Figure 4 [40].

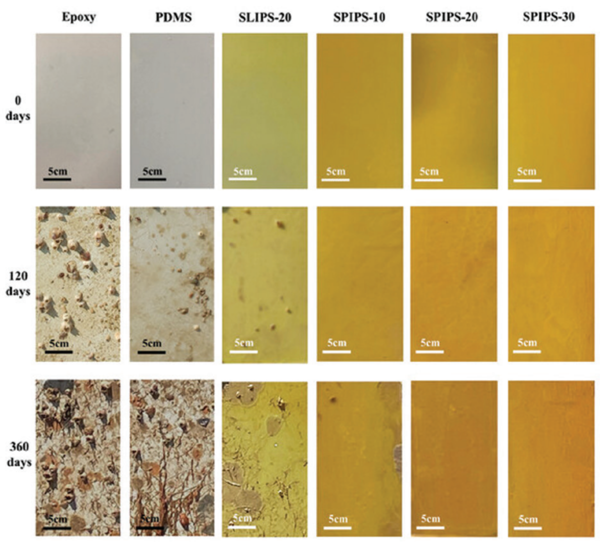

Figure 4: *Marine field test of experimental slippery porous-infused liquid porous surface (SPIPS) with different increments of porous liquid performed in the Zhoushan Sea over the course of 360 days [40].*

This adaptive, bioinspired approach offers a promising solution to improve anti-fouling efficiency, reduce lubricant usage, and extend the lifespan of coatings, which supports the broader goal of sustainable and smart marine lubricant technologies for the future.

Enhanced lubricants performance for engines

Lubricants are used in various marine applications to ensure that the engines of ships run smoothly as lubricants reduce friction between moving parts, preventing excessive wear and tear, overheating, and power loss, leading to greater performance and longevity [2]. However, lubricants must be carefully matched to the specific hardware of the engine and applied in careful amounts for optimal usage. Any improper application of marine lubricants may lead to problems, such as overheating, and cause damage to the engine [2].

As stated below, many strict regulations are encouraging greater sustainability for marine lubricants. Marine lubricants are uniquely emphasised for their detergency, thermal stability, and oxidation resistance. Many industrial and environmental drivers strive to push for better fuel efficiency, emission control, lower carbon footprint, and greater reliability and performance compared to traditional lubricants [41]. These pressures have led to a surge in interest towards nanotechnology-based additives and biolubricants as sustainable alternatives to traditional formulation in order to deliver performance without compromising environmental standards.

Nanotechnology is emerging as a transformative approach in the development of lubricants, aiming to enhance engine efficiency and performance while ensuring environmental compatibility. The use of nanoparticle additives has demonstrably reduced friction and wear by a significant degree, which continues to lengthen engine life and lower fuel consumption, and thus lower greenhouse gas emissions [42, 43].

In 2025, Wang et al. [44] conducted a study focusing on the synergistic effects of 1,3-diketone, an environmentally friendly friction modifier, and nano-copper particles, which are eco-friendly, within a commercial marine engine lubricant. Their goal was to enhance the lubrication performance in the piston ring-cylinder liner tribo-pair that are essential in the operation of marine vehicles, in order to reduce wear under harsh conditions. The results indicated a 16.7% reduction in friction, and a 21.6% and 16.7% reduction in wear on piston rings and cylinder liners, respectively, compared to using the standard base oil without additives. These improvements were attributed to the low shear resistance of copper nanoparticles and their ability to fill surface defects, forming a smoother protective layer that enhances lubrication [44].

Furthermore, the interaction between nano-copper, diketone, and traditional anti-wear additives resulted in a synergistic enhancement of anti-wear properties, offering improved durability under high-load marine conditions [44]. These findings highlight the potential of nanoparticle-based additives to support the development of high-performance, eco-friendly marine lubricants, contributing to greater engine efficiency and reduced greenhouse gas emissions.

Improving lubrication in marine engines is essential for enhancing fuel economy, reducing operating costs, and minimising greenhouse gas emissions. The growing demand for environmentally conscious products has spurred interest in the development of eco-friendly lubricant additives that can deliver high performance while meeting environmental regulations.

In a recent study by Wang et at. [45], the researchers explored how the morphology of aluminium oxide (Al2O3) nanoparticles affects their tribological behaviour when used as lubricant additives. While Al2O3 has been recognised for its anti-wear and anti-friction properties, this study indicates that Al2O3 nanosheets significantly outperformed other nanostructures such as the nanorods, nanospheres, and nanoparticles – as seen in Figure 5 [45].

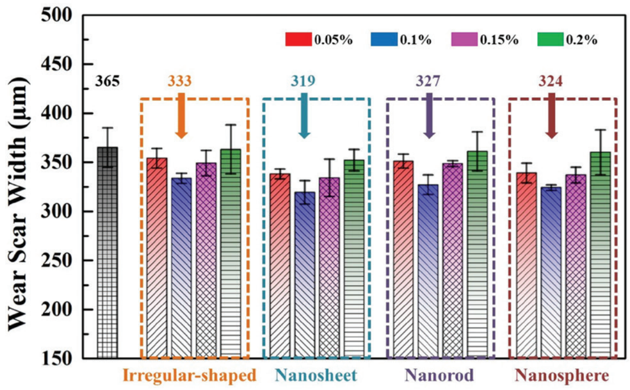

Figure 5: *Comparison of wear scar width of Al2O3 with varying content percentages and different shapes [34].*

These nanosheets have a broad surface area and layered structure that lowers friction by forming a protective, low-shear film on the contact surface, allowing smoother motion and reducing mechanical stress [45]. These findings suggest that not only the presence of nanoparticles but also their shape and structure are critical in determining performance. The average wear scar width of Al2O3 was the lowest as a nanosheet at 319 μm which was 12.6% less than that of using the base oil [45]. Nanosheet particles have a larger bearing area which reduces the stress effect on the friction surface and exhibits the best tribological properties compared to the other shapes. The use of tailored nanostructures like Al_2O_3 nanosheets offers a promising route toward high-efficiency, sustainable marine lubricants.

As the demand grows for sustainable alternatives to synthetic lubricants, biolubricants have emerged as a promising solution due to their non-toxic, renewable, and biodegradable properties, offering high performance with minimal environmental impact [46]. One notable approach involves using oils derived from macroalgae, which present a sustainable and eco-friendly alternative to fossil-based oils and additives. In a recent 2024 study, González-Meza et al. [47] evaluated Sargassum spp. oil as an additive in synthetic lubricants. The results demonstrated improved anti-friction and anti-wear performance, with a significant reduction in the coefficient of friction, supporting the potential of algae oils in green lubricant formulations [47]. Algal biomass is especially attractive due to its rapid growth rate, non-competition with arable land, and suitability for integrated biorefineries. Incorporating algae-based oils into lubricants not only reduces dependency on fossil fuels but also promotes a circular bioeconomy, enabling the development of eco-friendly, high-performance lubricants that align with climate goals and greenhouse gas reduction strategies.

Conclusion

With the developing maritime industry and an increasing emphasis on sustainability, new laws, regulations, and policies have encouraged the development of innovative strategies to improve the performance and environmental compatibility of marine lubricants.

Advancements in nanotechnology and biolubricants have enabled the design of enhanced anti-fouling solutions and high-performance lubricants that reduce toxicity and environmental harm. These alternative, eco-friendly approaches demonstrate that the maritime industry can adopt sustainable technologies that both protect marine ecosystems and support the efficient operation of marine vessels.

While past practices have contributed significantly to pollution and ecological damage, emerging green technologies offer a path forward towards minimising harmful impacts while maximising operational effectiveness and long-term environmental sustainability.

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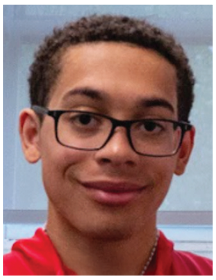

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