Frontiers in Marine Science

TYPE Perspective
PUBLISHED 01 May 2023
DOI 10.3389/fmars.2023.1175270

Transitioning towards environmentally benign marine antifouling coatings

Andrew J. Carrier[1*], Megan Carve[2], Jeff Shimeta[2], Tony R. Walker[3], Xu Zhang[1], Ken D. Oakes[4], Kshitij C. Jha[5], Tim Charlton[6] and Martina H. Stenzel[7]

[1]Department of Chemistry, Cape Breton University, Sydney, NS, Canada, [2]School of Science, RMIT University, Bundoora, VIC, Australia, [3]School for Resource and Environmental Studies, Dalhousie University, Halifax, NS, Canada, [4]Department of Biology, Cape Breton University, Sydney, NS, Canada, [5]Kavacha, Canoe Cove, PEI, Canada, [6]School of Biological, Earth & Environmental Sciences, The University of New South Wales, Sydney, NSW, Australia, [7]School of Chemistry, The University of New South Wales, Sydney, NSW, Australia

OPEN ACCESS

EDITED BY
Laurent Urios,
Université de Pau et des
Pays de l'Adour, France

REVIEWED BY
Geoffrey Swain,
Florida Institute of Technology,
United States

*CORRESPONDENCE
Andrew J. Carrier
✉ Andrew_Carrier@cbu.ca

RECEIVED 27 February 2023
ACCEPTED 17 April 2023
PUBLISHED 01 May 2023

CITATION
Carrier AJ, Carve M, Shimeta J, Walker TR, Zhang X, Oakes KD, Jha KC, Charlton T and Stenzel MH (2023) Transitioning towards environmentally benign marine antifouling coatings.
Front. Mar. Sci. 10:1175270.
doi: 10.3389/fmars.2023.1175270

Marine biofouling has been an issue since antiquity whose solutions have a history of negative environmental impact. The development of environmentally sustainable solutions is paramount as society is becoming more conscious of anthropogenic impacts on the global ecosystem, particularly the global oceans. Herein we include a brief overview of common strategies in the development of sustainable marine antifouling coatings in terms of their efficacy, durability, and environmental impact. We discuss technical challenges to the development of sustainable antifouling coatings; barriers and incentives to their market uptake; and advocate the necessity of multi-stakeholder collaboration, including scientists, engineers, industry groups, and regulators, toward the development of marketable and sustainable antifouling coating solutions.

KEYWORDS

biofouling, sustainability, microplastics, standardization, incentives

Introduction

Marine biofouling and its effect on hull integrity and hydraulic resistance have been a concern for seagoing vessels since antiquity; even today, biofouling poses significant negative economic and environmental effects, not only in the context of marine shipping but also in any situation where substrates are immersed in aqueous environments, such as aquaculture infrastructure (Woods Hole Oceanographic Institution and United States. Navy Dept. Bureau of Ships, 1952). Given the economic, e.g., increased fuel use and maintenance, and environmental, e.g., increased carbon dioxide emissions and transportation of invasive species, costs, much work has gone towards developing fouling-resistant coatings.

Biofouling occurs as a stepwise process initiated by the adsorption of dissolved macromolecules and followed by the adhesion of microorganisms that excrete extracellular polymeric substances forming a biofilm slime (microfouling), which acts as an anchor for the adhesion of larger sessile organisms (macrofouling). Antifouling (AF) strategies can target fouling at any of these stages, the most famous being biocidal tributyltin (TBT)-based coatings developed in the 1960s that were subsequently phased out and banned by the International Maritime Organization (IMO) in 2001 when their high persistence and unselective toxicity in the environment was discovered (Updegraff and Davis, 1965; Cooksley and Parham, 1966; Antizar-Ladislao, 2008; Gipperth, 2009). The need for effective AF coatings nonetheless persists, and research continues toward suitable replacements.

Strengths and challenges of contemporary coatings

To date, a major motivation in AF coating development is the production of more sustainable materials with good efficacy and minimal off-target impact (Yebra et al., 2004; Chambers et al., 2006; Banerjee et al., 2011; Callow and Callow, 2011). Copper-based coatings rapidly replaced TBT (Ranke and Jastorff, 2000), but there is some concern regarding the ecotoxicity of copper in marine environments (Gu et al., 2020). As such, research activity is largely focused on using degradable synthetic organic or natural-product-based biocides, photocatalytic surfaces, or biocide-free coatings that exploit surface chemistry to reduce adhesion or dislodge adhered organisms.

Organic and natural product biocides are potentially biodegradable alternatives to copper, reducing their long-term impact when leached into the environment (Armstrong et al., 2000; Bhatnagar and Kim, 2010; Qian et al., 2010; Ma et al., 2017; Ferreira et al., 2020). However, there are challenges involved in their application and regulatory pressures appear to disfavor any biocidal coatings (Aldred and Clare, 2008; Banerjee et al., 2011; Almeida and Vasconcelos, 2015). Natural products may not be easily available or affordable depending on whether they are extracted in sufficient quantities from commercially available species or if there is a scaled total synthesis. Synthetic organic biocides have an advantage in this respect, but the off-target acute and chronic ecotoxicity of biocides need to be evaluated before regulatory approval. Food safety must be considered when used in aquaculture or infrastructure applications where coatings may leach into food or water supplies.

A popular mechanism for dosing these biocides is through the slow degradation of self-polishing polymeric coatings (Ma et al., 2017; Pan et al., 2022). These coatings can be engineered to manage their dosing rate and longevity. These have the advantage of a continuously renewing surface that maintains its properties over the coating lifetime. Naturally, these coatings have a limited lifetime as they are designed to slough off protected surfaces, and their applications may be limited to seasonal use, e.g., on fishing or aquaculture equipment that is removed seasonally where coatings can be reapplied. These coatings will enter their receiving environment faster than more durable coatings, so attention should be given to the impact and degradability of these oligomers or microplastics. Polyethylene glycol and biodegradable esters, e.g., poly(lactic acid), are promising matrix materials in this regard.

Another alternative that results in the localized destruction of microbes are photocatalytic coating materials (Scandura et al., 2016; Liu et al., 2022). Photocatalysts use light to generate powerful free-radical oxidants that eradicate bacteria and can also mineralize near-surface organic pollutants. Although these seem to be a straightforward solution to fouling, they suffer from some challenges. Photocatalysts are typically UV-active, and UV light is strongly attenuated by water so deeper structures receive less protection. The efficacy is also modulated by season and latitude. Novel photocatalysts that can either directly use or upconvert more readily available visible or near-infrared light are promising alternatives (Richards et al., 2021). For efficacy, these photocatalysts are typically in the form of nanoparticles, which also have environmental concerns and they may not be environmentally benign (Marcone et al., 2012), and depending on the matrix they are embedded in, may accelerate the physical deterioration of the coating through photodegradation, reducing coating longevity and accelerating the deposition of microplastics in the marine environment. Detailed studies into the interaction of photocatalysts with their matrix, the free radicals involved, and their environmental fate (particularly for newer, less well studied, photocatalysts) may promote their durability, efficacy, and sustainability.

Other biocide-free coatings rely on novel surface chemistry and physical effects that retard fouling adhesion or promote fouling release (FR) (Yang et al., 2014; Hu et al., 2020). The most common strategies include using amphiphilic coatings with both superhydrophilic and superhydrophobic phases (Krishnan et al., 2008; Park et al., 2010; Galli and Martinelli, 2017), using biomimetic or “bioinspired” coatings that have multiple (micro or nano) scales or surface topographies (Statz et al., 2006; Schumacher et al., 2007; Wong et al., 2011; Kirschner and Brennan, 2012; Carve et al., 2019; Selim et al., 2020; Jin et al., 2022), and using low-surface-energy FR coatings (Dobretsov and Thomason, 2011; Martinelli et al., 2012) containing silicones (Galhenage et al., 2016; Selim et al., 2017; Hu et al., 2020) and/or fluorous phases (Gudipati et al., 2005; Xiao et al., 2013). These coatings minimize microbial adhesion through physical effects and benefit from the application of shear forces, making them most suitable for non-stationary applications. These coatings benefit from regular grooming to dislodge slime or macrofouling to maintain their efficacy (Tribou and Swain, 2010). The lack of biocidal components provides a clear benefit regarding ecotoxicity, but these coatings still face challenges. Abrasion resistance is a concern, especially for biomimetic coatings where a loss of topographical structure results in a loss of function (Liu et al., 2023). These can be difficult to apply on large scales, with self-assembly strategies being critical to their practical adoption (Su et al., 2021). Self-assembled micro- and nanostructures can form either during curing/drying or in contact with water. FR coatings are less technically demanding during application, but silicone and fluorous phases may eventually be deposited as persistent non-degradable particulate matter. Innocuous or degradable alternatives to fluorous phases can make this strategy more sustainable and highly competitive in the marketplace.

Biomimetic coatings and marine natural product biocides are both examples of exploiting natural AF products and mechanisms for human endeavours. It stands to reason that other biomass-derived materials may contribute to effective, sustainable, and biodegradable coating materials. Waxy compounds derived from, or mimicking leaf cuticles produce slick surfaces (Ma et al., 2011) and chitosan, which is derived from marine biomass waste, has known antibacterial properties (Yang et al., 2011). Such materials can be components of zero waste economies in coastal communities and support local fisheries using their own upgraded waste products (Ubando et al., 2020).

Although these strategies appear more sustainable and responsible than using non-selective and persistent inorganic biocidal coatings, their complete cradle-to-grave life cycles should be assessed to estimate their long-term impacts. An often-overlooked concern regarding any coating materials, whether they contain biocidal compounds or not, is their ultimate fate in the environment. Coatings degrade over time, either intentionally in the case of self-polishing coatings or unintentionally through normal aging and abrasion. Additionally, coated equipment, such as fishing gear, may become lost or discarded at sea. In any case, coatings will find their way into the environment where they will contribute to the micro/nanoplastic waste problem currently plaguing our watercourses and oceans. Apart from their impact on ocean life through ingestion, bioaccumulation, and a general decrease in water quality (Peters et al., 2018; Park et al., 2020; Dibke et al., 2021), microplastic particles have a high surface area-to-volume ratio and act as effective mobile vectors and reservoirs for hydrophobic chemical compounds. AF coating microplastics also potentially contain biocides and other active ingredients, which may extend their impacts in areas they are applied most often, e.g., harbours, fishing grounds, and seawater intakes (Soroldoni et al., 2018).

Biofouling is a serious issue that requires immediate action. While numerous creative solutions are available, stakeholders must take a careful and thoughtful approach to their selection and implementation. The economic cost, application complexity, durability, and resource use of each solution must be weighed against their potential benefits. Equally important is the long-term impact of these solutions on our planet's ecosystem. We must consider the potential consequences of their widespread use and eventual accumulation in oceans to prevent another ecological disaster, like TBT contamination, from occurring. It is our responsibility to act now and ensure that we are taking the most effective and responsible measures to address biofouling. By carefully considering the advantages and disadvantages of each solution and prioritizing their long-term impact on our planet, we can work towards a more sustainable future.

Discussion

Despite the tremendous efforts of small and medium-sized enterprises and academic researchers, there are still very few viable alternatives to inorganic biocidal coatings available on the market today. Scientists, engineers, industry groups, consumers, and regulators must work together to identify and address the key barriers that are preventing the development and implementation of novel coatings. There are several significant challenges that must be overcome, including a complex regulatory environment, a lack of standardized evaluation methods, and limited access to high-quality performance data for comparison. The cost and availability of raw materials, such as marine natural product biocides, also pose a significant challenge. In addition, there is a pervasive sense of inertia, which can hinder progress and discourage innovation. The belief that currently available solutions are sufficient creates a barrier to change.

To address these challenges, we must collaborate to develop a program of incentives and barriers that encourage the adoption of sustainable AF solutions and establish standards and evaluation methods that allow for accurate performance data comparison. We must identify actionable pathways toward marketable and sustainable AF solutions. With the right collaborative efforts and strategic implementation, we can overcome these barriers and create a better, more sustainable future.

Technical challenges

The development of novel AF coatings requires an objective standard method for evaluating coating efficacy. Without one, competing technological solutions cannot be directly compared for different uses. For example, infrastructure, such as floating docks, buoys, and water inlets, are not exposed to the same shear forces as ocean-going vessels and do not similarly benefit from FR strategies.

Although there is a great deal of work by academics to develop standard laboratory methods to assess AF efficacy under static (Ribeiro et al., 2008) and hydrodynamic conditions (Swain et al., 2007; Nolte et al., 2018), and under potentially accelerated time frames and/or with high throughput (Cassé et al., 2007; Webster et al., 2009; Stafslien et al., 2012; Pansch et al., 2017) to compliment field assessments (Rittschof et al., 2008; Zhang et al., 2013; Stafslien et al., 2016), current ASTM standard methods (D01 Committee, 2020a; D01 Committee, 2020b), which were last updated in 2020 and represent a consensus of producers, consumers, scientists, and engineers, are still highly subjective and involve visual inspection of coated panels submerged in natural seawater. As seawater composition varies with geography and season (Swain et al., 2000), such tests lack reproducibility under varying cases and limits their effectiveness in providing accurate and reliable data. Moreover, they presume a biocidal effect whereas FR coatings are better assessed via adhesion testing (Swain and Schultz, 1996). Testing is also generally over short time scales and cannot capture the effects of aging on coated surfaces (Webster et al., 2009). Therefore, a critical research gap exists in evaluating the long-term efficacy of AF coatings in relevant environments, including establishing long-term compatibility with different substrates, e.g., steel and plastic. ASTM methods are widely used in industry, and consensus regarding better standards would improve communicating reproducible efficacy data. These research questions are best addressed through pilot studies where the coatings will be exposed to realistic operating conditions for target applications (Bellas Bereijo and Beiras Garcia-Sabell, 2010; Callow et al., 2014; Guerin and Clare, 2018). Additionally, the long-term ecological impact should be addressed on a smaller scale to minimize the potential for deleterious effects on the environment. However, such testing is challenged by local regulations regarding what can be intentionally introduced to natural waters. Such realistic long-term tests can be supplemented by small-scale aquarium models of the receiving environment. To address the variation of fouling based on environment, application, and season, standardized model systems must address the speciation, nutrient profiles, temperature, and photoperiods relevant to each application.

Laboratory efficacy data should also be supplemented with economic feasibility studies and the practical application for desired uses, e.g., complex layer-by-layer syntheses of hierarchical structures on panels at the lab scale may never be practically applicable on large ocean-going vessels and rare marine natural products may never be economically viable in large-scale applications. Questions regarding scale-up, cost-effectiveness, and commercialization potential require contributions from engineers and industry groups that can evaluate the practicability of laboratory-scale ideas and determine whether additional funding investment is worthwhile. The establishment of relevant standards and participation by stakeholders at all levels can ensure the best use of research funding towards the overall goal of economically viable, practical, and effective sustainable AF solutions.

Finally, cradle-to-grave life cycle analyses are essential to determine if a technology is sustainable, rather than just assuming it must be if it does not include currently deleterious components. Inert coatings may have long-term persistence and any coating applied to a submerged surface will find its way into the environment. Modern AF coatings can reduce the monetizable fuel and maintenance costs, and their environmental impacts have been widely explored in the literature, but subsequent studies of their impacts on ecosystem services, both monetizable and environmental value, should be performed. The impact of coatings should be well understood early rather than after several decades when any potential problems become difficult to resolve. Sustainability must be necessarily forward-looking. Our future economies, environment, and health depend on it.

Barriers and incentives to market uptake

Although our current reliance on biocidal coatings requires urgent action, inertia among stakeholders has slowed progress. The lack of viable replacements allows current manufacturers to continue profiting while avoiding regulation. Conversely, small market entrants struggle to compete due to large financial and time barriers, with few competitors on the horizon. Incentives, such as grants, commercial research and development, and public-private ventures, that encourage the development and application of effective, sustainable solutions to overcome these barriers can bring alternatives to the market. New benign technologies can rapidly gain market share as older materials face regulatory pressure. Thus, the long-term incentive for investment in innovative and sustainable AF solutions is strong as their market share would be supported by strong barriers to entry, i.e., regulatory approval and intellectual property protection. Incentivizing the development and adoption of sustainable AF solutions is a sound investment. For example, public investment in research and development helps fund the creation of new and effective solutions, whereas tax credits or rebates for consumers can encourage the adoption of sustainable coatings while incentivizing collaborative partnerships to help resolve technical challenges and lead to more effective solutions.

The establishment of industry standards for both efficacy and sustainability can impart consumers with a clear understanding of competing products, allowing manufacturers to provide direct comparisons in a more competitive marketplace. Additionally, independent certification programs provide confidence for consumers, helping to increase demand. Finally, pilot projects, education, and awareness campaigns can effectively demonstrate the efficacy and sustainability of products and attract new consumers. By investing in sustainable AF solutions and providing the necessary incentives, we can create a cleaner and healthier future for our oceans and rivers, while supporting the economies that rely on these environments.

Disincentivizing the use of current biocidal coatings will rely on regulatory pressure, as was used for TBT-based coatings. Regulators, however, hesitate to act because there are few viable alternatives available on the market, and industries remain dependent on biocidal coatings. The development of commercially viable and marketed sustainable alternatives will enable regulators to act, give consumers alternatives, and disincentivize the use of older, less sustainable materials.

Outlook

A ban on biocidal coatings, and their current environmental impact, will have a delayed effect as previously applied coatings come out of service, making the timely development of novel active coatings critical for regulators, global marine shipping, and related industries. This presents many challenges as novel active agents must demonstrate both sufficient AF activity for industrial applications and minimal environmental impact to meet various regulatory agency standards, a time-consuming and expensive process.

Considering the critical concern for time-to-market, disruptive technologies using marine natural products and their derivatives, among other low environmental concern materials, present promising alternatives to established biocidal compounds now facing regulatory pressure. The overall life-cycle assessment of these products, in combination with their effects on their proposed application, must also be considered. Do the economic and environmental benefits of reduced fuel use, greenhouse gas emissions, and faster shipping cycles overcome any drawbacks of the manufacture, application, and ultimate disposition of coating materials in the environment? It is essential to understand the technical gaps in reducing and eliminating marine debris and toxic pollutants arising from marine AF coating applications to create a framework for coating technology development and a roadmap to support the development of innovative commercially viable coatings and standards.

There is an urgent need to address the environmental impact of AF coatings. The development of novel active coating modalities is a critical step toward achieving sustainability in the marine industry. Together we can create innovative, commercially viable coatings that are environmentally sustainable and meet the needs of the marine industry. By doing so, we can minimize the environmental impact of AF coatings and preserve the health of our shared marine ecosystems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

AC coordinated the perspective manuscript and prepared the first drafts of the synopsis and manuscript. All authors contributed to the article and approved the submitted version.

Funding

AC, XZ, and KO have received funding from the Natural Science and Engineering Research Council of Canada (NSERC) Discovery Development grants, Canada Research Chairs program, the Canada Foundation for Innovation John R. Evans Leaders Fund, and the Cape Breton University Research Innovation Scholarship Exploration program. TW has received funding from the NSERC Discovery grant program. KJ was an industrial partner with Cape Breton University in obtaining funding from NSERC Alliance Missions, Mitacs Accelerate, the Information and Communications Technology Council, and the National Research Council (Canada). KJ has also received funding from Canada's Ocean Supercluster. TC and MS received funding from the UNSW Faculty of Science Industry Network Seed Fund.

Acknowledgments

KJ acknowledges multiple discussions and insightful feedback on the topic from Eric Siegel of the Ocean Startup Project and Ocean Frontier Institute.

Conflict of interest

KJ is a founder of Kavacha, a company working in the field of marine antifouling coatings. TC is a Director of Ecozean Pty Ltd., which has developed an anti-fouling coating for aquaculture.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Aldred, N., and Clare, A. S. (2008). The adhesive strategies of cyprids and development of barnacle-resistant marine coatings. *Biofouling* 24, 351–363. doi: 10.1080/08927010802256117

Almeida, J. R., and Vasconcelos, V. (2015). Natural antifouling compounds: effectiveness in preventing invertebrate settlement and adhesion. *Biotechnol. Adv.* 33, 343–357. doi: 10.1016/j.biotechadv.2015.01.013

Antizar-Ladislao, B. (2008). Environmental levels, toxicity and human exposure to tributyltin (TBT)-contaminated marine environment. *Environ. Int.* 34, 292–308. doi: 10.1016/j.envint.2007.09.005

Armstrong, E., Boyd, K. G., and Burgess, J. G. (2000). "Prevention of marine biofouling using natural compounds from marine organisms," in *Biotechnology annual review* (Elsevier), 221–241. doi: 10.1016/S1387-2656(00)06024-5

Banerjee, I., Pangule, R. C., and Kane, R. S. (2011). Antifouling coatings: recent developments in the design of surfaces that prevent fouling by proteins, bacteria, and marine organisms. *Adv. Mater. (Weinheim Ger.)* 23, 690–718. doi: 10.1002/adma.201001215

Bellas Bereijo, J. D., and Beiras Garcia-Sabell, R. (2010). *Screening the efficacy of antifouling and anti-incrustation agents with a bioassay for settling of ascidian larvae. Spanish patent no 2,333,573* (Madrid, Spain: Spanish Patent and Trademark Office).

Bhatnagar, I., and Kim, S.-K. (2010). Immense essence of excellence: marine microbial bioactive compounds. *Mar. Drugs* 8, 2673–2701. doi: 10.3390/md8102673

Callow, J. A., and Callow, M. E. (2011). Trends in the development of environmentally friendly fouling-resistant marine coatings. *Nat. Commun.* 2, 1251/1. doi: 10.1038/ncomms1251

Callow, M. E., Callow, J. A., Conlan, S., Clare, A. S., and Stafslien, S. (2014). "Efficacy testing of nonbiocidal and fouling-release coatings," in *Biofouling methods* (John Wiley & Sons Ltd), 291. doi: 10.1002/9781118336144.ch10

Carve, M., Scardino, A., and Shimeta, J. (2019). Effects of surface texture and interrelated properties on marine biofouling: a systematic review. *Biofouling* 35, 597–617. doi: 10.1080/08927014.2019.1636036

Cassé, F., Stafslien, S. J., Bahr, J. A., Daniels, J., Finlay, J. A., Callow, J. A., et al. (2007). Combinatorial materials research applied to the development of new surface coatings v. application of a spinning water-jet for the semi-high throughput assessment of the attachment strength of marine fouling algae. *Biofouling* 23, 121–130. doi: 10.1080/08927010701189583

Chambers, L. D., Stokes, K. R., Walsh, F. C., and Wood, R. J. K. (2006). Modern approaches to marine antifouling coatings. *Surf. Coat. Technol.* 201, 3642–3652. doi: 10.1016/j.surfcoat.2006.08.129

Cooksley, M. V., and Parham, D. N. (1966). Organotin compounds in antifouling compositions. *Surf. Coat.* 2, 280.

D01 Committee (2020a). *Test method for subjecting marine antifouling coating to biofouling and fluid shear forces in natural seawater* (ASTM International). doi: 10.1520/D4939-89R20

D01 Committee (2020b). *Test method for testing antifouling panels in shallow submergence* (ASTM International). doi: 10.1520/D3623-78AR20

Dibke, C., Fischer, M., and Scholz-Böttcher, B. M. (2021). Microplastic mass concentrations and distribution in German bight waters by pyrolysis–gas chromatography–mass Spectrometry/Thermochemolysis reveal potential impact of marine coatings: do ships leave skid marks? *Environ. Sci. Technol.* 55, 2285–2295. doi: 10.1021/acs.est.0c04522

Dobretsov, S., and Thomason, J. C. (2011). The development of marine biofilms on two commercial non-biocidal coatings: a comparison between silicone and fluoropolymer technologies. *Biofouling* 27, 869–880. doi: 10.1080/08927014.2011.607233

Ferreira, O., Rijo, P., Gomes, J. F., Santos, R., Monteiro, S., Vilas-Boas, C., et al. (2020). Biofouling inhibition with grafted econea biocide: toward a nonreleasing eco-friendly multiresistant antifouling coating. *ACS Sustain. Chem. Eng.* 8, 12–17. doi: 10.1021/acssuschemeng.9b04550

Galhenage, T. P., Hoffman, D., Silbert, S. D., Stafslien, S. J., Daniels, J., Miljkovic, T., et al. (2016). Fouling-release performance of silicone oil-modified siloxane-polyurethane coatings. *ACS Appl. Mater. Interfaces* 8, 29025–29036. doi: 10.1021/acsami.6b09484

Galli, G., and Martinelli, E. (2017). Amphiphilic polymer platforms: surface engineering of films for marine antibiofouling. *Macromol. Rapid Commun.* 38, 1600704. doi: 10.1002/marc.201600704

Gipperth, L. (2009). The legal design of the international and European union ban on tributyltin antifouling paint: direct and indirect effects. *J. Environ. Manage.* 90, S86–S95. doi: 10.1016/j.jenvman.2008.08.013

Gu, Y., Yu, L., Mou, J., Wu, D., Xu, M., Zhou, P., et al. (2020). Research strategies to develop environmentally friendly marine antifouling coatings. *Mar. Drugs* 18, 371. doi: 10.3390/md18070371

Gudipati, C. S., Finlay, J. A., Callow, J. A., Callow, M. E., and Wooley, K. L. (2005). The antifouling and fouling-release perfomance of hyperbranched fluoropolymer (HBFP)–poly(ethylene glycol) (PEG) composite coatings evaluated by adsorption of biomacromolecules and the green fouling alga *Ulva*. *Langmuir* 21, 3044–3053. doi: 10.1021/la048015o

Guerin, A. J., and Clare, A. S. (2018). Mini-review: effect sizes and meta-analysis for antifouling research. *Biofouling* 34, 1185–1199. doi: 10.1080/08927014.2018.1550196

Hu, P., Xie, Q., Ma, C., and Zhang, G. (2020). Silicone-based fouling-release coatings for marine antifouling. *Langmuir* 36, 2170–2183. doi: 10.1021/acs.langmuir.9b03926

Jin, H., Tian, L., Bing, W., Zhao, J., and Ren, L. (2022). Bioinspired marine antifouling coatings: status, prospects, and future. *Prog. Mater. Sci.* 124, 100889. doi: 10.1016/j.pmatsci.2021.100889

Kirschner, C. M., and Brennan, A. B. (2012). Bio-inspired antifouling strategies. *Annu. Rev. Mater. Res.* 42, 211–229. doi: 10.1146/annurev-matsci-070511-155012

Krishnan, S., Weinman, C. J., and Ober, C. K. (2008). Advances in polymers for anti-biofouling surfaces. *J. Mater. Chem.* 18, 3405–3413. doi: 10.1039/b801491d

Liu, C., Wang, W., Zhang, M., Zhang, C., Ma, C., Cao, L., et al. (2022). Synthesis of MXene/COF/Cu2O heterojunction for photocatalytic bactericidal activity and mechanism evaluation. *Chem. Eng. J. (Amsterdam Neth.)* 430, 132663. doi: 10.1016/j.cej.2021.132663

Liu, Y., Wu, Y., and Zhou, F. (2023). Shear-stable polymer brush surfaces. *Langmuir* 39, 37–44. doi: 10.1021/acs.langmuir.2c03012

Ma, J., Sun, Y., Gleichauf, K., Lou, J., and Li, Q. (2011). Nanostructure on taro leaves resists fouling by colloids and bacteria under submerged conditions. *Langmuir* 27, 10035–10040. doi: 10.1021/la2010024

Ma, C., Zhang, W., Zhang, G., and Qian, P.-Y. (2017). Environmentally friendly antifouling coatings based on biodegradable polymer and natural antifoulant. *ACS Sustain. Chem. Eng.* 5, 6304–6309. doi: 10.1021/acssuschemeng.7b01385

Marcone, G. P. S., Oliveira, A. C., Almeida, G., Umbuzeiro, G. A., and Jardim, W. F. (2012). Ecotoxicity of TiO2 to daphnia similis under irradiation. *J. Hazard. Mater.* 211–212, 436–442. doi: 10.1016/j.jhazmat.2011.12.075

Martinelli, E., Sarvothaman, M. K., Galli, G., Pettitt, M. E., Callow, M. E., Callow, J. A., et al. (2012). Poly(dimethyl siloxane) (PDMS) network blends of amphiphilic acrylic copolymers with poly(ethylene glycol)-fluoroalkyl side chains for fouling-release coatings. II. laboratory assays and field immersion trials. *Biofouling* 28, 571–582. doi: 10.1080/08927014.2012.697897

Nolte, K. A., Koc, J., Barros, J. M., Hunsucker, K., Schultz, M. P., Swain, G. W., et al. (2018). Dynamic field testing of coating chemistry candidates by a rotating disk system. *Biofouling* 34, 398–409. doi: 10.1080/08927014.2018.1459578

Pan, J., Ai, X., Ma, C., and Zhang, G. (2022). Degradable vinyl polymers for combating marine biofouling. *Acc. Chem. Res.* 55, 1586–1598. doi: 10.1021/acs.accounts.2c00187

Pansch, C., Jonsson, P. R., Berglin, M., Pinori, E., and Wrange, A.-L. (2017). A new flow-through bioassay for testing low-emission antifouling coatings. *Biofouling* 33, 613–623. doi: 10.1080/08927014.2017.1349897

Park, T.-J., Lee, S.-H., Lee, M.-S., Lee, J.-K., Lee, S.-H., and Zoh, K.-D. (2020). Occurrence of microplastics in the han river and riverine fish in south Korea. *Sci. Total Environ.* 708, 134535. doi: 10.1016/j.scitotenv.2019.134535

Park, D., Weinman, C. J., Finlay, J. A., Fletcher, B. R., Paik, M. Y., Sundaram, H. S., et al. (2010). Amphiphilic surface active triblock copolymers with mixed hydrophobic and hydrophilic side chains for tuned marine fouling-release properties. *Langmuir* 26, 9772–9781. doi: 10.1021/la100032n

Peters, C. A., Hendrickson, E., Minor, E. C., Schreiner, K., Halbur, J., and Bratton, S. P. (2018). Pyr-GC/MS analysis of microplastics extracted from the stomach content of benthivore fish from the Texas gulf coast. *Mar. pollut. Bull.* 137, 91–95. doi: 10.1016/j.marpolbul.2018.09.049

Qian, P.-Y., Xu, Y., and Fusetani, N. (2010). Natural products as antifouling compounds: recent progress and future perspectives. *Biofouling* 26, 223–234. doi: 10.1080/08927010903470815

Ranke, J., and Jastorff, B. (2000). Multidimensional risk analysis of antifouling biocides. *Environ. Sci. pollut. Res. Int.* 7, 105–114. doi: 10.1065/espr199910.003

Ribeiro, E., Stafslien, S. J., Cassé, F., Callow, J. A., Callow, M. E., Pieper, R. J., et al. (2008). Automated image-based method for laboratory screening of coating libraries for adhesion of algae and bacterial biofilms. *J. Comb. Chem.* 10, 586–594. doi: 10.1021/cc800047s

Richards, B. S., Hudry, D., Busko, D., Turshatov, A., and Howard, I. A. (2021). Photon upconversion for photovoltaics and photocatalysis: a critical review. *Chem. Rev. (Washington DC U. S.)* 121, 9165–9195. doi: 10.1021/acs.chemrev.1c00034

Rittschof, D., Orihuela, B., Stafslien, S., Daniels, J., Christianson, D., Chisholm, B., et al. (2008). Barnacle reattachment: a tool for studying barnacle adhesion. *Biofouling* 24, 1–9. doi: 10.1080/08927010701784920

Scandura, G., Ciriminna, R., Xu, Y.-J., Pagliaro, M., and Palmisano, G. (2016). Nanoflower-like Bi2WO6 encapsulated in ORMOSIL as a novel photocatalytic antifouling and foul-release coating. *Chem. - Eur. J.* 22, 7063–7067. doi: 10.1002/chem.201600831

Schumacher, J. F., Carman, M. L., Estes, T. G., Feinberg, A. W., Wilson, L. H., Callow, M. E., et al. (2007). Engineered antifouling microtopographies - effect of feature size, geometry, and roughness on settlement of zoospores of the green alga ulva. *Biofouling* 23, 55–62. doi: 10.1080/08927010601136957

Selim, M. S., El-Safty, S. A., Shenashen, M. A., Higazy, S. A., and Elmarakbi, A. (2020). Progress in biomimetic leverages for marine antifouling using nanocomposite coatings. *J. Mater. Chem. B* 8, 3701–3732. doi: 10.1039/C9TB02119A

Selim, M. S., Shenashen, M. A., Elmarakbi, A., Fatthallah, N. A., Hasegawa, S., and El- Safty, S. A. (2017). Synthesis of ultrahydrophobic and thermally stable inorganic–organic nanocomposites for self-cleaning foul release coatings. *Chem. Eng. J.* 320, 653–666. doi: 10.1016/j.cej.2017.03.067

Soroldoni, S., Martins, S. E., Castro, I. B., and Pinho, G. L. L. (2018). Potential ecotoxicity of metals leached from antifouling paint particles under different salinities. *Ecotoxicol. Environ. Saf.* 148, 447–452. doi: 10.1016/j.ecoenv.2017.10.060

Stafslien, S., Daniels, J., Bahr, J., Chisholm, B., Ekin, A., Webster, D., et al. (2012). An improved laboratory reattachment method for the rapid assessment of adult barnacle adhesion strength to fouling-release marine coatings. *J. Coat Technol. Res.* 9, 651–665. doi: 10.1007/s11998-012-9409-7

Stafslien, S. J., Sommer, S., Webster, D. C., Bodkhe, R., Pieper, R., Daniels, J., et al. (2016). Comparison of laboratory and field testing performance evaluations of siloxane-polyurethane fouling-release marine coatings. *Biofouling* 32, 949–968. doi: 10.1080/08927014.2016.1211269

Statz, A., Finlay, J., Dalsin, J., Callow, M., Callow, J. A., and Messersmith, P. B. (2006). Algal antifouling and fouling-release properties of metal surfaces coated with a polymer inspired by marine mussels. *Biofouling* 22, 391–399. doi: 10.1080/08927010601004890

Su, X., Yang, M., Hao, D., Guo, X., and Jiang, L. (2021). Marine antifouling coatings with surface topographies triggered by phase segregation. *J. Colloid Interface Sci.* 598, 104–112. doi: 10.1016/j.jcis.2021.04.031

Swain, G., Anil, A. C., Baier, R. E., Chia, F., Conte, E., Cook, A., et al. (2000). Biofouling and barnacle adhesion data for fouling-release coatings subjected to static immersion at seven marine sites. *Biofouling* 16, 331–344. doi: 10.1080/08927010009378456

Swain, G. W., Kovach, B., Touzot, A., Casse, F., and Kavanagh, C. J. (2007). Measuring the performance of today's antifouling coatings. *J. Ship Production* 23, 164–170. doi: 10.5957/jsp.2007.23.3.164

Swain, G. W., and Schultz, M. P. (1996). The testing and evaluation of non-toxic antifouling coatings. *Biofouling* 10, 187–197. doi: 10.1080/08927019609386279

Tribou, M., and Swain, G. (2010). The use of proactive in-water grooming to improve the performance of ship hull antifouling coatings. *Biofouling* 26, 47–56. doi: 10.1080/08927010903290973

Ubando, A. T., Felix, C. B., and Chen, W.-H. (2020). Biorefineries in circular bioeconomy: a comprehensive review. *Bioresour. Technol.* 299, 122585. doi: 10.1016/j.biortech.2019.122585

Updegraff, D. M., and Davis, H. R. (1965). *Tributyltin oxide esters as antifouling compounds. U.S. patent no 3,211,680* (Washington, DC: U.S. Patent and Trademark Office).

Webster, D. C., Chisholm, B. J., and Stafslien, S. J. (2009). "High throughput methods for the design of fouling control coatings," in *Advances in marine antifouling coatings and technologies* (Elsevier), 365–392. doi: 10.1533/9781845696313.2.365

Wong, T.-S., Kang, S. H., Tang, S. K. Y., Smythe, E. J., Hatton, B. D., Grinthal, A., et al. (2011). Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. *Nat. (London U. K.)* 477, 443–447. doi: 10.1038/nature10447

Woods Hole Oceanographic Institution and United States. Navy Dept. Bureau of Ships (1952) *Marine fouling and its prevention; prepared for bureau of ships, navy dept*

(Woods Hole, MA: United States Naval Institute). Available at: https://hdl.handle.net/1912/191 (Accessed February 19, 2021).

Xiao, L., Li, J., Mieszkin, S., Di Fino, A., Clare, A. S., Callow, M. E., et al. (2013). Slippery liquid-infused porous surfaces showing marine antibiofouling properties. *ACS Appl. Mater. Interfaces* 5, 10074–10080. doi: 10.1021/am402635p

Yang, W. J., Cai, T., Neoh, K.-G., Kang, E.-T., Dickinson, G. H., Teo, S. L.-M., et al. (2011). Biomimetic anchors for antifouling and antibacterial polymer brushes on stainless steel. *Langmuir* 27, 7065–7076. doi: 10.1021/la200620s

Yang, W. J., Neoh, K.-G., Kang, E.-T., Teo, S. L.-M., and Rittschof, D. (2014). Polymer brush coatings for combating marine biofouling. *Prog. Polymer Sci.* 39, 1017–1042. doi: 10.1016/j.progpolymsci.2014.02.002

Yebra, D. M., Kiil, S., and Dam-Johansen, K. (2004). Antifouling technology-past, present and future steps towards efficient and environmentally friendly antifouling coatings. *Prog. Org. Coat.* 50, 75–104. doi: 10.1016/j.porgcoat.2003.06.001

Zhang, J., Lin, C., Wang, L., Zheng, J., Xu, F., and Sun, Z. (2013). Study on the correlation of lab assay and field test for fouling-release coatings. *Prog. Organic Coatings* 76, 1430–1434. doi: 10.1016/j.porgcoat.2013.05.002