



National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Antifouling systems for pleasure boats

Overview of current systems and
exploration of safer alternatives

RIVM Report 2018-0086

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Colophon

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Synopsis

Antifouling systems for pleasure boats

Antifouling paints are often used on the surfaces of pleasure boats to prevent the growth of algae and shellfish below the waterline. These paints contain toxic substances. The Dutch government is committed to encouraging boat owners to switch to the use of antifouling systems that are safer and have less environmental impact. The National Institute for Public Health and the Environment (RIVM) has therefore drawn up an overview of current and future possibilities for preventing the fouling of the surfaces of pleasure boats under the waterline. A number of systems are expected to have considerably less impact on the environment than those now in use. RIVM also puts forward suggestions for promoting the use of these cleaner antifouling systems.

Existing antifouling paints are often 'self-polishing paints' which contain copper as a biocide and zinc as a co-formulant: the paints wear during sailing, gradually releasing these substances. As a result, heavy metals end up in the water and impact the environment.

There are already various systems available for pleasure boats that do not contain biocides, some of which have probably less impact to the environment than the self-polishing paints that do. These include hard 'foul release coatings', other hard coatings, films with flexible plastic fibres that act as spines and systems based on ultra sound. Some promising antifouling systems that, for example, use ultraviolet light or natural, readily degradable biocides that stay in the coating are still in the research phase.

RIVM recommends examining the legal possibilities for reducing the use of antifouling systems that contain biocides and self-polishing paints. How well or badly existing possibilities score in the field of antifouling performance, safety and environmental impact should, furthermore, be clearer for consumers. The development of a standardised test that can be used to determine the efficacy of antifouling systems under different conditions is also desirable.

Keywords: antifouling systems, pleasure boats, biocides, paints and coatings, safety, environmental impact, alternatives assessment

Publiekssamenvatting

Antifouling systemen voor pleziervaart

Op pleziervaartuigen worden momenteel vaak verven gebruikt die ervoor zorgen dat er op het oppervlak onder water geen algen en schelpdieren aangroeien (antifouling). Deze verven bevatten giftige stoffen. De Nederlandse overheid wil stimuleren dat booteigenaren overstappen naar minder milieubelastende antifouling-systemen. Het RIVM heeft daarom een overzicht gemaakt van de huidige en toekomstige mogelijkheden om aangroei op het onderwateroppervlak van plezierboten te voorkomen. Een aantal systemen is naar verwachting aanzienlijk minder milieubelastend dan de huidige. Het RIVM doet ook suggesties om het gebruik van dergelijke schonere antifouling-systemen te bevorderen.

De huidige antifouling-verven zijn vaak 'zelfslijpende verven' met koper als bestrijdingsmiddel en zink als hulpstof: de verf slijt tijdens het varen af waarmee de stoffen steeds opnieuw uit de coating vrij komen. Hierdoor komen zware metalen in het water terecht die het milieu belasten.

Er zijn al verschillende systemen zonder bestrijdingsmiddelen beschikbaar voor pleziervaartuigen, waarvan een deel waarschijnlijk minder milieubelastend is dan de zelfslijpende verven met bestrijdingsmiddelen. Dit gaat onder meer om harde 'foul release coatings', andere harde coatings, folies met kunststof 'stekeltjes', en systemen op basis van ultrasoon geluid. Sommige veelbelovende antifouling-systemen bevinden zich nog in de onderzoeksfase, zoals het gebruik van ultraviolet licht en de ontwikkeling van natuurlijke, goed afbreekbare bestrijdingsmiddelen die in de coating blijven.

Het RIVM raadt aan te onderzoeken wat de wettelijke mogelijkheden zijn om het gebruik van middelen die bestrijdingsmiddelen bevatten en zelfslijpende verven te verminderen. Daarnaast zou het voor consumenten duidelijker moeten zijn hoe goed of slecht de bestaande mogelijkheden scoren op het gebied van werkzaamheid, veiligheid en milieubelasting. Ook is het wenselijk dat er een gestandaardiseerde test komt om de werkzaamheid van antifouling-systemen onder verschillende omstandigheden beter vast te stellen.

Kernwoorden: antifouling-systemen, pleziervaartuigen, biociden, verven en coatings, veiligheid, milieubelasting, beoordeling van alternatieven

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Summary

Rationale and aim

About 80% of boat owners use paint containing copper and/or zinc as an antifouling coating. This is a relevant source of emissions of toxic substances into the aquatic environment. As part of its strategy for a 'non-toxic environment', the Dutch Ministry of Infrastructure and Water Management promotes the application of the 'Safe-by-Design' principle. This approach focuses on safer non-chemical alternatives with a similar performance, taking the total lifecycle of the product into account, as well as aspects such as cost and legal and societal factors. As a step towards stimulating the development and use of innovative and safer antifouling products with low environmental impact, the Ministry asked the RIVM to prepare a report on the current and potential status of antifouling products for pleasure craft.

Overview of available and new antifouling systems

This report does not present a complete lifecycle analysis of specific products. Instead, it gives an overview of categories of traditional antifouling systems for recreational craft and alternatives that are either available or in development. The focus is on the constitution of the products, their antifouling performance and environmental impact, and their development status, where applicable, as well as on user needs and human safety issues. User needs cover aspects such as whether a product is suitable for a boat that travels at a particular speed, what cleaning options it allows, how easy it is for consumers to apply and repair, and whether it is appropriate for a broad range of hull materials.

The table below summarises the main findings with regard to the antifouling systems currently available on the Dutch market.

Type	Availability and use	Safety	Research & development
Biocidal paints	Conventional paint. Performance has been tested. Suitable for DIY ^a use.	Safety has been assessed, according to the BPR ^b . Leaching of copper into the water. Emission of VOCs ^c to the air.	Copper and zinc contents have been lowered, to meet the BPR.
Self-polishing paints	Conventional paint, suitable for DIY use.	Leaching of zinc into the water. Emission of VOCs to the air.	None found.

Type	Availability and use	Safety	Research & development
Foul release coatings	Some conventional coatings and some new products. Not easy for DIY use. 'Hard foul release coatings' seems to be a separate category.	Some products might emit toxic substances into the water. Emission of VOCs to the air.	Many developments in progress, e.g. better antifouling performance and tougher materials.
Hard coatings	Some conventional paints and some new products. This is a diverse category.	Some products might emit toxic substances into the water. Emission of VOCs to the air.	New products with a long service life are emerging.
Film with fibres	One new product on the market.	No information; safer in principle.	Field tests are being performed.
Ultrasound systems	A number of products have entered the market.	Little information; safer in principle.	Proving performance.
Cleaning systems, washers/brushing stations, cleaning robots	Many options available. Washers/brushing stations have recently been introduced to the Netherlands.	Safer in principle. Coatings must be hard enough to withstand cleaning.	There is renewed interest in washers/brushing stations.
Storage out of the water, boat lifts	Several products available.	Considered safer.	None found.

a: DIY = Do-it-yourself

b: Biocidal Products Regulation

c: Volatile Organic Compounds

Of the new and developing antifouling systems, UV light, structures for physical defence and natural, easily degradable biocides that stay inside the coating could be safer options, but these are still rather far from the market stage for pleasure craft.

The following antifouling systems are expected to have less environmental impact than traditional biocidal and/or self-polishing paints:

- 'hard foul release coatings';
- hard coatings – alone, or in combination with cleaning systems;
- films with fibres;
- ultrasound systems;
- storage out of the water.

Recommendations for alternatives assessment

The overview identifies important questions regarding the safety and environmental impact of several alternatives. For most coatings and films, more information is needed on the leaching of substances into the water, the emission of VOCs to the air and emissions during production of the product itself. The efficacy and safety of ultrasound systems and cleaning systems are still not scientifically proved, either.

To identify safer antifouling systems we recommend an alternatives assessment of existing promising specific products following the Safe-by-Design approach. This means that the assessment should have a broad scope. For coatings in particular, not only the outer layer but also the required primer system should be taken into account. To inform boat owners and persuade them to buy alternative products, the durability and antifouling performance of the different alternatives should be demonstrated by a standardised test.

Other recommendations

We recommend designing a system to better inform consumers of the safety and performance of the different biocide-free and non-self-polishing antifouling options. In addition, legislative and political means of decreasing emissions of toxic substances to water, air and soil should be investigated. Supporting infrastructure to facilitate the cleaning of boats could stimulate the use and development of non-toxic coatings that need cleaning depending on the severity of fouling.

It seems that producers are trying to make products suitable for DIY use, because the current market demands this. We recommend investigating whether 'suitable for DIY' is an important quality for antifouling systems for pleasure craft. Systems that are not suitable for DIY use can be safer, because activities such as application and repair can be better controlled when performed by professionals.

1 Introduction

1.1 Rationale, aim and scope

Antifouling paint used for pleasure boats is a relevant source of emissions of toxic substances into the aquatic environment. The Netherlands has over 10,000 kilometres of waterways. The number of pleasure boats in the Netherlands is estimated to be about 500,000, of which 250,000 have a cabin. They are located in about 1,000 marinas, along our waterways and on moorings by houses (Waterrecreatieadvies Nederland, 2005, 2015). More than 60% of owners of a boat with a cabin use antifouling paints containing copper compounds as biocide (Milieu Centraal, 2018). Biocides are toxic to organisms by definition. The above mentioned numbers indicate that there is a potentially large source of emissions of copper from antifouling paint on pleasure boats. This is confirmed by recent studies in Germany, which estimate that 15–19% of copper emissions to water can be attributed to antifouling paints (Daehne et al., 2017; Feibicke et al., 2018). Copper is among the compounds that exceed the water quality standards in Dutch surface waters (Van Puijenbroek, 2014).

The implementation of the European Biocidal Products Regulation (BPR; Regulation (EU) No. 528/2012) has led to changes in the composition of biocidal paints on the European Union (EU) market, especially for recreational craft. Biocidal paints with high concentrations of copper are no longer authorised for use on freshwater pleasure boats, because of environmental risks. This regulatory pressure reinforces the need for innovation in this area. The question is how policy can stimulate innovative antifouling products without toxic biocides or other drawbacks. This fits very well with the 'Union strategy for a non-toxic environment that is conducive to innovation and the development of sustainable substitutes including non-chemical solutions', which the European Commission is currently developing¹.

The Dutch Ministry of Infrastructure and Water Management (IenW) embraces the 'Safe-by-Design' concept. Safe-by-Design involves much more than simply replacing a toxic chemical by a less toxic alternative during the innovation stage of a product (IenW, 2018). It focuses on non-chemical alternatives, thereby maintaining (or even improving) the technical performance of a product. Moreover, the Safe-by-Design approach tackles not only safety ((eco)toxicity), but also aspects such as the re-use and recycling of the product and the saving of energy and feedstock resources. Close attention also has to be paid to economic, legal and societal factors.

In this context the Dutch government developed the Safer Chemicals Innovation Agenda², which outlines a research framework for the development and adoption of Safe-by-Design solutions for chemical

¹ http://ec.europa.eu/environment/chemicals/non-toxic/index_en.htm

² <https://www.chemischestoffengedgergeld.nl/sites/default/files/39982%20-%20Safe%20Chemicals%20Innovation%20Agenda%20-%2020180613i6%20final%20copy.pdf>

functions of concern where innovation is needed. It is also closely linked to the European Chemical Agency's (ECHA) "Strategy to promote substitution to safer chemicals through innovation"³. The Ministry has chosen the subject alternatives to hazardous antifouling paint for pleasure boats as a pilot project in accordance with the Safe-by-Design concept.

As a step towards stimulating innovative, safer antifouling products with low environmental impact, the Ministry of Infrastructure and Water Management asked the RIVM to prepare this report on the current and potential status of antifouling products for pleasure boats. Many innovative alternatives exist or are emerging, but most of them are failing to penetrate the market. An overview of relevant information on these innovative alternatives is lacking. More insight into their status and performance will help to shape an innovation strategy.

An additional reason for this report is the need to better inform boat owners and other stakeholders about potentially safer alternatives to conventional antifouling systems. A stakeholder meeting in 2015, organised by the Dutch Kennisnetwerk Biociden (Knowledge Network for Biocides, KNB), emphasised this need. As a follow-up, information was made available on the website of Milieu Centraal⁴ and Varen doe je samen⁵. This report also provides technical background to that work.

This report gives an overview of the currently available antifouling systems for pleasure boats and potential developments in this area. The aim of the report is to investigate alternatives to traditional biocidal antifouling paints and to assess their development stage, relevance to consumers and potential to serve as a safer choice. Knowledge gaps are identified and recommendations are made for further action.

The report focuses on antifouling systems for recreational craft. Some legal aspects are considered (e.g. whether the BPR is applicable), but an in-depth regulatory analysis was beyond the scope of this study. We also do not make a complete assessment of specific products. Although it is relevant, we did not search for information on the costs of the different options, either. Information on antifouling systems for commercial and seagoing vessels has been included where this might be relevant to pleasure boats.

1.2 Content of this report

Chapter 2 describes fouling and its impact. Chapter 3 presents the history of biocidal antifouling paints and the EU approval process for biocidal antifouling substances and products in the context of the BPR. Chapter 4 provides an overview of existing alternatives to biocidal paints and discusses a number of new developments. Chapter 5 explores in greater detail the range of safer alternatives to biocidal paints and discusses the human and environmental impacts of the alternatives. At

³ See ECHA's (January 2018). Strategy to promote substitution to safer chemicals through innovation. Available at: <https://echa.europa.eu/substitution-to-safer-chemicals>

⁴ <https://www.milieucentraal.nl/in-en-om-het-huis/klussen/antifouling-tips-voor-milieuvriendelijk-bootonderhoud/>

⁵ <https://www.varendoejesamen.nl/kenniscentrum/artikel/antifouling>

the end of Chapter 5 an overview of the findings on antifouling systems for pleasure boats is given. Chapter 6 gives an overview of the current Dutch market situation. Chapter 7 presents conclusions and recommendations for a transition to safer antifouling systems for pleasure boats.

1.3 Disclaimer

The selection of the developments in antifouling systems made for this report was based on information from stakeholders, internet searches and the open literature and gives an overview of the type of systems that are currently available or in development. It is not the intention of the authors to present a complete list of potential new products. In some cases, trade names and specific companies are mentioned because these form the only reference to a specific antifouling system. The authors have not verified information retrieved from manufacturers' data. The RIVM does not endorse or recommend any specific product or system. Information from websites is referred to by footnotes, and references to other documents are included in the References list.

2 Fouling, its impact and prevention

2.1 Fouling and its impact

Fouling is the growth and settlement of biological material on hard underwater surfaces such as boat hulls, piers and cooling water piping. Fouling starts with the settlement of microscopic animal larvae or weed. These form an adhesive bond to which larger organisms may attach themselves. In freshwater, fouling mainly consists of slime, filamentous algae and shellfish such as mussels. In seawater, it includes barnacles, algae, shellfish and hydroids.



Figure 1. Fouling on pleasure boats.

Source: harsonic.com and yachtingmonthly.com

Fouling of a boat's hull causes more resistance in the water, makes it less easy to control, reduces its speed and, in the case of motor boats, increases fuel consumption. The increase in fuel consumption due to increased resistance in comparison with a clean hull may be as much as 50% (IMO, 2002). A boat with a clean hull moves faster through the water and, in the case of motor boats, uses less energy. Especially in commercial shipping, fuel is a major cost, which makes the prevention of fouling cost-effective. This is often less relevant to pleasure boats, which are moored most of the time and only in use for short periods. On the other hand, long mooring periods result in more fouling than regular use, and may increase the need for antifouling treatment. Removing fouling may damage the hull's protective coating and may lead to corrosion.

Besides the above-mentioned impacts on boat use, fouling may also increase the spread of invasive species. Usually this is regarded as a problem of particular relevance to commercial ships that operate between continents. However, the spread of invasive species can also be relevant to recreational vessels. Small craft can facilitate the introduction of new species and the spread of already established invasive species to inland waters. An example of the latter case is the spread of the freshwater mussel *Dreissena polymorpha* in Ireland (Minchin et al., 2006). The website 'Invasive Species Ireland'⁶ specifically refers to antifouling treatment in this context.

⁶ <http://invasivespeciesireland.com/biosecurity/water-users/leisure-and-industrial-crafts/>

2.2 Factors that influence fouling

The growth of fouling organisms depends on many factors, including water characteristics such as pH, salinity, turbidity, temperature, level of pollution and nutrient availability. The higher the temperature and the salinity, the higher the severity of fouling, but fouling can be severe even in temperate zones or brackish waters. In the Netherlands, fouling peaks between spring and early autumn. The movement of vessels is an important factor: boats that are moored for long periods experience more fouling than those that are in regular use.

Freshwater fouling is often less severe than marine fouling. Fouling is also less severe when boats are only used in relatively cold water. Boats used in shallow water experience more fouling. When in use, boats that move through the water relatively fast experience less fouling than slower boats. However, as stated above, stationary boats experience the most fouling. For commercial freshwater vessels, which move relatively fast and operate more or less continuously in larger, flowing waters, fouling may not be of major concern, but information on this topic is scarce. There are indications that vessels operating in the Amsterdam–Rotterdam–Antwerp (ARA) region use antifouling paints⁷. However, this report does not address commercial ships.

2.3 Antifouling systems

When searching for information on 'antifouling', it immediately becomes apparent that the term is used in different contexts. The International Maritime Organization (IMO) uses the phrasing 'antifouling system', which is defined as 'a coating, paint, surface treatment, surface or device that is used on a ship to control or prevent attachment of unwanted organisms'⁸. The IMO specifically refers to copper-based antifouling paints, tin-free antifouling paints, non-biocidal non-stick coatings, periodic cleaning, natural biocides, electricity and prickly coatings (IMO, 2002). A similar definition is found in the Dutch version of Wikipedia⁹, which considers antifouling as 'a collective term for all measures taken to prevent that micro-organisms, mussels and algae attach to the ship's hull beneath the water surface'. These definitions thus include all kinds of measures, including mechanical and non-biocidal treatments. In contrast, most regulatory bodies associate the term antifouling with biocide use (see text box).

⁷ <https://www.schuttevaer.nl/nieuws/scheepsbouw-en-reparatie/nid21187-binnenvaart-gebruikt-weinig-antifouling.html>; email from Expertise- en Innovatiecentrum Binnenvaart (Inland Shipping Expertise and Innovation Centre)

⁸ <http://www.imo.org/en/OurWork/Environment/Anti-foulingSystems/Pages/Default.aspx>

⁹ <https://nl.wikipedia.org/wiki/Antifouling>; translation by authors

Definitions of antifouling used by regulatory bodies

- The Swedish Transport Agency states on its website that an 'anti-fouling system refers to a coating, paint, surface treatment or device used on a ship to control or prevent attachment of unwanted organisms', but the following text refers to the ban on organotin and how other biocides are regulated¹⁰;
- On the website of the Danish Environmental Protection Agency, a factsheet on antifouling paint can be found as part of information on biocides legislation¹¹;
- The German Umweltbundesamt also places information on antifouling under the heading 'biocides';
- In Swiss environmental legislation it is stated that 'antifouling products are biocidal products of product type 21'¹²;
- The Dutch Board for the Authorisation of Plant Protection Products and Biocides (Ctgb) uses the word antifouling and its Dutch equivalent 'aangroeiwerend' in its communication, thus implicitly connecting these terms to biocide use.

Definition used in this report (per IMO, 2002)

Antifouling systems comprise any coating, paint, surface treatment, surface or device that is used on a ship to control or prevent attachment of unwanted organisms.

From a historical point of view, it is understandable that the term antifouling is associated with biocide use. However, since many non-biocidal paints and coatings and non-chemical systems have been developed, it is appropriate to follow the IMO definition (see text box), which is based on function (see Figure 2). The category 'paints and coatings' can be divided into biocidal and non-biocidal products. To prevent misunderstanding, we add 'biocidal', 'non-biocidal' or similar phrasing to paints and coatings where appropriate.

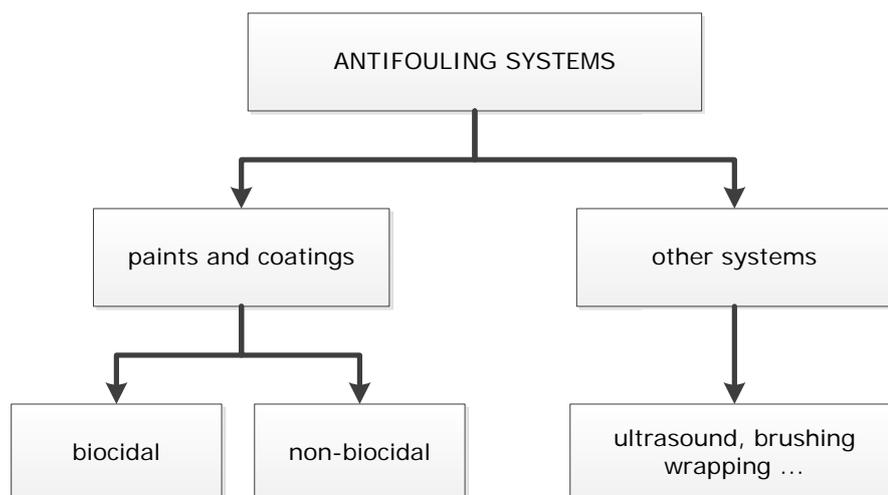


Figure 2. Types of antifouling systems for boat hulls considered in this report

¹⁰ <https://transportstyrelsen.se/en/shipping/Environmental-protection/Anti-Fouling-Systems-for-Ships/>

¹¹ <https://eng.mst.dk/chemicals/biocides/legislation/fact-sheet-anti-fouling-paint/>

¹² <https://www.admin.ch/opc/en/classified-compilation/20021524/index.html>

3 Biocidal antifouling paints: history, legal aspects and current status

3.1 History of biocidal antifouling paints

Antifouling treatments have a long history. A combination of lead sheathing and copper nails was used by the ancient Greeks. Grease, sulphur pitch, tar and other organic compounds were used on early wooden ships, until copper became the prominent antifouling agent (De Mora, 2009; Deloitte MCS Ltd, 2016; Price & Readman, 2013; Readman, 2006). Copper was patented as an antifouling agent as early as 1625 (Nurioglu et al., 2015), and copper-based paints remained the most effective antifouling agent on the market until the organotin compound tributyltin (TBT) was introduced in the early 1960s (De Mora, 2009; Deloitte MCS Ltd, 2016). TBT is effective against a wide range of organisms and it can be incorporated in resin-based paints that can be used on all kinds of vessels (De Mora, 2009).

The spread of TBT throughout the world resulted in serious damage to the ecosystem, such as sex changes in snails and shell thickening in oysters, resulting in a collapse of the shellfish industry in France (see e.g. (Price & Readman, 2013; Readman, 2006); and references cited therein). The impact on ecosystems led to legislative steps to control the use of TBT (Deloitte MCS Ltd, 2016). The European Commission banned TBT use on small boats (< 25 m) in 1989. In 2001, the IMO adopted the International Convention on the Control of Harmful Anti-fouling Systems (IMO, 2001). This international treaty led to a complete ban on the application of organotin-based coatings by 2003, and the global absence of organotin-based coatings by 2008.

According to resolution MEPC.195(61), small quantities of organotin compounds acting as a chemical catalyst (such as mono- and di-substituted organotin compounds) are permitted, provided they are present at a level that does not cause a biocidal effect. When used as a catalyst, an organotin compound should not be present above 2,500 mg total tin per kilogramme of dry paint, which is 0.25% (MEPC, 2010). Surprisingly, a paint containing 10–25% tributyltin methacrylate (3–8% tin) and 30–60% copper(I) oxide is still offered by an American company, but the product 'may not be sold or applied in the United States'¹³.

The ban on using organotin compounds as biocides led to the development of new biocidal antifouling paints. Most marine paints were still copper-based but incorporated additional toxic substances to enhance their effectiveness, particularly against algae. These substances are generally referred to as 'booster biocides'. Examples are cybutryne (commonly known as Irgarol 1051), diuron, 4,5-dichloro-2-octyl-2H-isothiazol-3-on (DCOIT, also known as Sea Nine 211), dichlofluanid, chlorothalonil, and zinc pyrithione (De Mora, 2009; Price & Readman,

¹³ <https://www.seahawkpaints.com/product/islands-44-plus-harder/>

2013; Readman, 2006). Some of these compounds have since been banned in certain countries or throughout the European Union (EU). The most recent development is the non-approval of cybutryne for use in antifouling paint under the BPR (see Section 3.2.1). Annex 1 presents information on the main groups of currently available biocidal antifouling paints.

3.2 Approval and authorisation process in Europe

3.2.1 Active substance approval

Antifouling systems that contain biocidal active substances and that are marketed with the claim that they control the growth of or kill organisms are biocidal products and should have national authorisation under the BPR. Prior to product authorisation, the active substance(s) contained in a biocidal product must be approved at EU level. Companies can apply for approval of an active substance by submitting a dossier to the European Chemicals Agency (ECHA). The dossier must include information on the substance's efficacy, physico-chemical properties, human toxicology, environmental fate and behaviour, and ecotoxicology, as well as the applicant's proposal for a human-toxicological and environmental risk assessment. After validation by the ECHA, the 'evaluating Competent Authority' (eCA) in one of the EU Member States carries out a completeness check and an evaluation. The Dutch CA for biocides and plant protection products is the Board for the Authorisation of Plant Protection Products and Biocides (Ctgb). The result of the evaluation is forwarded for peer review to the ECHA's Biocidal Products Committee (BPC), which, after discussion in its working groups, prepares an opinion. The opinion serves as a basis for the decision on approval or non-approval of biocidal active substances by the European Commission and the Member States¹⁴.

Special considerations are made for hazardous chemicals. According to the BPR, chemicals meeting the following criteria cannot be approved¹⁵:

- carcinogenic, mutagenic or reprotoxic (CMR); or
- persistent, bio accumulative and toxic (PBT); or
- very persistent and very bio accumulative (vPvB); or
- having endocrine disrupting (ED) properties.

An exception can be made where exposure to humans, animals or the environment is negligible; the active substance is essential to prevent or control a serious danger to human health, animal health or the environment; or not approving the active substance would have a disproportionately negative impact on society when compared with the risk to human health, animal health or the environment arising from the use of the substance¹⁶. If an active substance is approved for these reasons, risk mitigation measures should be taken and the availability of alternatives should be considered. In addition, compounds fulfilling two of the PBT criteria are subject to a shorter approval period and, if a comparative assessment indicates that a better alternative is available, the approval is withdrawn.

¹⁴ For more information, see: <https://echa.europa.eu/regulations/biocidal-products-regulation/approval-of-active-substances/approval-of-active-substances/evaluation-process-for-active-substances>

¹⁵ BPR, Article 5 (1)

¹⁶ BPR, Article 5 (2)

Biocidal products are categorised into 'product types' (PT) according to the main use of the product¹⁷. Biocidal antifouling products belong to PT21: products 'used to control the growth and settlement of fouling organisms (microbes and higher forms of plant or animal species) on vessels, aquaculture equipment or other structures used in water'. Note that PT21 thus includes not only products that are used on boats, but also those used on other aquatic equipment (like fishing nets) and structures outside the scope of this report. The status of the EU approval of active substances for PT21 (as at May 2018) is shown in Table 1. Note that diuron and chlorothalonil are not included. This means that no dossier for the validation of these substances was submitted before the deadline for inclusion in the Review Programme for biocidal substances. Substances that are not approved or included in the Review Programme for PT21 may not be used in antifouling paints sold in the EU since September 2006.

Table 1. Current EU biocidal approval status of active substances for PT21 use

Active substance	CAS No. ^a	Date of approval
Copper	7440-50-8	1 January 2018
Copper pyrithione	14915-37-8	1 October 2016
Copper thiocyanate	1111-67-7	1 January 2018
Cybutryne	28159-98-0	Not approved
DCOIT ^b	64359-81-5	1 January 2016
Dichlofluanid	1085-98-9	1 November 2018
Dicopper oxide	1317-39-1	1 January 2018
Free radicals ^c		Under review
Medetomidine	86347-14-0	1 January 2016
Tolyfluanid	731-27-1	1 July 2016
Tralopyril	122454-29-9	1 April 2015
Zinc pyrithione	13463-41-7	Under review
Zineb	12122-67-7	1 January 2016

a: unique numerical identifier assigned by the Chemical Abstracts Service (CAS)

b: 4,5-dichloro-2-octyl-2H-isothiazol-3-on

c: Described by the ECHA as 'free radicals generated in-situ from ambient air or water'.

3.2.2 Environmental risk assessment: approval requirements for active substances

To approve an active substance for a specific PT, one safe use within the PT has to be shown. For PT21 paints and coatings, the environmental risk assessment concerns emissions to the environment during the application and removal of the paint and the ecological impact of leaching during use on boats. For their use to be considered safe, the predicted environmental concentration (PEC) should be lower than the predicted no effect concentration (PNEC). The PNEC is derived by extrapolation from ecotoxicological data for selected species, and serves as a limit to protect the whole ecosystem. The PEC is derived from a model for a marine shipping lane and the 'wider environment' just outside a commercial harbour or seaport. The commercial seaport itself is in accordance with an EU decision regarded as a 'technosphere', for which there is no need to consider the environmental risks. The approval process for biocidal active substances in PT21 at EU level also takes into consideration the

¹⁷ <https://echa.europa.eu/regulations/biocidal-products-regulation/product-types>

environmental impact of maintenance and repair activities, including emissions from shipyards to surface water, soil and sewage treatment plants. In some cases, the EU assessment of active substances also includes their impacts in a marina for recreational craft. However, following the rule that demonstration of one safe use is sufficient for approval, an unacceptable risk for marinas will not be a reason for non-approval if a safe use is demonstrated for the shipping lane and the wider environment outside a commercial seaport.

Cybutryne has been the only substance so far for which a safe use was not demonstrated. In 2016, the European Commission decided on non-approval of this compound for PT21, which means that antifouling products containing cybutryne can no longer be authorised. In the Netherlands, the last authorisation of cybutryne-based products expired in 2014.

3.2.3 *Product authorisation*

When an active substance is approved for use in PT21, companies can apply for product authorisation. A common process is national authorisation, followed by mutual recognition. In this case, product authorisation is first requested in a single Member State; then access to other markets can be gained by applying for mutual recognition in other Member States. Until three years after the approval of an active substance, the substance can still be used in biocides under former national law. The approval date for copper as a biocidal active substance is 1 January 2018. This means, for instance, that until 1 January 2021 a product containing 99% copper can still be sold by a British company¹⁸ in the UK. After 1 January 2021 authorisation according to the ECHA-guidelines for the risk assessment under the BPR is necessary and a product with such a high copper concentration will not be considered safe and hence will not be authorised in EU Member States.

Intended uses must be safe

In contrast to the evaluation of active *substances*, where safety has to be shown for use on marine commercial ships only, biocidal antifouling *products* must be safe for all the intended uses applied for in the respective Member State. Recreational marinas are more vulnerable to emissions from biocidal antifouling paints than commercial seaports. In Europe they are not politically regarded as a 'technosphere', so environmental risks inside marinas must be taken into account. Both freshwater and seawater marinas may be situated near nature protection areas. Especially in inland marinas, antifouling substances will not be flushed away with the tide, so these substances can accumulate in the water and the sediment of the marina. Marinas also tend to have a much smaller entrance than seaports, which can cause less spreading and higher concentrations of antifouling substances in the surrounding environment. These circumstances lead to the fact that biocidal paints with high concentrations of copper as active substance will no longer be authorised for use on freshwater pleasure boats.

¹⁸ <http://coppercoat.com/coppercoat-info/>

In the past, some antifouling paints were approved in the Netherlands for 'marine and freshwater ships'. These products are still on the market. Since 2017, however, there has been a new policy, and companies applying for authorisation of an antifouling paint in the Netherlands must choose from one or more of the following categories of vessels (see Evaluation Manual Ctgb¹⁹):

- Recreational craft (hull length from 2.5 to 24 m) for both freshwater and marine waters;
- Commercial vessels in freshwater;
- Commercial vessels in marine waters.

Biocidal antifouling paints for recreational craft can only be authorised in the Netherlands when it is proved that they are environmentally safe in both freshwater and saltwater marinas. This is because in the Netherlands it is not possible for inspectors to prevent pleasure boats with antifouling paint authorised for seawater from entering freshwater.

All pleasure boats with a hull length of 24 m or more ('superyachts') are categorised as commercial vessels. Naval ships are also treated as commercial vessels, even if they are shorter than 24 m. Besides ship type, companies specify how their product should be applied – either only by professional users or also by non-professional users. The product has to be shown safe for the intended users.

Maintenance and repair

In the case of pleasure boats, the Organisation for Economic Co-operation and Development (OECD) estimates that, on average, 30% of paint is removed by high-pressure washing and abrasion (OECD, 2005). In the Netherlands, it is legally required that measures are taken to prevent the spread of antifouling paints into the environment during application and removal activities before reapplying a new paint layer. Direct emissions from maintenance and repairs in shipyards to water and soil should be minimised by the implementation of mitigation measures in accordance with the Activities Decree ('Activiteitenbesluit'). Similarly, emissions to air must be minimised by mitigation measures to prevent indirect contamination of water and soil. For do-it-yourself (DIY) products, maintenance and repair activities by boat owners will mostly take place in marinas, under the supervision of marina staff. However, from the interviews (see Chapter 4) it became clear that it is practically impossible to prevent the spread of dust into the environment, especially during the sanding of a boat's hull, even if sheets are used to cover the soil during this process. This fact is of particular interest to Water Boards ('Waterschappen'), which are responsible for preventing the pollution of surface waters.

3.3 Authorised biocidal antifouling paints in the Netherlands

The Ctgb holds a database of authorised and expired products²⁰. Information on antifouling paints can be found by selecting the 'PT21' authorised biocides. Currently, 52 products are authorised for the Dutch market in PT21 (as at May 2018; see Annex 2). This situation can

¹⁹ <https://english.ctgb.nl/biocidal-products/assessment-framework/evaluation-manual>

²⁰ <https://pesticidesdatabase.ctgb.nl/>

change every month. Products can reach their expiration date and disappear from the market, while other new products can be authorised and sold from then on. Table 2 provides an overview of products authorised for the different categories of use.

Table 2. Summary of authorised products in the Netherlands (May 2018)

Authorised use	Number of products	Active substance(s)
Marine commercial ships	36	copper(I) oxide; copper pyrrithione; copper thiocyanate; zinc pyrrithione; zineb; DCOIT ^a
Marine and freshwater recreational craft	11	copper(I) oxide copper thiocyanate
Marine and freshwater ships ^b	5	copper(I) oxide

a: 4,5-dichloro-2-octyl-2H-isothiazol-3-on

b: See Section 3.2.3 above; this use cannot be chosen any more for new products, but already authorised products for this use can still be on the market for years

As can be seen from this table, more products are authorised for use on marine commercial ships. These are mainly products with high copper concentrations (> 40%). These products may not be sold to or used by private users, nor may they be applied by professionals on pleasure boats, because the risk assessment showed that high copper concentrations in inland marinas leads to unacceptable risks for the environment. The products currently authorised for pleasure boats contain copper(I) oxide or copper thiocyanate in relatively low concentrations (< 13%). A total of 11 products are authorised for use in freshwater (as at May 2018), which includes authorisation for marine use. The products containing copper(I) oxide cannot be used on boats with an aluminium hull, since electrolysis may dissolve the aluminium instead of the copper ions. Instead, products with copper thiocyanate are suitable for aluminium hulls. Products for pleasure boats are authorised for use by non-professional users.

3.4 Assessment of other ingredients in biocidal paints

As indicated in Section 3.1, booster biocides can enhance the efficacy of copper²¹. Being active substances, boosters are subject to approval under the BPR and thus included in the risk assessment during product authorisation. Furthermore, the BPR requires that Substances of Concern (SoCs) are also included in the risk assessment of a product. SoCs are compounds other than active substances, i.e. co-formulants (additives) in biocidal products that may pose a risk to humans and the environment. Producers are obliged to disclose all the ingredients of their biocidal paints to the CA. An ingredient is a SoC:

- when its presence leads to classification of the product as dangerous according to Directive 1999/45/EC, or as hazardous according to Regulation (EC) No. 1272/2008/EC; or

²¹ The term booster is generally used for biocides that are used in addition to copper. In the past, the Netherlands had some authorised products for pleasure boats containing boosters such as dichlofluanid and diuron as sole biocidal ingredient. None of these products is authorised any longer.

- if the ingredient meets the criteria for being a persistent organic pollutant (POP) under Regulation (EC) No. 850/2004, or meets the criteria for being persistent, bio-accumulative and toxic (PBT) or very persistent and very bio-accumulative (vPvB) in accordance with Annex XIII to Regulation (EC) No. 1907/2006²².

In December 2013, the Ctgb officially announced that it would henceforth include the risk assessment of SoCs in the national authorisation procedure²³.

According to the European Council of the Paint, Printing Ink and Artists' Colours Industry (CEPE), zinc oxide is not used as a biocidal active substance in antifouling paints, but as a co-formulant to regulate the dissolution of the paint film during the service life of the paint (i.e. control the film polishing rate), to stabilise wet paint in the can, to modify dry film properties, and as a pigment (CEPE, 2011a,b). Therefore, in the EU approval process of PT21 paints, zinc oxide is not considered as an active substance and is not subject to review as such. However, zinc is known to be toxic to aquatic organisms, and is considered a SoC. Release of zinc from zinc oxide in copper-based antifouling paints was demonstrated in the BONUS CHANGE project (Lagerström et al., 2018), see further Section 5.2.4. Other ingredients may be SoCs and have to be assessed as well. A non-exhaustive list of SoCs is published on the Ctgb website. Separate lists are presented for human health and the environment. In the authorisation decisions, however, components are anonymised for reasons of confidentiality. A direct coupling of the listed SoCs with authorised biocidal antifouling products is thus not possible.

It should be noted that non-biocidal antifouling paints do not need any authorisation at all, so the composition of non-biocidal coatings is always partly confidential and known only by the producer.

²² <https://english.ctgb.nl/biocidal-products/application-active-substance/substances-of-concern>

²³ Staatscourant, 2013, no. 36360 23 December 2013

4 Alternatives to biocidal paints: available techniques and new developments

4.1 Introduction

This chapter presents an overview of currently available alternatives to conventional copper-based biocidal antifouling paints, and developments in this field, whose development status and market availability are discussed where applicable. Information on safety and environmental impact is included in Chapter 5. The information in this chapter is based on:

- previous inventories from 2003 and 2007 (Klijnstra et al., 2007; Verhoeven & Vermij, 2003);
- scientific literature;
- information from the internet;
- information gathered by Milieu Centraal to inform consumers (De Waart, 2017);
- interviews with stakeholder organisations (Waterrecreatie Nederland, HISWA) and some individual users;
- discussions with a consultant company on antifouling (Endures);
- interviews with eight companies that develop, produce and sell antifouling systems (see below).

We interviewed the following companies supplying antifouling systems:

- two multinationals developing and marketing paints and coatings (CMP Chugoku and AkzoNobel/International Paint/Interlux). We also had contact with Hempel by email;
- one small/medium-sized enterprise (SME) developing, producing and selling a 'hard foul release coating' (Dutch Durable Coatings (Neosil));
- two SMEs developing, producing and selling a hard coating (Subsea Industries/Hydrex (Ecospeed) and Green Power Nano (PP14));
- one SME developing, producing and selling a film with fibres (Finsulate);
- one SME selling an ultrasound system (Lamers System Care (Sonihull)) working together with an SME selling a 'hard foul release coating' (MCoating (Oceanspeed)).

The aim of the interviews was to obtain information on specific new products and to be able to construct a general overview of the Dutch market situation for antifouling systems for pleasure boats (see Chapter 6). The fact that a product is biocide-free should not be regarded as a guarantee that it is safe and environmentally friendly. More information on safety and environmental impact is therefore included in Chapter 5. No additional information on conventional biocidal antifouling paints and self-polishing paints was gathered; nor did we aim to provide a complete list of products in development.

4.2 Biocide-free coatings

At present, three main types of biocide-free coatings appear in the literature: foul release or non-stick coatings, biocide-free self-polishing paints, and hard composite coatings.

4.2.1 *Foul release / non-stick coatings*

Some authors make a distinction between non-stick coatings, which prevent the attachment of fouling, and foul release coatings, from which fouling is easily removed (Nurioglu et al., 2015), but these approaches are not mutually exclusive and a clear distinction is not easy to make (Callow & Callow, 2011). We therefore consider both types of coating together in this section, and refer to them as 'foul release coatings'. Foul release coatings do not contain biocides for antifouling purposes. They have a smooth surface, which does not dissolve in water. The characteristics of the coating inhibit the attachment of organisms; even if that happens, the fouling detaches during use of the boat or it can easily be removed when the boat is lifted out of the water (Callow & Callow, 2011; IMO, 2002; Nurioglu et al., 2015; Takahashi, 2009).

Most foul release coatings are based on silicone elastomer (PDMS), fluoropolymers or a combination of the two. Silicone coatings have an ultra-smooth, slippery and hydrophobic surface. They are flexible and have a low surface tension, which inhibits chemical interaction between fouling and the hull (Buskens et al., 2013; Callow & Callow, 2011; Nurioglu et al., 2015). A major disadvantage of silicone coatings is that they are difficult to bind to a substrate without an appropriate tie coat. In addition, they are less durable and more easily damaged than other coatings, and cannot resist diatom-dominated brown slimes, which attach more firmly to hydrophobic substances (Callow & Callow, 2011; Nurioglu et al., 2015). For that reason, there has been extensive research into improving the performance of these coatings, e.g. by developing primers, using new tie coats, incorporating inorganic fillers, and introducing polyurethane or epoxy segments into the coatings (Nurioglu et al., 2015). Silicone coatings are available as paints or films (see Section 4.5 for further details).

Other foul release coatings are based on fluoropolymers. Several fluorinated polymers have been investigated for use as antifouling substances. Amongst these, the most common are fluorinated (meth)acrylates, perfluoropolyethers (PFPE) and poly(ethylene glycol) (PEG) fluoropolymers (Camós Noguera et al., 2016; Nurioglu et al., 2015). To date, PEG-based coatings are the most common approach to preventing protein adhesion and biofouling settlement via hydrophilic interactions (Nurioglu et al., 2015), but their action is mainly directed towards microfouling (the first fouling layer of microscopic animal larvae or weed).

Some 'next generation' fluoropolymer coatings combine hydrophobic and hydrophilic properties and minimise the chemical and electrostatic adhesion of a range of species (Callow & Callow, 2011; Nurioglu et al., 2015). These 'amphiphilic' coatings create a dynamic and complex surface with local variations in surface chemistry, topography and

mechanical properties, deterring the settlement of organisms (Callow & Callow, 2011). Liquid surface technology is the basis for a newly developed coating, based on nano-/micro-structured porous material infused with a lubricating fluid. This creates a thin, ultra-smooth and slippery liquid layer that prevents the attachment of organisms. This technology, called SLIPS (Slippery Liquid-Infused Porous Surfaces), was developed by the Harvard Wyss Institute for Biologically Inspired Engineering, and was inspired by the pitcher plant, which repels all kinds of liquids and solids²⁴. It is now commercially available and has been tested for marine applications²⁵. See Section 4.3 for information on other bioinspired antifouling solutions.

Two of the SMEs interviewed stated that they sell a 'hard foul release coating' (Neosil and Oceanspeed). The composition of these coatings is confidential and we do not know where these fit in with the above-mentioned options. Neosil is said to be based on silicones. These coatings are advertised as 'extremely hard' and they should have much greater longevity than conventional silicone coatings – possibly up to ten years, compared with the commonly mentioned service life of foul release coatings of 3–5 years. Endures states that almost all foul release coatings are based on relatively soft silicone compounds, so these cannot be extremely hard.

4.2.2 *Biocide-free self-polishing paints*

Some biocide-free coatings are specifically designed as self-polishing paints. A continuous hydrolysis reaction causes the active surface to be continuously renewed, thereby releasing the upper layer to which organisms can attach themselves. There is no general picture of the constitution of biocide-free self-polishing paints, although it appears that zinc oxide is a common ingredient that stimulates polishing. A copper-free paint is advertised on the internet as a 'half-synthetic underwater paint based on alkyd and colophonium resin'. The product information sheet gives bitumen and zinc oxide as additional ingredients. Lack of ingredient disclosure is a barrier to assessing the risks of these kinds of paints.

4.2.3 *Hard coatings*

Hard coatings are a diverse category. One of the alternatives to fluoropolymer- or silicone-based coatings is a hard coating or a 'surface-treated composite coating'. Hard coatings are generally made of epoxies, polyesters, vinylesters or ceramic-epoxy compounds, sometimes reinforced with glass flakes. The element silicon (Si) can be a basic ingredient, and these coatings can contain more than 50% volatile organic compounds (VOCs) before application. Hard coatings can also be designed to protect the hull against corrosion. In general these coatings are intended to be used in conjunction with routine cleaning, using either high-pressure washing in a dry dock or underwater cleaning with the vessel still afloat. Routine and timely cleaning keeps fouling to a minimum and the hull operating at optimum performance (Van Rompay, 2012). According to the producer of Ecospeed, the main advantages of hard coatings over foul release coatings are greatly increased service

²⁴ <https://wyss.harvard.edu/technology/slips-slippery-liquid-infused-porous-surfaces/>

²⁵ <https://adaptivesurface.tech/marine-coatings/>

life, easier maintenance (including underwater), less loss of zinc or aluminium from the anode to prevent corrosion and the fact that only a few coats need to be applied²⁶. According to the producer, the coating can be removed with sufficient pressure-washing. However, frequent cleaning of hard coatings is necessary. Some products sold for use in freshwater should be applied every two years.

4.2.4 *Market availability and applicability to pleasure boats*

Several self-polishing coatings for pleasure boats are available, and are suitable for non-professional users. In the case of foul release and hard coatings, there is not much information on their applicability to pleasure boats, and scientific information is related to applications on marine commercial vessels. Some websites refer to products for pleasure boats, but application seems to be largely restricted to professional use. In general, application of these coatings is complicated, as special equipment and experience are necessary to obtain the required quality (see also Section 4.2.5).

According to information from producers, foul release coatings may have a service life of up to five years²⁷, although other references mention low durability as a disadvantage (Callow & Callow, 2011; Cao et al., 2013). In 2002, the IMO claimed that damage to the coating is not easy to repair (IMO, 2002), but this is probably not applicable to modern coatings. The interviews provided diverging opinions: excessive softness and difficulties in repairing damaged parts were indicated as problems by some, while others stated that some coatings are sufficiently hard and easy to repair and have a service life of seven or even ten years. In the case of the glass-reinforced hard coating mentioned in Section 4.2.3, the producer claims that this will last the full service life of the boat. A longer service life is considered an advantage for consumers, and also minimises emissions upon maintenance.

A drawback of foul release coatings is that they are effective only at a certain speed. The minimum speed that is required for foul release coatings to be effective (as well as their cost) may limit use for pleasure boats (Cao et al., 2013). According to old information from the IMO, a minimum speed of 30 knots is required (IMO, 2002). Most recent sources indicate that a minimum of 15 knots is needed, combined with high activity, i.e. short mooring periods (Callow & Callow, 2011; Tripathi, 2016), but some suppliers claim that their most advanced products will keep the hull clean at speeds of as little as 8 knots. Because the maximum permitted speed for recreational vessels in Dutch inland waters is 20 km/h (about 11 knots)²⁸, the effectiveness of foul release products may be less than under optimum conditions. Recently, a test method of establishing the minimum speed for fouling release was presented at the bi-annual International Conference on Marine Corrosion and Fouling (ICMCF) in Florida, USA (Klijnstra & Bakker, 2018).

²⁶ http://schonescheepvaart.nl/downloads/seminars/doc2_1457348868.pdf

²⁷ <http://www.hempel.com/en/marine/resource-centre>

²⁸ <https://www.rijkswaterstaat.nl/water/wetten-regels-en-vergunningen/verkeer-op-het-water/regels-voor-snelvaren.aspx>

When a foul release coating is used on a boat that is too slow or remains moored for too long for it to be effective, timely cleaning can be an option, as is also necessary for hard coatings. The foul release coating should be hard enough to endure such cleaning.

4.2.5 *Do-it-yourself application of biocide-free coatings*

When considering a switch from a biocidal paint to a non-biocidal coating, a major factor for consumers will be whether the coating can easily be applied over old systems, or whether these should first be removed. If the latter is the case, this will be a major drawback in terms of work and cost. There is no generic answer to this question, as it depends on the type of use and the existing coating.

Applying silicone paints is not easy, even for professionals without experience, let alone non-professional boat owners. Silicones are transparent, so it is not easy to cover the whole boat with a layer of the same thickness. AkzoNobel tried to market a fluoropolymer coating for pleasure boats, which was a three-component system. This turned out to be too difficult for do-it-yourself (DIY) application. Hempel is now selling a new one-component silicone foul release coating for pleasure boats²⁹. The same applies to CMP Chugoku³⁰. A disadvantage of this kind of product for DIY use is that during application VOCs are released to the air and personal protective equipment should be used. Before applying the silicone topcoat (twice), a sealer and a tie-coat should be applied. This makes a lot of application steps for DIY. An advantage of films with a silicone top (see Section 4.5) is that the evaporation of VOCs can be controlled during production and that an even thickness can be achieved at the production site.

Self-polishing paints are sold for DIY use and we did not hear of any practical problems with respect to application or maintenance. These paints have to be renewed every one or two years and the spread of dust and/or paint particles during removal by sanding or high-pressure cleaning is hard to prevent. Besides, these paints can contain VOCs, which can be emitted to the air and require personal protective equipment.

Some hard paints are sold for DIY use and have to be renewed every one or two years. The hard coating Ecospeed is not suitable for DIY use, but it only has to be applied once. The producers of Neosil state that it is a hard coating, but also a silicone coating. It is a two-component system (a paint and a hardener), which is suitable for DIY application. Green Power Nano is testing a hard foul release coating which can only be applied by their own experienced staff. This coating contains a high percentage of VOCs, which are captured during the application procedure. The company is considering to develop another product that might be used as a foul release coating, which is (or can be made) suitable for DIY use. According to the manufacturers, repairing a damaged hard coating should not be a problem.

²⁹ <http://www.hempel.co.uk/en-GB/products/hempels-silic-one-77450>

³⁰ <https://www.seajetpaint.com/en/about-seajet/protect-the-environment-and-go-faster-/>

4.3 Innovations in coating technology: biomimetic approach

The technology of antifouling coatings is still evolving, as manufacturers explore all kinds of combinations of silicones, fluoropolymers and other components. Knowledge of the biology of fouling organisms and their settlement strategies, as well as study of the natural mechanisms that protect marine organisms from colonisation, is being used to develop 'bioinspired' fouling-repellent surfaces. Strategies involve physical defence based on surface topography, chemical defence based on natural compounds, and a combination of the two (Callow & Callow, 2011; Nurioglu et al., 2015; Trepos et al., 2014; Wang & Cao, 2016). These three strategies are discussed below.

4.3.1 *Physical defence*

Some research has been done on chemical compounds that are known to repel organisms by physical action. An example of this is the use of a silicone elastomer with a coloured glow-in-the-dark phosphor powder that inhibits the settlement of diatoms by emitting a weak light (Cao et al., 2013). Related to this is the development of a coating with integrated UV light-emitting diodes (LEDs), which is discussed separately in Section 4.8. Most physical strategies, however, involve the creation of surfaces with micro-patterns that prevent fouling. Where the SLIPS technology, mentioned in Section 4.2.1, is an example of a bioinspired super-smooth foul-repellent coating, other technologies are based on the replication of natural hostile surfaces, such as molluscan shells or sharkskin. Articles on repellent surfaces can be found in scientific reviews (Buskens et al., 2013; Callow & Callow, 2011; Cao et al., 2011; Nurioglu et al., 2015), but it should be noted that most of these are still at an experimental stage, or are used for other purposes only, e.g. in the biomedical sector (Damodaran & Murthy, 2016). In general, their commercial application as an antifouling system for boats requires further research (Callow & Callow, 2011; Wang & Cao, 2016), although some technologies, such as the above-mentioned SLIPS, are at the stage of beta-testing³¹.

Within the European 6th framework research project AMBIO, which ran between 2005 and 2010, an interdisciplinary group conducted research on the nanoscale interfacial properties of different surfaces. The structure at the nanoscale is the controlling factor of many properties that are relevant to foul release coatings (Callow, 2010). AMBIO focused on the development of chemically heterogeneous surfaces that prevent protein binding, as there is growing recognition that an appropriate level of heterogeneity – in topography or in surface chemistry – may be more effective than a homogeneous surface (Callow, 2010). The project led to patents on some materials, and at least one product has reached the level of field studies (De Smet, 2014). This product combines a nanocoating with ultrasound (see Section 4.7) and is now in the stage of field testing on several vessel types, including pleasure boats³².

4.3.2 *Chemical defence – natural compounds*

The ability of some organisms to prevent fouling by chemical defence has led to research into natural antifouling compounds. The BPR does

³¹ <https://adaptivesurface.tech/beta-program/>

³² <http://www.nanowaves.net/technologies.htm?lng=en>

not distinguish between natural and manufactured substances. Natural antifouling substances have to be approved according to the BPR when used as active substances in antifouling paint.

Research into natural compounds

A recent review discusses over 200 natural marine compounds and some of their synthetic analogues discovered between 2009 and 2014 and reported to have medium to high bioactivity (Qian et al., 2015). Among these are fatty acids extracted from algae and bacteria, polyketides and alkaloid-related compounds isolated from fungi, and terpenoids and steroid-related compounds from soft corals and sponges (Qian et al., 2015; Trepos et al., 2014). Research into the use of naturally occurring compounds seems to be driven by the view that these have less environmental impact than manufactured substances. According to Qian et al. (2015), only a few natural marine products are considered as promising candidates for antifouling purposes, and most claims are based solely on small-scale laboratory testing. Trepos et al. (2014) give a more positive picture, but also indicate that there are many challenges to the development of antifouling systems from natural products, such as up-scaling production for the coatings market.

Below is a discussion of examples that have reached the semi-field stage or are already commercially applied.

Enzymes

Enzymes are a group of natural compounds that seem to have reached the commercial stage. Many types of enzymes, such as oxidoreductases, transferases, hydrolase, lyase, isomerase and ligase, have been reported to have antifouling capabilities (Cao et al., 2011). Enzymatic antifouling technology is based on the knowledge that biofouling problems are caused by the formation and reproduction of biofilms, and the adhesion of spores and the larvae of macro-organisms. Enzymes that inhibit these processes, by degrading the adhesives used for settlement, disrupting the biofilm matrix, generating deterrents/ biocides, or interfering with intercellular communication, are candidates for application in antifouling paints (Cao et al., 2011). In an internet article, reference is made to enzyme-based antifouling paints as a potential bio-based, non-accumulating alternative to traditional antifouling paints (Tripathi, 2016). According to this article, scientists tested a hydrogen peroxide-producing system composed of hexose oxidase, glucoamylase and starch.

Products on the Dutch market

In our inventory of commercially available products in the Netherlands, we found a self-polishing paint that is claimed to be a 'biological antifouling' system, using enzymes to reduce fouling and not containing 'traditional' biocides such as copper. According to the product datasheet, the enzymes are released continuously with the self-polishing layer to provide a repellent action that protects the hull from fungi, algae and micro-organisms. In 2018 this product appears to be withdrawn from sale. For another paint, the mode of antifouling action is described as 'the photochemical formation of hydrogen peroxides, disintegrating into the natural elements oxygen and water; the paint layer is polished due to resistance during sailing, thus maintaining a smooth hull'. We did not find evidence that the described process, which depends on light under

water, is effective in preventing fouling. It should be noted that hydrogen peroxide is an active biocidal substance, and in-situ generation of a biocidal active substance for antifouling purposes is subject to biocides legislation.

Chitosan

There is at least one example of another natural compound that has reached the stage of field testing, a coating based on chitosan³³. Chitosan is made by deacetylation of chitin (N-acetylglucosamine), a component in the exoskeleton of crabs, shrimps and other arthropods. Chitin and chitosan are subjects of agricultural research because they improve crop yields. This may be due to the direct toxicity of chitosan to pathogens, the induction of plant defences and/or the stimulation of beneficial microbes (Sharp, 2013). Chitosan is also applied in wastewater treatment for binding proteins, and this property is also the reason for its more controversial use in slimming pills. If the antifouling properties of chitosan are due to a toxic mode of action, the substance falls under the definition of biocides according to the BPR.

4.3.3

Combined physical and chemical low-emission antifouling systems

Trepos et al. (2014) describe research into the synergistic effects of surface topography and chemistry. They characterised and replicated the surface of two macro-algae species and evaluated the antifouling properties of a brominated furone extracted from algae. The highest antifouling potential was obtained when the two were combined. Studies on seaweed showed that some species allow the primary settlement of organisms, thus forcing them to come into contact with the biocide inside (Trepos et al., 2014). Using this concept, they developed a soft coating with 0.1% ivermectin, which prevented barnacle settlement, while no effect was seen when ivermectin was added to a hard coating. They postulate that the mechanism of action could be shifted from the solid/water interface to the first layers inside the coating, avoiding the emission of biocides into the water column. The concept was further developed within an EU 7th Framework LEAF project (Low-Emission Antifouling), which ran until December 2015³⁴. Between April and May 2015, a field test was carried out by 55 boat owners throughout Scandinavian, European, Mediterranean and Caribbean waters. They tested the LEAF prototype paint, in which copper oxide (normally constituting 30% of the paint) was replaced by 0.1% abamectin. Abamectin is a biocide produced by a soil bacterium (*Streptomyces avermitilis*). Overall, the results of the prototype test were considered as very positive concerning paint applicability, efficacy in use and functionality³⁵. It should be noted that a low percentage of active ingredient is not necessarily more environmentally friendly than a higher percentage of another active substance. Depending on the leaching characteristics and ecotoxicity, a low percentage biocidal paint may still be less favourable than a paint with a high content of other active ingredients. In this respect, it is relevant to mention that the Dutch surface water quality standard for abamectin is more than 2,000 times lower than that for copper, and for seawater the difference is even

³³ <https://www.deingenieur.nl/artikel/natuurlijke-coating-voor-schepen-getest>

³⁴ <http://leaf-antifouling.eu/>

³⁵ <http://leaf-antifouling.eu/media/Report-Final-Results-DEMO-downloadable.pdf>

larger³⁶. However, the project information states that compliance with the BPR is likely according to the human exposure and aquatic risk assessments performed within the project³⁷. The project is unique, because a prototype was developed and tested within three years. Moreover, much effort has been put into an organised field trial with a substantial number of boats, including reporting of the results.

4.4 Grease

Discussions on internet forums suggest udder cream as an alternative antifouling system^{38,39} and some such greases are commercially marketed for use on propellers⁴⁰. Udder cream ('Melkfett' in German, 'uierzalf' in Dutch) is applied to a boat's hull in a thin layer, which prevents organisms from adhering to it and thus settling on it. These products are relatively cheap, but wear down rapidly. It is further noted that some brands contain antibacterial compounds such as triclosan, which is a suspected PBT substance⁴¹. Since lifting the boat in and out of the water may damage the grease layer, the method is useful only for small boats that are in the water only for a couple of months. Currently, most marinas forbid the use of grease, since the hull becomes slippery and this raises safety issues when boats are lifted in and out of the water (pers. comm. Jeroen van den Heuvel, HISWA, 9 March 2017). The use of this option is not further considered in this report.

4.5 Films

Films to glue to the boat's hull are an alternative for paints or coatings. Also the terms 'foils' and 'wraps' are used. We could not make a clear distinction between films, foils and wraps and refer to all these products as 'films'.

About 30 years ago, a copper film was presented in a popular scientific magazine as an alternative to copper-containing antifouling paint. The product, called Hydro-Foil, consisted of a thin copper-nickel layer (0.13 mm) glued with a strong adhesive to the boat's hull. Its antifouling properties were based on the production of toxic cuprous oxide at the surface, but reportedly without leaching of copper (Renner-Smith, 1984). Based on the mode of action, this product would most likely fall under the BPR. However, apart from the 1984 article, no further reference to this product was found.

In 2002, the American professor Dr Anthony Brennan performed research for the US Navy to find new antifouling strategies⁴². He realised that sharks are slow-moving marine animals that do not foul. Based on the structure of the shark's dermal denticles, he developed the 'Sharklet micro pattern'. It is about three microns tall and two microns wide with

³⁶ <http://wetten.overheid.nl/BWBR0027502/2015-11-19>

³⁷ <http://leaf-antifouling.eu/leaf-final-reporting/>

³⁸ <https://zeilersforum.nl/index.php/forum-hoofdmenu-37/lakken-en-verven/569346-iemand-ervaring-met-melkfett-antifouling>; <http://www.ybw.com/forums/showthread.php?333924-Udder-cream-antifoul-it-works>

³⁹ <http://www.compromisclub.nl/ctips/ct20042melkfett.html>

⁴⁰ <http://www.prop-shield.com/>

⁴¹ Persisten, Bioaccumulative, Toxic, see also 3.4

⁴² <https://www.sharklet.com/>

tiny riblets arranged in a distinctive diamond pattern. The pattern is used in films, but at present only used in medical applications.

Since 2012, a Dutch firm has been selling a bioinspired antifouling film⁴³ called Finsulate. The film contains millions of tiny resilient fibres or hairs stuck to a polyester layer with acrylic adhesives. The nylon fibres resemble the spiky hairs used by organisms to combat fouling. They vibrate constantly with the movement of the water. The combination of prickliness and swaying makes the fibres unattractive for organisms to settle on. After initial development for fish cages and commercial shipping, Finsulate became available for pleasure boats in 2017. The company performed collision tests and, according to the producer, the film remains on the hull at much higher collision speeds than conventional paints. The producer of Finsulate claims a service life of at least five years. Cleaning can be done at the end of the season using low- or high-pressure equipment. The product can be applied on existing layers, but it is essential that the surface to which the film is applied is clean, dry and free of grease or oil, and an appropriate tie coat should be applied, e.g. an epoxy or a vinyl primer. According to the producer, the film is not suitable for DIY use, but application is not really complicated and easy to learn by professionals. The material can get out of shape when lifting the boat. The film also could be damaged along the quay, but is easy to repair, and removal is possible with high-pressure hot water or with hot air. When testing the film on fast boats, there were problems due to drag of the material. Developments aim to make films suitable for fast boats.

Some other references to antifouling films for boats were found, but the internet sources did not provide detailed information⁴⁴.

Another company that sells a film with a silicone top is Renolit⁴⁵, which produces functional films for a variety of surfaces, including boats. Their silicone-based foul release film is presented as giving the surface of the vessel a smooth, water-like finish. Fouling organisms have difficulty attaching themselves to hulls and are washed off when the boat moves (at about 7 knots). Another company is also trying to develop an adhesive film system, based on silicone foul release technology⁴⁶.

4.6 Electro-chemical

Klijnstra et al. (2007) mention several electro-chemical principles that may be applied to antifouling systems. Based on this there are systems that generate chloride or copper, and systems that create strongly variable pH conditions. Systems based on copper release are commercially available for water purification in cooling systems and other pipework. An electrolytic antifouling system dissolves both copper and alternatively aluminium- or iron-based anodes in the seawater system. The anode dissolution prevents the settlement of organisms and the development of fouling, which can cause blockages, reduce flow

⁴³ <http://www.finsulate.com/>; international commercial marketing takes place under the tradename Micanti (<http://www.micanti.com/>); <http://www.micanti.com/>; the tradename Finsulate is used for pleasure boats

⁴⁴ <http://www.nauticalfoil.nl/toepassingen/pleziervaart/>

⁴⁵ <https://renolit-maritime.de/>, <https://www.renolit.com/contact/en/products/renolit-maritime/>

⁴⁶ <http://corporate.ppg.com/Media/Newsroom/2016/PPG-working-with-industry-partners-to-develop-inno>

rates and accelerate corrosion⁴⁷. No information was found on large-scale applications for ship hulls. Dissolution of copper or other biocidal ions would require approval under the BPR.

4.7 Ultrasound

The use of ultrasound waves for fouling control is mostly referred to in the context of the control of blue-green algae blooms in reservoirs or ponds (Colucci, 2010). Sound waves are also used for ballast water treatment (Estévez-Calvara et al., 2017; Holm et al., 2008). Application to boats for antifouling purposes was suggested in the literature a few years ago (Guo et al., 2011). Nowadays, ultrasonic sound wave systems are sold by many companies as antifouling systems for boats⁴⁸. A small transmitter is placed on the inside of the boat's hull. Some systems are based on cavitation. Ultrasonic waves (≈ 23 kHz) continuously pass through the hull, which acts as a soundboard, causing microscopic vibrations within a diameter of 10 meter of the hull's surface around the transmitter. These vibrations form cavitation bubbles that implode, locally increasing temperatures to 5,000 °C and pressure to 500 Atm (Park et al., 2017). In this way, the system kills unicellular organisms and thereby prevents the establishment of biofilms and removes the settlement surface for larger fouling organisms like cockles and mussels. Other ultrasound systems function in a different way and do not cause cavitation (Guo et al., 2012). The working principle is unknown to us. Some companies supply dedicated software so that the frequency can be adapted to the type of fouling. The systems can be used on all hull materials except wood, and can be combined with existing foul release or hard coatings⁴⁸.

Another system employs low-frequency sound⁴⁹. Sound is emitted in the 17–20 Hz range by an oscillator, using the hull as a soundboard. According to the producer's website, fouling organisms experience the sound as a sign of a predatory environment and avoid the area. It is stated that the system works on any material and is also effective on propellers, shafts and rudders.

As indicated above, literature exists on the effectiveness of ultrasound waves in reducing algal growth (Park et al., 2017). For lower frequency waves, we could retrieve only one paper describing a 3-month field trial in which panels were vibrated at frequencies between 70 and 445 Hz. Only barnacles were affected, and reduced settlement was observed on panels vibrating at relatively higher frequencies (> 260 Hz), but lower frequencies (in the 70–100 Hz range) had little or no effect on barnacles, and the settlement of other organisms appeared not to be affected, either (Choi et al., 2013).

Testimonials from boat owners on producers' websites and on internet forums suggest that these systems work adequately^{50,51}, but we could

⁴⁷ <http://www.cathwell.com/ships/systems/electrolytic-antifouling/description/>

⁴⁸ For example: <http://www.nanowaves.net/>, <https://lscare.nl/anti-fouling-for-yachting/>, <http://www.dutchdurablecoatings.com/neosonic/>, <https://www.lgsonic.com/>, <https://www.sonihull.nl/>, <https://www.ultrasonicworks.com/antifouling/>, <http://www.shipsonic.nl/>, <https://cleanahull.com/>, <http://ultrasonicmarine.com/index.html>, <http://h2obiosonic.com/applications/vessel-hulls-and-running-gear/>

⁴⁹ <https://thenox.com/ultrasound-antifouling>

⁵⁰ <https://cleanahull.com/ultrasonic-antifouling/ultrasonic-antifouling-testimonials/>

⁵¹ <http://emcsindustries.com/wp-content/uploads/2016/02/BC-Ferries-Fastcat-testimonial.pdf>

not retrieve scientific literature on their effectiveness on boats. A similar conclusion was drawn in an alternatives assessment in the USA, which also states that manufacturers recommend combining ultrasound devices with a protective coating, biocidal or otherwise (TechLaw & Northwest Green Chemistry, 2017).

Several companies sell systems for pleasure boats^{48,52}. The company we interviewed states that it has installed more than 25,000 systems worldwide and can give many positive testimonials. From the interviews we learned that non-effective systems have been on the market in the Netherlands, and producers are working to enhance and prove their performance.

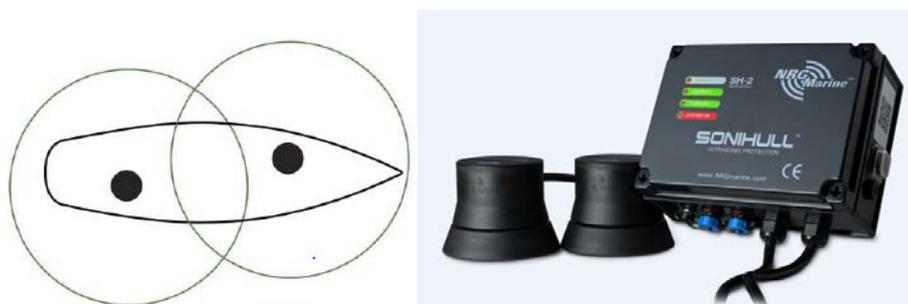


Figure 3. From installation advice for an ultrasound system for a boat up to 15 m in length.

Source: <https://lscare.nl/anti-fouling-for-yachting/>

4.8 UV light

UV irradiation is applied for antifouling purposes in marine situations. While about ten years ago it was still mentioned as a promising antifouling method (Delauney et al., 2010; Patil et al., 2007), the technique is now commercially available for application in marine sensors and equipment (Crystal IS, 2015). The antifouling action is due to UV irradiation causing DNA damage to micro-organisms and algae, thereby preventing biofilm formation and the settlement of larger organisms. The concept of integrating UV-LEDs into protective coatings was described by Salters & Piola (2017), who successfully tested 30 x 30 cm prototypes for a period of 1 year. They indicate that for a successful commercial application, a service life of at least 5 years but preferably 15 years would be needed. Other practical matters and feasibility questions, that need to be resolved before scaling-up is possible, include the energy demands of full-scale applications and manufacturing of units that can cover large hulls (Salters & Piola, 2017). In February 2018, AkzoNobel announced that it is cooperating with Philips to further develop this technology⁵³.

4.9 Mechanical measures and storage options

4.9.1 Cleaning and brushing

The option of brushing and cleaning has already been mentioned in connection with hard coatings (Section 4.2.3). Regular cleaning using

⁵² <http://cmsmarine.co.uk/index.php>, <http://www.ultrasonic-antifouling.com/>

⁵³ <https://www.akzonobel.com/for-media/media-releases-and-features/akzonobel-develops-pioneering-marine-fouling-prevention>

high-pressure water seems suitable for smaller boats. When this is done at the end of the season when the boat is lifted out of the water, almost all freshwater fouling may be removed relatively easily. Cleaning works best when the fouling has not yet dried. For smaller boats, this is easier to accomplish than for larger boats. Using high-pressure water is not possible for boats with self-polishing biocidal or non-biocidal coatings, as these will be damaged or (partially) removed.

Fouling may also be removed using a brush or a sponge. This method is especially suitable for freshwater pleasure boats. This technique reduces the need to treat the whole hull with antifouling paint. Brushing can be performed on land, but also underwater. Underwater brushing stations ('borstelbaan') are one way of underwater cleaning. Such systems were tested in the late 1990s and mentioned in some documents, but a commercial breakthrough did not follow⁵⁴. In 2013, there was only one brushing station in service in the Netherlands, which was not publicly accessible. Currently this is out of order. The lack of success was probably due to the fact that the systems could not reach and clean all parts of a boat, whereas at that time brushes could only be used on a hard coating. According to a newspaper article from 2014, modern systems do not suffer from these drawbacks, which could be a reason for renewed interest in such systems, which in Sweden are seen as an environmentally friendly alternative to biocidal paints⁵⁵. The Swedish firm Drive-in Boatwash sells stationary and mobile washers. The stationary version cleans motorboats and sailing boats up to 16 m long and requires a dock space of about 7 to 8 m. The mobile version is mounted on a trailer and the boat is slid back and forth over rotating brushes (see Figure 4). It should be noted that the use of biocidal paint on freshwater pleasure boats is prohibited in Scandinavia, which is expected to promote alternative solutions to consumers. Currently, a Dutch firm is launching Drive-in Boatwash washers on the Dutch market⁵⁶.

Underwater cleaning can also be performed with cleaning robots⁵⁷. These can be operated by remote control (no divers necessary). The brushes are adjustable, and so can be used for hard coatings and self-polishing paints. When cleaning painted boats underwater, there is a risk of removing paint, and debris needs to be collected carefully. It is possible to fit a vacuum cleaner bag to the robot, so that all debris, including pieces of old paint, is collected and does not enter the environment.

⁵⁴ <https://www.trouw.nl/home/plezierjachten-testen-wasstraat-a46a2744/>

⁵⁵ <https://www.telegraaf.nl/nieuws/1145217/milieutrend-bootwasstraat>

⁵⁶ <http://www.yachtwash.nl/>

⁵⁷ keelcrab; www.keelcrab.nl



Figure 4. Pictures of a brush cleaning station and a cleaning robot.

Source: <http://driveinboatwash.com/en/products/miniwash/> and <http://www.keelcrab.nl/keelcrab-sail-one/>

4.9.2 Storing a boat out of the water

When a boat is stored out of the water, the growth of fouling will be significantly reduced. Small boats can be pulled out of the water and stored on a trailer. When the boat is only stored out of the water during the wintertime, this will not have much effect on fouling, since fouling mainly happens during spring, summer and autumn. Several companies sell hydraulic boatlifts that will raise a boat out of the water in minutes, and can thus be used during the boating season. As the system requires space in and under water, this has implications for marinas.

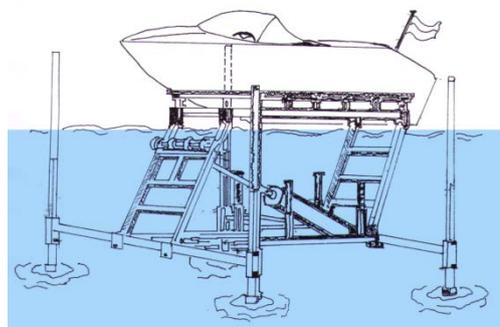


Figure 5. Pictures of a boatlift.

Sources: <http://bootliftnederland.nl/hoer-werkt-de-bootlift/>, <http://www.blombootliften.nl/>. For examples see <https://www.bootlift.nl/>, <http://www.steigerstad.nl/>, <http://nauticnederland.nl/bootlift>, <http://airdock.nl/>, <https://www.techno-bootliften.nl/>

4.9.3 Slip liners

In their list of alternatives for copper-based paint, Johnson & Gonzalez (2008) mention slip liners, which are a kind of floating dry dock. Two American suppliers were found on the internet⁵⁸. The system consists of a kind of sheet with an 'air-gate' system that is lowered when the boat enters the 'dock' and is raised afterwards. When the boat is inside the slip liner, the water therein is no longer in contact with the surrounding water. One of the suppliers indicates that an automated system chlorinates the water within the closed slip liner at a tap drinking water chlorine level (1.0–4.0 mg/l) to prevent fouling. Johnson & Gonzalez (2008) mention that chlorine should be neutralised before the air-gate is opened. Chlorination of water is considered as a biocide use, and would

⁵⁸ <http://armoredhull.com/>, <http://www.barnacleprotection.com/>

require authorisation under the BPR. The formation of by-products, that may be toxic, should be considered in the risk assessment.

4.10 Summary of market status and applicability to pleasure boats

Based on the above descriptions, Table 3 summarises the alternatives with respect to market availability, development stage, applicability to pleasure boats and possibility of DIY use. Of the existing systems, innovative coatings, films, ultrasound and mechanical measures seem to be most relevant. UV light systems are in development.

Table 3. Summary of availability and (potential) applicability of alternative antifouling techniques to pleasure boats in the Netherlands

Type	Commercially available	Development stage			Applicable to pleasure boats?	DIY?
		Lab stage	Field test ^a	Boat test		
Coatings						
Foul release	Yes				Yes	No / Yes
Self-polishing	Yes				Yes	Yes
Hard	Yes				Yes	No / Yes
Structures	No	Yes	Yes	?	?	?
Natural compounds ^b	? ^c	Yes	Yes	?	Yes	?
Grease	Yes				No	Yes
Films	Yes				Yes	No
Electro-chemical^d	?	?	?	?	?	?
Ultrasound	Yes				Yes	Yes
UV light	No	Yes	Yes	?	Yes	?
Mechanical measures						
Cleaning/brushing	Yes				Yes	Yes
Storage out of the water	Yes				Yes	?
Slip liners	Yes				No	?

For systems that are commercially available, the columns for development stage are left blank, although further development of the system will continue in almost all cases.

a: Small-scale, e.g. on panels

b: Note that natural compounds with a chemical mode of action should comply with the BPR

c: An enzyme-based paint appears to be withdrawn from sale, for another paint it is not clear if the mode of action really is enzyme-based

d: Release of metal ions should comply with the BPR

DIY: System can be applied or installed and maintained by non-professionals.

?: No information found

5 Safety and environmental impact of antifouling systems

5.1 Introduction

There is ongoing concern about emissions of biocidal antifouling paint in the Netherlands. In 2003, a report was published discussing legal and policy instruments for emission reduction and strategies to influence different stakeholders (Verhoeven & Vermij, 2003). In 2007, an inventory of antifouling techniques was published to inform various stakeholders of environmentally friendly alternatives to biocidal antifouling paints (Klijnstra et al., 2007). However, most consumers continue to use biocidal paints (see Chapter 6).

In this chapter, we explore the criteria and information on safer alternatives to biocidal paints. In Section 5.3 we give information on the safety of biocidal paints, to compare this with information on the alternatives in Section 5.4. Information on the safety for DIY use of the alternatives has already been presented in Section 4.2.5. We have used the Safe-by-Design approach (see Section 1.1) as a general guideline, but have not considered aspects such as cost, recycling and energy saving. It is not the intention of the current report to present a systematic comparison of alternative antifouling systems on the Dutch market, but to discuss the alternatives mentioned in the previous chapter (as summarised in Table 3) and highlight important issues with respect to human and environmental safety. Where possible, this is done using information from products commercially available on the Dutch market. First, in Section 5.2, the report by Klijnstra et al. (2007) and some more recent evaluations of alternatives are discussed.

5.2 Available assessments of antifouling systems

5.2.1 *Inventory of Antifouling Techniques by Klijnstra et al.*

Klijnstra et al. (2007) qualitatively assessed the then existing systems and (potential) alternatives for recreational craft with respect to their efficacy, development stage, ease of application, environmental impact during service life, and costs. Biocidal paints based on copper or on other biocides and available alternatives were included. A decision-tree for pleasure boats owners, based on their habits regarding boating frequency, boat speed and willingness to periodically clean their vessel was presented (see Figure 6). This indicates that user habits are highly relevant to the choice of an alternative antifouling system (presented in blue) instead of a biocidal paint (presented in red). The inventory gives only general information on the environmental impact of the various alternative systems and human risks are not discussed. Of the systems that were indicated as developments in the lower part of Figure 6, ultrasound now seems to have reached the market stage for pleasure boats, alone or in combination with foul release or hard coatings⁴⁸. Most of the other alternatives to copper-based biocidal antifouling paints presented in the present report were also mentioned in 2007, but these are either not further developed or have not yet enter the market.

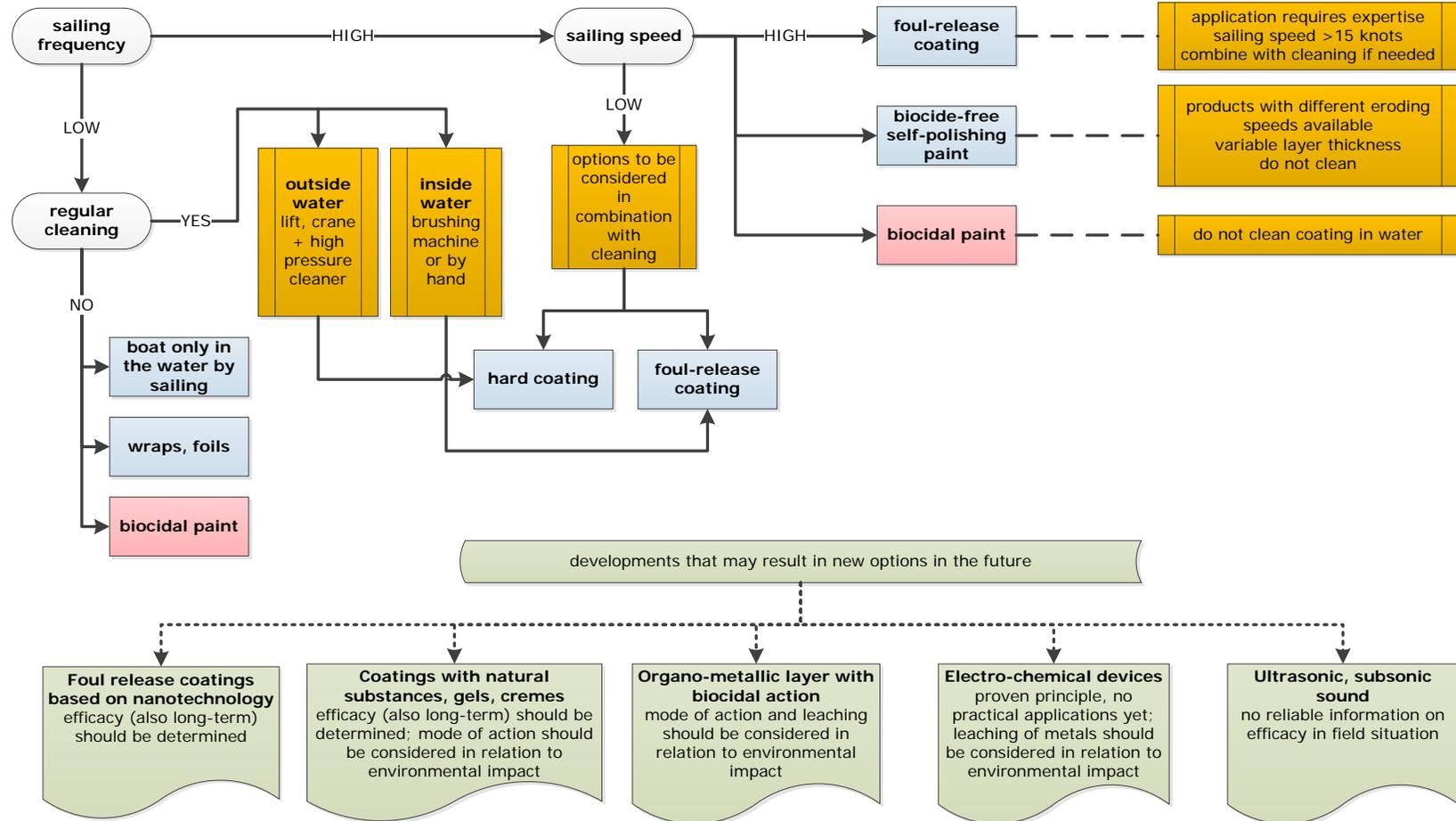


Figure 6. Decision-tree for boat owners, adapted from Klijnstra et al. (2007)

5.2.2 *Alternative Antifouling Strategies Sampler*

Johnson & Gonzalez (2008) published an *Alternative Antifouling Strategies Sampler*, in which they presented information on a number of alternatives to traditional copper-based antifouling paints. Their overview contains a list of options, divided into coatings (epoxy, ceramic epoxy, siliconised epoxy/siloxane, and polymer-based), bottom wax (grease), physical systems (brushing, lifting), and slip liners. Bottom wax and slip liners are not considered as realistic alternatives (see Sections 4.4 and 4.9.3). For the other alternatives, some considerations regarding their human and environmental impact are given in Section 5.4.

5.2.3 *Washington State Antifouling Boat Paint Alternatives Assessment*

In a recent assessment prepared for Washington State, alternatives to copper-based antifouling paints were evaluated with respect to human and environmental exposure and risks and antifouling performance (TechLaw & Northwest Green Chemistry, 2017). The report focuses on biocidal and non-biocidal alternatives without copper, because the use of copper in antifouling paints for recreational vessels had been phased out by legislation to protect salmon. For this reason, biocidal paints with e.g. zinc pyrithione or tralopyril are assessed as an alternative. Costs and availability are included as well, as these are important factors for consumer acceptance. The comparative assessment includes non-copper biocides (alone or in combination with hydrogen peroxide releasing agents), foul release coatings (ceramic, silicone or polymer-based), low- and high-frequency sound waves, and mechanical systems (trailing, cleaning, etc.). As a result of the project, a user's guide was published along with a five-point 'take-home message' (see Figure 7) that highlights the importance of avoiding products containing CMR or ED substances, neurotoxicants and inhalation sensitizers. Regarding environmental impact, biocidal products and self-polishing (ablative) paints as well as products containing volatile organic compounds (VOCs) are discouraged. The report further indicates performance and cost over time as important decision criteria.



Figure 7. The '5 Takeaways' highlighting the primary conclusions from the alternatives assessment (TechLaw & Northwest Green Chemistry, 2017)

Source: <https://www.northwestgreenchemistry.org/news/release-of-the-washington-state-antifouling-boat-paint-alternatives-assessment-report>

5.2.4 BONUS CHANGE project

Within the framework of the BONUS CHANGE project⁵⁹, the environmental impact of different antifouling methods, including biocidal paints and biocide-free techniques, was tested and evaluated with the aim of reducing the amount of antifouling toxins released into the Baltic Sea. The project had a multidisciplinary approach with contributions from natural science, environmental law and social science/economy. The report containing the

⁵⁹ <https://www.ri.se/en/projects/changing-antifouling-practices-for-leisure-boats-in-the-Baltic-Sea>

conclusions and final recommendations of the project (Watermann & Dahlström, 2017) lists a number of the non-biocidal antifouling systems discussed in Chapter 4, and concludes that mechanical methods worked just as well as copper-containing paints in extensive field tests with boat owners. Based on efficacy testing at various sites with different severity of fouling and salinity, it is concluded that the amount of copper in antifouling paints used on pleasure boats in the Baltic region can be substantially lowered. It should be noted that all the copper-based paints evaluated in the study contained zinc oxide, and it was confirmed that copper release increased with increasing zinc content. Zinc release was dependent on the paint type (Lagerström et al., 2018).

Because of the specific nature of the Baltic ecosystem the results of the efficacy tests are probably not directly applicable to the situation in the Netherlands or in other countries. However, the combination of technical, legal and socio-economic research makes this an interesting project. An important point is that the BONUS CHANGE project makes a plea for regulatory and policy actions, and makes a clear connection with the European Water Framework Directive (WFD). Competent authorities are urged to oppose the classification of marinas as 'technospheres', if this discussion is reopened. Based on a legal assessment conducted within the project, it is stated that the BPR leaves room for a requirement that antifouling paints should not contain unnecessary high amounts of biocides. Therefore, future authorisation of biocidal antifouling paints should require paint producers to show that their product does not contain higher amounts of copper than necessary for sufficient antifouling performance. The Baltic region Member States' competent authorities are urged to apply the BPR's articles and paragraphs supporting a restrictive national implementation of the BPR, and, in view of the WFD objectives, to oppose the use of any organic biocidal antifouling product.

Another recommendation is to improve the methods for release estimation as currently used for biocide evaluations under the BPR. Copper leaching rate behaviour was found to be dependent on environmental conditions and the composition of the paint (e.g. zinc content). In-situ release rates as measured by new XRF (X-Ray Fluorescence) techniques were up to eight times higher than predicted by laboratory or calculation methods (Lagerström et al., 2018). Therefore, release rate prediction models based on biocide content cannot be used, regardless of differences in paint formulation. BONUS CHANGE recommends standardisation of the XRF technique to measure condition- and paint-specific leaching rates that are relevant to the field situation.

The observation that copper release is dependent on external conditions indicates that risks are region- or even site-specific. This challenges the concept of EU-wide harmonised authorisations and mutual recognition of biocidal antifouling products. At the same time, the fact that boats may move to other, potentially more vulnerable, environments, requires a risk assessment that takes the most critical conditions as a starting point. In that respect, it is interesting that the BONUS CHANGE project concludes that, in view of the large number of pleasure boats that move between seawater and freshwater environments, banning a product for freshwater use only is not possible. In line with current practice in the Netherlands, products should be authorised only if they meet the criteria for both

freshwater and seawater. BONUS CHANGE recommends that, to reach the goal of a Baltic Sea free of biocidal antifouling paints, during the transition-phase (2020–2030) only low-copper paints based on copper flakes, dicopper oxide or copper thiocyanate should be authorised for use on pleasure boats.

The project also paid attention to antifouling practices and maintenance work in marinas and recommends that these are improved by regulation and infrastructure development, e.g. high-pressure cleaning areas, designated areas for scraping and sanding, receptacles for hazardous waste and collection equipment. This relates to the observation that emissions from maintenance and repairs are probably not sufficiently addressed in the current product authorisation procedure (see Section 3.2.3).

5.3 Comparison of alternatives with biocidal systems

Most of the evaluations summarised above included a comparison with existing conventional biocidal paints. When judging alternative antifouling systems, it makes sense to demand that they cause less environmental impact than biocidal products that are currently authorised under the BPR. Before being authorised, biocidal paints are assessed for their efficacy, risks for professionals and consumers that apply the product, and risks for the environment due to emissions on application, during service life, and from maintenance and repair work. Producers are obliged to disclose the ingredients of biocidal paints to the competent authority. The currently authorised products have shown efficacy in (simulated) field tests and do not present unacceptable risks to humans and the environment, as required by the ECHA guidelines under the BPR.

As described in Section 3.2.1 chemicals meeting the criteria for CMR, PBT/vPvB or ED are in principle not approved as active substances for biocidal products. From this it follows that alternatives can only be considered as safer than currently approved biocides if they do not contain (or do not release) chemicals classified as CMR, PBT/vPvB or ED, and their use does not pose an unacceptable risk to humans or the environment.

5.4 Human and environmental safety of alternatives

5.4.1 *Presence of hazardous compounds in biocide-free paints and coatings*

The antifouling properties of foul release coatings, biocide-free self-polishing paints and hard coatings are not based on biocidal active substances. However, they do contain a variety of compounds with different functions. Some of these substances are classified with respect to human toxicology or environmental effects (see text box). Epoxy and vinyl coatings may contain alkylphenols, such as nonylphenol and bisphenol A, and stabilisers and in-can preservatives are added to increase the shelf life of water-based paints and to prevent microbial and physical deterioration during use. The binder for silicone coatings contains a high percentage of volatile organic compounds (VOCs) such as xylene, ethylbenzene, toluene and N-butylacetate.

Examples of hazardous compounds in biocide-free paints and coatings

We found reference to dioctyltin dilaurate (CAS 3648-18-8) and dibutyltin dilaurate (CAS 77-58-7) in two foul release coatings and 1,2-benzisothiazool-3(2H)-on (BIT; CAS 2634-33-5) in a hard coating. The former two are organotin compounds, which according to the IMO are allowed in paints when present at a level that does not provide a biocidal effect in the coating. On a practical level, when used as a catalyst, an organotin compound should not be present above 2,500 mg total tin per kilogramme of dry paint (MEPC, 2010). BIT is used as an active ingredient in a series of broad-spectrum biocide formulations, but in this case it is most likely added as an in-can preservative to increase the shelf life of products. Biocidal in-can preservatives should comply with the BPR. According to the harmonised classification and labelling approved by the EU, BIT is very toxic to aquatic life, is harmful if swallowed, causes serious eye damage, causes skin irritation and may cause an allergic skin reaction.

Another constituent encountered in a foul release coating in our survey is octamethylcyclotetrasiloxane (D4; CAS 556-67-2). This compound is under review by the European Chemical Agency (ECHA) because it is a suspected PBT compound (persistent, bioaccumulative, toxic). Biomagnification in the aquatic food chain has been demonstrated in several field studies (Smit et al., 2012).

At present, there is no regulatory context that specifically addresses the human and environmental impact of non-biocidal antifouling paints during the application, service life and waste stages. Only general chemical regulations, such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) and CLP (Classification, Labelling and Packaging) apply. Compounds that are classified as hazardous should be declared to users on the material safety datasheets (MSDS) when present in levels of 0.1% or higher. However, it is hard to obtain information on constituents other than those mentioned in the MSDS, as this is often claimed as confidential information. In the Washington State Alternatives Assessment (see Section 5.2.2), it was concluded that knowledge of the presence or absence of hazardous chemicals can only be achieved via transparency and disclosure of ingredients. In that study, the disclosure of ingredients was only possible thanks to cooperation by the industry. Even then, only some of the producers were willing to cooperate (TechLaw & Northwest Green Chemistry, 2017). Furthermore, there is no systematic regulatory check on MSDS. In an American study, numerous errors were discovered on safety datasheets, including mis-identification of ingredients, inaccurate quantities and listing of wrong chemicals (Nicol et al., 2008).

Another problem is that producers are not legally obliged to attach MSDS to consumer products. Consumers can ask the retailer or retrieve the MSDS from the producer's website, but even then the information is difficult to understand. Moreover, some paints are sold as consumer products, but in the MSDS all kinds of personal protective equipment normally used only by professionals (such as gas masks) are mentioned. Under the BPR such products would not be authorised for consumer use,

but since these are non-biocidal paints, the BPR does not apply. The Dutch government took the initiative to inform consumers of safety issues relating to the chemicals in consumer products, but antifouling systems are not yet included⁶⁰.

5.4.2 *Environmental and health impact of production stage*

When discussing safer alternatives to traditional antifouling systems, the environmental impact of the production of the chemicals they contain is another factor that should be considered. Reduced emissions during service life are considered as an advantage of foul release coatings, but the production of some constituents of these coatings may have a significant environmental impact. It is not the intention of the present report to perform life-cycle analysis, but it is relevant to consider, for example, that the production of fluoropolymers requires perfluoro octanoic acid (PFOA) in almost all cases (Gardiner, 2015), and PFOA is classified as a Substance of Very High Concern in Europe because of its carcinogenic and PBT characteristics. Restrictions on the production and use of PFOA in Europe and the USA has led to the development of alternatives, but also to a shift in production to less regulated regions in Asia (Fang et al., 2014; Heydebreck et al., 2015).

5.4.3 *Environmental fate of biocidal-free paints and coatings*

Little is known about the environmental fate of the chemical backbone of coatings and the leaching of the constituents from these coatings (Watermann et al., 2005). In a laboratory study, several types of biocide-free antifouling paints were subjected to bioassays and selected chemical analysis of leachate and incorporated substances. The study included different types of non-eroding coatings (silicones, fibre coats, epoxies, polyurethane, polyvinyl) and self-polishing coatings. It was confirmed that none of the analysed coatings contained leachable biocides. Nevertheless, some products contained or leached dangerous compounds, such as silicone oils, organotin catalysts, nonylphenol and bisphenol A. Other authors also highlight the depletion and leaching of silicone-based species as the surface wears out (Nurioglu et al., 2015; Van Rompay, 2012). Some of the interviewees question the use of organotin compounds as a catalyst in foul release coatings. According to them, the concentrations used are too high for this purpose and in reality the organotin compounds act as biocides. The organisation Fairplay has written an article about this, but we could not verify the information⁶¹. The replacement of organotin compounds by other catalysts should be possible.

The antifouling principle of self-polishing paints is that the upper layer erodes during use, thereby loosening the fouling. Self-polishing paints by definition cause emissions to the environment. As already mentioned in Section 4.2.2, copper-free self-polishing paints often contain zinc oxide. This is usually claimed as not being biocidal (see Section 3.4), but in one reference it is stated that zinc ions are released for antifouling purposes (Cao et al., 2011). However, even when zinc is present for other reasons

⁶⁰ The Dutch government website "Waar zit wat in" that gives information on chemicals in consumer products and their safe use, and already includes some indoor paints <https://waarzitwatin.nl/categorieen/verf>

⁶¹ <https://fairplay.ihs.com/safety-regulation/article/4282591/organotins-make-toxic-return-nine-years-after-being-outlawed>

than biocidal action, emissions may pose an environmental threat because zinc is toxic to aquatic organisms and is considered as a Substance of Concern (see also Section 3.4). Zinc (and copper) are among the compounds that most frequently exceed the water quality standards in national legislation under the WFD (Anonymous, 2012; Van Puijenbroek, 2014). The number of surface waters exceeding the quality standards may be reduced when a bioavailability assessment is implemented for all locations (Van Puijenbroek, 2014), but it is expected that locations where the water quality standard is exceeded will still remain (Verschoor et al., 2011). Although boat paints are certainly not the only emission source of zinc, they are likely to contribute to the environmental concentrations of zinc. According to one study, if zinc oxide is essential to the erosion process, the content should be restricted to values below 10% (Watermann et al., 2005).

Regarding hard coatings, some information is available from research performed in 2008 by Rijkswaterstaat on a vinyl ester resin-based coating, reinforced with glass platelets (Wijga et al., 2008). The aim of the experiments was to determine environmental emissions during underwater hardening and during the polishing and cleaning of hulls. Polishing led to the emission of suspended particles but, based on the results of bioassays, these were considered not to be harmful to the environment. The study of cleaning showed that the particles entering the environment were mainly of biological origin (remains of fouling organisms) and it was concluded that the product was environmentally safe. Since then, this product has been the only one allowed to be used for underwater cleaning in the Netherlands²⁶. Furthermore, in the above-mentioned leaching study by Watermann et al. (2005), the leaching of nonylphenol and bisphenol A was observed for a 'glass-reinforced epoxy', but it is unclear exactly which types of hard coating cause this kind of emissions.

5.4.4 *Natural compounds*

The available literature on bioinspired antifouling systems does not contain information on the effects on non-target organisms (Qian et al., 2015). In general, authors and producers tend to position natural compounds, including enzymes, as being environmentally friendly. There is a general feeling that the properties of substances that are produced by nature itself are preferred to man-made chemicals. From the viewpoint of sustainability, bio-based production from renewable resources certainly has advantages. Naturalness, however, is not a guarantee of low impact on ecosystems. It is important to note that the definition of biocides in the BPR is not restricted to chemicals, but also applies to biological material⁶². Natural or bio-based compounds are not excluded from this definition and the fact that a biocidal action is based on natural compounds does not relieve producers from their obligations under the BPR. Many known pesticides have a natural origin, e.g. pyrethrins, essential oils, and fermentation products applied in biocidal and plant protection products. The efficacy of these pesticides against target organisms most often

⁶² According to the BPR, article 3, 1(a), a biocidal product means any substance or mixture, in the form in which it is supplied to the user, consisting of, containing or generating one or more active substances, with the intention of destroying, deterring, rendering harmless, preventing the action of, or otherwise exerting a controlling effect on any harmful organism by any means other than mere physical or mechanical action.

includes that they have impact on non-target organisms as well. For a proper comparison, new non-biocidal coatings should be assessed in a similar way to the biocidal paints currently in use.

5.4.5 *Films*

Little or no information is available on the human health and environmental impacts of films with nylon fibres. From a first impression, the environmental impact of these films during service would seem to be low. Theoretically, the nylon fibres could add to the micro plastics in the environment when they wear down, but according to the website of Finsulate, practical tests on boats show no wear-down of the material, although no further details are provided. The producer states that the film is applied with an acrylic glue and contains no PVC or softeners. When assessing the risks, the whole coating system should be taken into account.

For information on environmental and human safety of a film with a silicone top: see the sections above on paints and coatings.

5.4.6 *Ultrasound*

Little information is available about the environmental impact of ultrasound. Laboratory research shows that water fleas (*Daphnia*) are killed by ultrasonic waves in water with a tendency towards longer survival times with decreasing frequency and increasing volume (Lürling & Tolman, 2014). In an experiment using 85-litre tanks containing a phytoplankton suspension of cyanobacteria and green algae, the decrease in daphnid density caused by the ultrasound treatment induced an increase in phytoplankton density because of reduced grazing. The authors therefore conclude that the envisaged control of phytoplankton may cause an opposite effect. It is not easy to translate the results of these experiments to the field situation. It is not clear how far the ultrasonic waves are transported through the water, nor how far away from a boat's hull the waves are still lethal to zooplankton. It is also not clear whether in the field situation water fleas would be affected by soundwaves, or whether they could avoid them without being harmed. The systems would primarily be used for moored boats, and more information on their effects in a busy marina would be needed to estimate environmental impact in the field.

5.4.7 *UV light*

UV light is harmful to humans, but its application under water is not expected to lead to human exposure. There is no information on the impact on non-target organisms. The occurrence of negative effects will depend on the distance from the boat hull at which the irradiation dose is still effective.

5.4.8 *Mechanical measures*

Brushing, cleaning and boat lifting are not considered hazardous to operators and boat owners. For boats with a hard coating, the environmental impact is also considered to be low, except that the release of dead organic matter is unwanted. However, when applied to old, damaged or soft coatings, high-pressure cleaning or brushing may release paint flakes, micro pollutants and micro plastics. When the brushing or cleaning is performed on land, the debris should be removed and

disposed of carefully, in order not to let it enter the watercourse. When an underwater brushing station is used, the release of debris is hard to prevent, although systems exist to collect this (see Section 4.9.1).

5.5 Overview of findings on antifouling systems for pleasure boats

Table 4 summarises the assessment of antifouling systems for pleasure boats in this study. Information is given on their commercial availability and suitability for DIY, along with remarks on their use, composition, human and environmental safety and current developments. In the following text we summarise the information on the main current and upcoming alternative antifouling systems for pleasure boats. The current Dutch market situation and developments are discussed in Chapter 6.

Table 4. Summary of findings on antifouling systems for pleasure boats in the Netherlands

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Biocidal antifouling paints</p> <p>Antifouling properties are based on emission of toxic copper compounds (current Dutch products).</p>	Yes, this is conventional paint.	<p>Suitable for DIY use.</p> <p>Has to be renewed every 1–3 years.</p> <p>Residue can be removed by sanding.</p>	<p>Performance is being assessed.</p> <p>Works also when boat is moored, but more effective when boat is in use.</p> <p>Can be used on all kinds of hulls, though some are not suitable for aluminium.</p>	<p>Can have a soluble or insoluble matrix.</p> <p>Can be abrasive or self-polishing.</p> <p>May also contain zinc compounds or other Substances of Concern.</p> <p>Can contain VOCs.</p>	<p>Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for intended users.</p> <p>If personal protective equipment is needed, the paint is not authorised for non-professionals.</p>	<p>Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for claimed application.</p> <p>Persistent compounds (heavy metals) are emitted into the water.</p> <p>Sanding the hull can spread dust.</p>	For pleasure boats, paints with lower copper (and zinc) concentrations are being developed to reduce environmental damage.

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Foul release coatings without biocides</p> <p>Antifouling properties are based on inhibition of attachment of organisms.</p>	<p>There are some products on the market, mainly meant for fast marine recreational and commercial craft.</p> <p>'Hard foul release coatings' seems to be a separate category.</p>	<p>3-component products have been marketed, but these are too complicated for DIY use.</p> <p>There are 1-component and 2-component DIY products.</p> <p>Not easy to get an even thickness everywhere due to transparency.</p> <p>Difficult to bond to a substrate. A sealer and a tie-coat are needed.</p> <p>Can be difficult to repair, but some are claimed to be easy to repair.</p> <p>Service life of 3–10 years is mentioned.</p>	<p>Ultra-smooth and slippery. This can create safety issues when boats are lifted.</p> <p>Can be rather soft and easily damaged, but there are products that claim to be 'hard foul release coatings'.</p> <p>Fouling detaches during use. A minimum speed of 8–15 knots is needed.</p> <p>Easy to clean, but some can be damaged when cleaned too vigorously.</p> <p>Some types of fouling can still adhere.</p> <p>Can be used on all kinds of hulls.</p>	<p>Based on silicones and/or fluoropolymers .</p> <p>Contains VOCs (about 2–20%). Binder can contain a high percentage of VOCs (up to 70%). Primer can contain zinc oxide or urea compounds.</p> <p>Organotin compounds can be used as a catalyst.</p>	<p>The production of fluoropolymers requires PFOA, which is a Substance of Very High Concern.</p> <p>VOCs require personal protective equipment, which is a problem for DIY use.</p>	<p>Silicone oils and organotin catalysts may leach into the water.</p> <p>It is suggested that the content of organotin compounds can be too high to serve as a catalyst and act as a biocide.</p> <p>Production of fluoropolymers requires PFOA (or comparable substances), a PBT substance that causes environmental damage.</p> <p>VOCs can be emitted to the air or captured during professional use.</p>	<p>Developments are focused on better antifouling performance, tougher materials, surface structures that reduce drag, and better suitability for DIY.</p> <p>Better products are being developed and introduced, such as 'amphiphilic' coatings and hydrogels.</p>

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Self-polishing biocide-free paints</p> <p>Antifouling properties due to continually releasing the upper layer of the coating.</p>	<p>Yes, this is conventional paint.</p>	<p>Suitable for DIY use.</p> <p>Has to be renewed every year.</p> <p>Paint residue can be removed with a high-pressure water cleaner.</p>	<p>Fouling detaches during boat use, provided a certain speed is reached.</p> <p>Will be damaged if cleaned too vigorously.</p> <p>Can be used on all kinds of hulls except aluminium.</p>	<p>Zinc oxide is a common ingredient.</p> <p>Can contain VOCs or in-can preservatives.</p>	<p>If contain VOCs, personal protective equipment is required, which is a problem for DIY use.</p>	<p>Emission to the environment is the working principle. Zinc is toxic to aquatic organisms.</p> <p>High-pressure cleaning of the hull can cause the spread of debris.</p> <p>VOCs can be emitted to the air.</p> <p>Sanding the hull can spread dust.</p>	<p>None found</p>

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Hard coatings</p> <p>No specific antifouling properties, but fouling can be easily removed.</p>	<p>There are products for freshwater craft and for larger marine commercial ships.</p> <p>This is a diverse category.</p>	<p>Some are suitable for DIY use.</p> <p>Depending on the specific product, longevity can be as little as 1 year or as much as 10 years or even the full service life of the boat.</p> <p>Some products can be removed with sufficient high-pressure water, but removal is not necessary. Easy to repair.</p>	<p>Some are extremely hard; some can be damaged.</p> <p>Coatings can also prevent corrosion.</p> <p>Cleaning is normally needed, but easy. Cleaning is not needed in very cold water/ice.</p> <p>There are specific products for all kinds of hulls. Some can be used directly on steel or aluminium or on an intact paint layer or polyester.</p>	<p>Can be epoxies, polyesters, vinyl esters or ceramic-epoxy. Can contain glass flakes. Can be a 'surface-treated composite'.</p> <p>Can be based on the element silicon (Si).</p> <p>Can contain > 50% VOCs.</p>	<p>VOCs require personal protective equipment, which is a problem for DIY use.</p>	<p>Nonylphenol and bisphenol A may leach into the water. It is unclear exactly which coatings produce such emissions.</p> <p>VOCs can be emitted to the air or captured during professional use.</p> <p>One product found: hull may be cleaned in the water in the USA and in the Netherlands.</p> <p>Sanding the hull can spread dust.</p>	<p>New coatings suitable for DIY use may be developed.</p> <p>There is renewed interest in washers/brushing stations. These can be combined with the use of hard coatings.</p>
<p>Structures for physical defence</p>	<p>Not yet on the market. Tests are being performed.</p>	<p>No information</p>	<p>No information</p>	<p>Can have the same basis as foul release coatings.</p>	<p>No information</p>	<p>No information</p>	<p>Research is ongoing.</p>

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Natural compounds used as biocides</p> <p>Antifouling properties are based on emission of toxic natural compounds.</p>	<p>Not clear if there are currently enzyme-based self-polishing products on the market.</p> <p>Field tests are being performed.</p>	<p>Self-polishing systems have to be renewed every year (or more).</p>	<p>No information; depends on the coating chosen.</p>	<p>Can be based on enzymes.</p> <p>Photochemical formation of hydrogen peroxides is mentioned.</p> <p>Can be based on chitosan.</p>	<p>Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for intended users.</p> <p>Natural composition is no guarantee of safety.</p>	<p>Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for claimed application.</p> <p>Naturalness is no guarantee of safety.</p>	<p>Research is ongoing, e.g. to keep the natural biocide inside the coating to avoid emission into the water.</p>
<p>Grease</p> <p>Antifouling properties are based on inhibition of attachment of organisms.</p>	<p>Yes, but for other purposes.</p>	<p>Suitable for DIY use.</p> <p>Has to be applied several times a year.</p>	<p>The hull becomes very slippery, which can create safety issues when boats are lifted.</p> <p>Seems not to be a practical option.</p>	<p>Can contain antibacterial compounds, such as triclosan.</p>	<p>In the case of antibacterial compounds, the BPR can come into force.</p>	<p>In the case of antibacterial compounds, the BPR can come into force.</p> <p>Triclosan is a suspected PBT substance.</p>	<p>None found</p>

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Films</p> <p>Antifouling properties are based on inhibition of attachment of organisms.</p> <p>The fibres resemble the spiky hairs used by organisms to combat fouling.</p>	<p>There are some products on the market or at the testing phase.</p>	<p><u>Film with fibres</u> Not suitable for DIY use, but application should not be too complicated. Should be easy to repair. Removal is possible with high-pressure hot water or with hot air. Longevity at least 5 years; 10 years or longer is expected.</p> <p><u>Film with a silicone top</u> See foul release coatings. Due to use as a film, the coating has an even thickness.</p>	<p><u>Film with fibres</u> Can be cleaned at the end of the season with high- or low-pressure water. It is not clear how easy cleaning would be.</p> <p>Material can get out of shape when lifted. Could be damaged along the quay.</p> <p>Can be used on all kinds of hulls, but corrosion protection is needed.</p> <p>Specific products for freshwater and seawater.</p> <p>More information on drag is needed. Drag problems for faster boats.</p>	<p><u>Film with fibres</u> Fibres made of nylon. Polyester film without PVC and softeners. Acrylic glue.</p> <p><u>Film with a silicone top</u> See foul release coatings.</p>	<p><u>Film with fibres</u> No information</p> <p>Professional use seems safe.</p> <p><u>Film with a silicone top</u> No information.</p> <p>Professional use seems safe.</p>	<p><u>Film with fibres</u> No information</p> <p>Micro plastics could enter the environment.</p> <p><u>Film with a silicone top</u> See foul release coatings.</p>	<p>Field tests are being performed.</p> <p><u>Film with fibres</u> There are still hydro dynamic questions. Developments aim to make the film suitable for fast boats.</p>

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
Electro-chemical Antifouling properties are based on emission of toxic ions.	Yes, but not for boat hulls.	No information	No information	Ions (copper, chloride, hydrogen) can be generated.	Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for intended users.	Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for claimed application.	None found
Ultrasound Vibration can cause cavitation bubbles, also other working principles, unknown to us.	In recent years, a number of systems have entered the market.	Not suitable for DIY use. Accurate placement is very important.	System should always be active. Suitable for all hull types except wood and hulls with a foam layer inside.	No information Can be combined with a foul release or a hard coating.	No information No human safety issues found.	Ultrasonic waves can kill water fleas, but it is not clear if this would happen in practice. More information is needed.	There have been ineffective systems on the market. Producers are focusing on enhancing and proving performance. Some producers have many positive testimonials.
UV light Antifouling action due to causing DNA damage.	Not yet on the market for boat hulls. Tests are being performed.	No information	Performance seems to be very good.	Depends on the coating chosen. Can be based on silicones.	Underwater application is expected to be safe for humans.	More information on environmental safety is needed.	A possible development is a system composed of tiles.

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Cleaning/ Brushing</p> <p>Removing fouling mechanically</p>	Yes, e.g. with high-pressure cleaners, with a brush or sponge, in washers/ brushing stations, or with a cleaning robot.	Yes	Care needed with self-polishing paints or softer foul release coatings.	No information	Considered safe	<p>Washers/ brushing stations have been assessed as environmentally friendly in Sweden. Coatings should be hard enough not to get damaged.</p> <p>When cleaning the hull in the water, the risk of spreading invasive species must be taken into account.</p>	Washers/ brushing stations are attracting renewed attention in Sweden and is being introduced to the Netherlands.
<p>Storage out of the water</p> <p>Fouling dies out of the water.</p>	Several types of boatlifts can be bought.	No information	Systems require space in and under the water.	No information	Considered safe	Seems environmental friendly.	We did not search for developments.

Type	Commercial availability	Suitability for DIY application and maintenance	Remarks on use	Composition	Human safety	Environmental safety	Research & developments
<p>Slip liners</p> <p>Fouling dies due to chlorination of the water inside the closed 'dock'.</p>	<p>In the United States.</p>	<p>No information</p>	<p>Chlorine must be added to the 'dock'.</p>	<p>Fouling is prevented by chlorination of the water.</p>	<p>Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for intended users.</p>	<p>Authorisation is required under the BPR. Risks are being assessed. Safety must be shown for claimed application.</p>	<p>None found</p> <p>It is questionable that this application would be authorised under the BPR.</p>

Biocidal antifouling and self-polishing paints

Biocidal antifouling and self-polishing paints are suitable for DIY. The working principle of biocidal antifouling and self-polishing paints is the emission of copper, zinc and other substances to the aquatic environment. These paints must be renewed every one or two years and the spread of dust and/or paint particles during removal by sanding or high-pressure cleaning is hard to prevent. During application, VOCs can be emitted to the air and users can be exposed to these unless using personal protection. Copper and zinc are not degradable and their release from antifouling paints contributes to their accumulation in the environment. Biocidal antifouling paints sold in the EU have the advantage that the risks have been assessed and ingredients are (confidentially) disclosed to the competent authority. However, biocides are toxic to organisms by definition.

Foul release coatings without biocides

Foul release coatings are advertised as environmentally friendly, but still there are questions. Are organotin catalysts in some cases added in too high concentrations and do they therefore act as biocides? Can fluoropolymers be produced without spreading carcinogenic and PBT-classified substances like PFOA into the environment? Is renewal after three years necessary due to leaching of silicone oils into the environment? When coatings are sold as suitable for DIY use, can human risks be eliminated if binders with a high percentage of VOCs, which are classified as CMR substances, are used?

Two of the SMEs we interviewed claim to produce 'hard foul release coatings' that are tougher than ordinary silicone coatings, have a longer life (5–7 years or even more), and are suitable for DIY use. These coatings seem to have less environmental impact than some other foul release coatings. However, their composition is only partly disclosed by the obligatory MSDS, which makes it difficult to fully assess the human and environmental risks. Besides, when assessing the risks of an antifouling system, the complete coating system should be taken into account, including necessary binders and primers, which is a gap in the alternatives assessment so far.

Ultrasound systems

Ultrasound systems can be combined with hard or foul release coatings. The current systems do not seem to send ultrasonic waves far from the hull, so the impact on the environment could be limited, but we have yet to find scientific evidence of that. We have also yet to find scientific literature on the effectiveness of such systems on boats, although producers give positive testimonials to that effect.

Hard coatings

Hard coatings are a diverse category. Hard coatings can be ordinary paints sold for DIY use, which must be renewed every one or two years. Some other hard coatings can have a very long service life (even the full service life of the boat) and some can also provide corrosion protection. However, these coatings are not suitable for DIY application. Some coatings contain a high percentage of VOCs. When applied by professionals in a controlled situation, human health risks can be mitigated by personal protective equipment and VOCs can be captured

before entering the environment. Consequently, the fact that a coating is not suitable for DIY can be seen as an advantage, but most likely not from the consumer's point of view. One study showed leaching of nonylphenol and bisphenol A into the water. It is unclear exactly which types of hard coatings produce such emissions. As with foul release coatings, the composition of hard coatings is only partly disclosed by the obligatory MSDS, which makes it difficult to fully assess the human and environmental risks.

Cleaning/brushing

There are many options to remove fouling mechanically, e.g. with high-pressure cleaners, with a brush or sponge, in washers/ brushing stations, or with a cleaning robot. Hard coatings need to be periodically cleaned, but the fouling can be easily removed. Some other coatings also can need cleaning. Cleaning in the water is an option and we found a product for which this is allowed in the USA and in the Netherlands. The Drive-in Boatwash could be a promising development to enable easy cleaning. In Sweden these washer/brushing stations are attracting renewed attention and they have been recently introduced to the Netherlands. It should be assessed whether the tougher foul release coatings mentioned above and the films with fibres mentioned below can also be effectively and safely cleaned in this way.

Films

Films with nylon fibres were recently introduced to the Dutch market and seem to be environmentally safe. However, scientific evidence of their limited impact on the environment is missing. Another product on the market is a film with a silicone top. An advantage of this is that professionals can produce it in a controlled situation. Applying a liquid coating directly on the boat is no longer necessary. This reduces the risk of non-professionals failing to use the necessary personal protection equipment. It also makes it easier to create a layer of an even thickness. For this kind of film the same questions on environmental risks as for foul release coatings apply.

Other possible future antifouling systems

UV light, structures for physical defence and natural, readily degradable biocides that stay inside the coating could be safer options, but these are still rather far from the market stage for pleasure boats.

6 Overview of the current Dutch market situation

6.1 Antifouling systems in use for pleasure boats

Although the number of interviews was limited (see Chapter 4), the broad knowledge of the interviewees and the overlap in viewpoints allowed us to create an overview of the antifouling systems currently in use in the Netherlands. Today, biocidal antifouling paints and self-polishing biocide-free paints are the most common solutions to hull fouling. There are some non-biocidal foul release coatings on the market, mainly intended for fast marine pleasure boats. Some foul release products have been available only for a short time and development is ongoing. The aim is to improve performance and produce tougher materials and surface structures that reduce drag and are more suitable for DIY application. Ultrasound systems entered the market for pleasure boats a couple of years ago, but mainly in foreign countries. In the Netherlands there are still questions over the performance of these systems, and producers are working to prove and improve their performance. Hard coatings include 'ordinary paints'. Other hard coatings focus on bigger marine commercial ships and seem not really to have entered the market for pleasure boats in the Netherlands yet. Recently, a film with nylon fibres intended for pleasure boats entered the Dutch market.

In the first half of 2018 Milieu Centraal, in cooperation with Varen doe je samen, Waterrecreatie Nederland and HISWA, produced a questionnaire on the use of antifouling systems by boat owners (Milieu Centraal, 2018). The results are not representative, but according to the report with a 'healthy volunteer bias'. Most of the respondents (89%) owned a boat with a cabin (49% a sailing boat and 40% a motorboat). Compared with the overall situation in the Netherlands (500.000 recreational vessels of which 250.000 have a cabin), boats with a cabin are over represented in this survey. There were 431 respondents, of whom 36% used a copper-based self-polishing paint, 27% a hard copper-based paint and 17% a self-polishing paint. In total, 80% of respondents used a copper-based and/or self-polishing paint. Of the other respondents, 8% used a general underwater paint, 4% used a hard coating, 3% stored their boat out of the water and 2% used a foul release coating. Only two respondents used an ultrasound system and one a 'foil or wrap'.

6.2 Factors that influence acceptance

Although human and environmental safety may be important for boat owners, cost-effectiveness, market availability and ease of use are perhaps even more important for acceptance of alternatives. A recent survey showed that a large proportion of Dutch consumers are willing to adapt their behaviour to reduce environmental impact (Hofstede, 2017). More than half of respondents stated that they were willing to consider buying sustainable products, mainly in order to reduce environmental impact. Nevertheless, price and service life are also important in deciding which product to buy, particularly for younger people. When a sustainable product is more expensive, about 70% will choose the conventional alternative, and a price premium of 12% is the maximum consumers are willing to pay for a sustainable product. Although the

survey was specifically focused on consumer goods in general, the results may give some idea of the general willingness of consumers to 'invest' in alternatives with less environmental impact. It shows that cost and quality are likely to be the determining factors in any attempt to change consumer use of antifouling systems. The recommendations of the BONUS CHANGE project indicate that 'soft' positive action to convince consumers may not be sufficient to induce such a change. Legal instruments and investments in infrastructure are seen as essential to achieve the goal of a biocide-free environment.

6.3 Market situation and innovation from a producer's perspective

This section, which is mainly based on the interviews, presents the views of representatives of multinationals in the coating and paint industry, as well as some 'green' SMEs, as these are considered key stakeholders in the development and use of safer antifouling systems.

Both multinationals and SMEs hope that the highly toxic products that are still in use – i.e. those with a high content of TBT or a very high copper concentration – will soon be banned. These paints are still offered and seem to be used in environments where fouling is very severe.

Most of the biocidal antifouling paints and self-polishing paints sold in the Netherlands are produced by multinationals. These paints wear off and/or their biocidal function decreases so that the paint has to be re-applied every 1–3 years. This makes production a profitable business. Consumers of antifouling systems are said to be conservative. They generally stick to the system they know and that works. But some SMEs see a favourable trend towards greater interest in solutions with less environmental impact. Due to the current economic situation, there are now people that can afford to 'invest' in something new.

The main producers of biocidal antifouling paints are developing alternatives with less environmental impact. They seem to realise that today's biocidal and self-polishing paints will not continue to be marketable for ever, because of their environmental burden. The current pressure of legislation on biocidal paints for pleasure boats may also be supporting innovation. In the Netherlands, biocidal paints for pleasure boats have to meet the authorisation criteria for both freshwater and seawater, even when a boat is used only at sea. According to the recommendations of the BONUS CHANGE project, the BPR is seen as an instrument for promoting a transition to biocide-free alternatives in the Baltic Sea region.

Some multinationals market a foul release coating especially for fast boats, but these products are not suitable for boats that are moored 90% of the time. Moreover, their focus for the consumer market is on DIY products, and because earlier silicone-based products proved to be too complicated for DIY application, they disappeared from the market after a few years. Some multinationals are now introducing one-component silicone paints, based on either fluoropolymers or silicone elastomers. However, in our interviews, the SMEs mentioned

disadvantages and possible risks of some silicone and fluoropolymer foul release coatings, such as the use of organotin catalysts.

The SMEs we interviewed are therefore focusing on systems with zero emissions to water. Biocidal paints and self-polishing paints will inevitably enter the environment and, typically, the SMEs stated that they do not want to support 'the poisoning of water'. The focus of the interviewed SMEs is on 'hard foul release coatings', (very) hard coatings with a long service life, films with fibres, and ultrasonic systems. Hard coatings may foul if the boats are moored for long periods. Easy ways to clean hard coatings and films with fibres are needed to increase market acceptance of these systems. Some SMEs are exploring combinations of 'hard foul release coatings' and ultrasonic systems to prevent the initial biofilm from forming. In the Netherlands, ineffective ultrasonic systems were put on the market in the past. The phrase 'these systems do not work' is still heard, although producers have positive testimonials. Producers are now focusing on enhancing and proving their performance.

Innovation budgets are an issue. Developments mainly focus on antifouling systems for commercial ships, because this is a bigger market. These innovations might, however, be useful for pleasure boats. Multinationals have budgets for innovation, because of a large market volume. A company like AkzoNobel is working, jointly with Philips, on the use of UV light for antifouling purposes (see Section 5.4.7) and is said to be interested in whether natural biocidal substances have a better risk profile than those currently in use. They are also working on 'riblets technology', to reduce drag. SMEs are also trying to develop innovative products, but a challenge for them is the long period of testing required before a product can be launched. Innovation, for them, is possible only with money from other sources.

7 Conclusions and recommendations

7.1 Conclusions

Biocidal antifouling and self-polishing paints are a relevant source of emissions of toxic substances such as copper and zinc into the aquatic environment. Given the long-term goal of a non-toxic environment and the principle of the Safe-by-Design concept, there is a policy preference to move to alternative, safer antifouling systems.

This overview shows that a variety of alternative antifouling systems are available for pleasure boats. A number of these are expected to be safer than biocidal self-polishing paints. These are:

- 'hard foul release coatings';
- other hard coatings;
- easy cleaning systems;
- films with fibres;
- ultrasound systems;
- storage out of the water.

Other promising alternative antifouling systems are still at a development stage, such as UV light and natural, readily degradable biocides that stay inside the coating.

Of the Dutch boat owners that have been surveyed, 80% still use a copper-based and/or self-polishing paint. All alternatives face challenges to market acceptance. Consumers seem to be conservative and generally keep using the system they know. To persuade consumers to change, clear and independent proof of the good performance and safety of the alternative systems is needed. Note that we did not investigate costs, although this is an important factor for consumers.

7.2 Recommendations for alternatives assessments

To identify safer antifouling systems we recommend performing an alternatives assessment of existing specific promising products following the Safe-by-Design approach. Such a testing programme might fit within existing European Research and Development programmes or Dutch innovation policy.

This alternatives assessment should have a broad scope, taking into account:

- user needs (such as suitability for a boat's normal sailing speed, ease of cleaning and repair, suitability for DIY application and maintenance, and suitability for the material of the hull);
- availability on the market;
- longevity of the system;
- yearly costs based on longevity;
- antifouling performance;
- human safety;
- environmental safety.

When comparing the human and environmental risks of antifouling systems, the whole coating system should be taken into account, including necessary binders, primers and glues. The assessment should focus not only on the risks during use, but also on the risks during production, application, maintenance, repair and removal.

We recommend focusing future alternatives assessments on promising safer antifouling systems. This overview shows that there are still questions over the safety and environmental impact of several alternatives.

Important questions are:

- What substances leach out from (hard) foul release coatings, other hard coatings, films with fibres and films with a silicone top (looking at the complete coating system) and in what amounts?
- Are known toxic substances, such as organotin compounds, used in the coating?
- Which VOCs in what amounts are emitted when applying the complete coating system, and is application safe for non-professionals and the environment?
- Can fluoropolymers be produced safely and without emitting persistent toxic substances into the environment?
- Do ultrasonic systems affect other organisms than the fouling on the hull?
- Are cleaning systems in combination with different types of coatings safe for the environment?

Answers to these questions are needed, in order to prevent products from entering the market that are less safe than the current ones. One problem to be tackled is that the composition of coatings is only partly disclosed.

A standardised test of antifouling performance should be used to compare products. The focus should not only be on how rapidly fouling appears, but also on how easily it can be removed. Different types of antifouling systems require a different type of test. For example, ultrasound systems cannot be tested on panels and foul release coatings do not work properly on static panels.

How easy a coating can be damaged, is also an important factor for consumers when choosing a product. A standardised test of durability designed for this purpose would help in comparing products. The same applies to the ease of cleaning the coating. Possible effects of cleaning of the coating to the environment and on the coating itself should be included.

7.3 Other recommendations

We recommend making the differences between all the available antifouling systems more evident to owners/users, retailers and builders of pleasure boats. One way of doing so is to 'rate' specific products on safety and performance based on the results of the above-mentioned alternatives assessment.

As stated in the BONUS CHANGE project regarding the Baltic Sea, legal instruments and investments in infrastructure are seen as essential to achieving the goal of a biocide-free environment. We recommend investigating legislative and political means of decreasing the use of biocidal and /or self-polishing paints and other coatings with 'Substances of Concern' (SoCs). These could include:

- legislation to decrease the content of substances like copper and zinc and/or SoCs in antifouling and/or self-polishing paints. For some components substitution might be an option.
- legislation to decrease emissions of and/or exposure to VOCs when coatings are applied;
- improved regulation of maintenance and repair procedures and enforcement of these could prevent environmental loading;
- investments in infrastructure for the easy cleaning of boats, using non-biocidal and non-self-polishing coatings or films.

It seems that producers are trying to make products suitable for DIY use, because the current market requires this. However, systems that are not suitable for DIY use can be safer, because activities like applying and repairing coatings can be better controlled when performed by professionals. We therefore recommend investigating whether users really need products that they can apply themselves or whether they will accept professional systems with a long service life that have to be cleaned periodically.

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Annex 1. Groups of biocidal antifouling paints

According to the OECD Emission Scenario Document on antifouling products (OECD, 2005), biocidal antifouling paints can be divided into four main categories, based on the type of matrix (Figure A1).

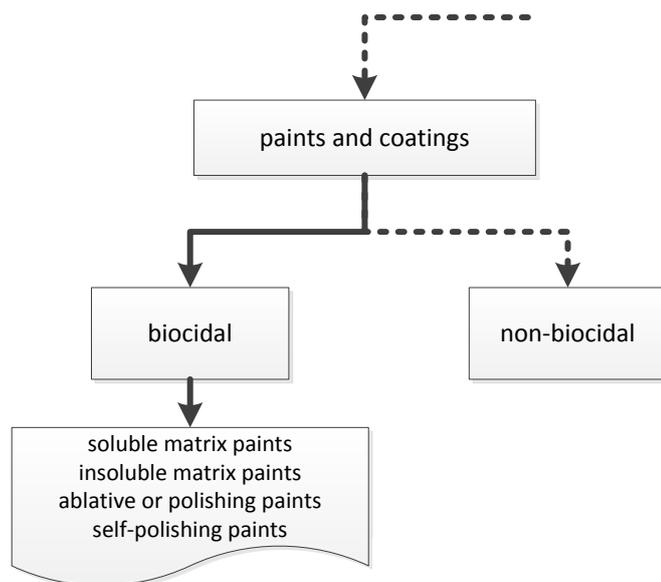


Figure A1. Categories of biocidal antifouling paints

Sources: EC (2004), (Nurioglu et al., 2015; Takahashi, 2009).

Soluble matrix

Soluble matrix coatings are based on a natural resin (rosin) and both the binder and the biocide gradually dissolved in the water. These paints are sometimes also referred to as conventional or classical antifouling paints (Berendsen, 1989), although other authors seem to use this term for insoluble matrix paints as well (Takahashi, 2009). Soluble matrix paints are susceptible to cracking and cannot be used on boats that are out of the water for long periods. Because of this, the service life of these paints tends to be shorter than that of other categories of paints (Berendsen, 1989).

Insoluble matrix

Insoluble matrix coatings, also referred to as contact leaching coatings, contain a polymer matrix that consists of insoluble and semi-soluble binders. The insoluble matrix often comprises chlorinated rubber or vinyl resin. These paints are resistant to mechanical pressure, oxidation and photodegradation. High concentrations of copper(I) oxide and booster biocides are physically dispersed in the matrix. When newly immersed in seawater, the free associated biocides and the soluble binder diffuse out of the matrix, leaving behind an empty 'skeleton' of the insoluble binder (Berendsen, 1989). Eventually, the remaining biocides have to diffuse through such a thick leached layer that the rate of release becomes too low to prevent fouling (Nurioglu et al., 2015; Takahashi, 2009). The service life of commercially available insoluble matrix paints

is reported as up to two years, but products for pleasure boats are advertised as offering protection for one 'season' only. The advantage of hard coatings is that they can be polished to obtain a very smooth surface, which is an advantage for fast boats. They are also resistant to dry conditions and can be scrubbed^{63,64}.

Ablative or polishing paints

As with soluble matrix paints, the matrix of ablative/hydration antifouling paints disappears over time, but this process is driven by hydrolysis rather than dissolution⁶⁵. These paints typically have a lifetime of 1.5–2 years, but they have the major disadvantage of having poor film characteristics, especially after dry-out (Takahashi, 2009).

Self-polishing paints

The release behaviour of biocides from self-polishing copolymer (SPC) anti-fouling paints differs from their release from insoluble and ablative paints. Most of the current TBT-free SPCs are acrylic copolymers. The immersed binder degrades by hydrolysis. The erosion proceeds in a controlled way, roughly linear with time, leaving a smooth underwater hull. Because no leached matrix remains, there is continuous availability of fresh biocide (Berendsen, 1989). Self-polishing paints are appropriate for moderately fast boats. Because the layer wears down during use, it needs to be reapplied regularly. Residue can be removed using a high-pressure water cleaner.

Some products are claimed to erode extremely slow, which implies that they do not need to be reapplied yearly. According to one reference, the normal lifetime of SPC antifouling paints is 3–5 years (Takahashi, 2009), but most product labels for self-polishing paints authorised for freshwater use in the Netherland claim protection against fouling for one season only⁶⁶.

Many self-polishing antifouling paints contain copper as an active ingredient and are thus subject to authorisation (see Section 3.2.33.2.1), but there are also biocide-free self-polishing coatings (see Section 4.2.2). Current research is directed towards the replacement of metal pigments by natural components, such as starch and starch-degrading enzymes (Olsen et al., 2010); see Section 4.3.24.1 for further information.

It should be noted that the classification of biocidal antifouling paints is confusing. Instead of the different types shown in Figure A1, some authors (Brooks & Waldock, 2009; Cao et al., 2011) distinguish only two general categories of TBT-free antifouling paints:

- controlled depletion paints (CDP), which are an upgrade of the traditional soluble matrix paints using modern resins, exposing fresh biocidal surface at a more controlled rate; and
- tin-free self-polishing copolymers (SPC), which function in a similar way to the former TBT paints, with mostly acrylic

⁶³ <http://coating.nl/antifouling-coating/>

⁶⁴ <http://www.yachtpaint.com/>

⁶⁵ Berendsen seems to use the term 'ablative paints' for self-polishing paints

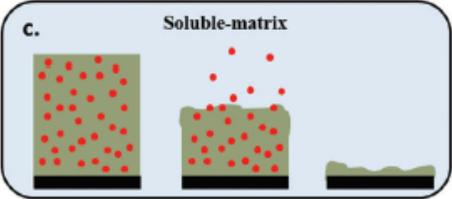
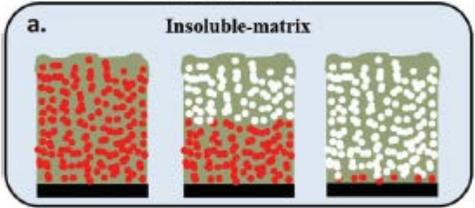
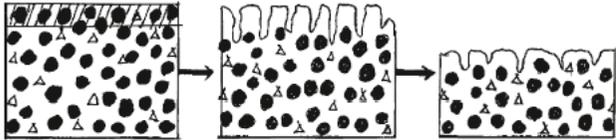
⁶⁶ <http://www.yachtpaint.com/nld/diy/producten/antifouling/zoek.aspx>

copolymer matrices, non-tin metals such as copper and zinc, and silicon (Si).

Table A1 provides an overview of biocidal antifouling paints based on the classification given in Figure A1.

Table A1. Overview of biocidal antifouling paints based on the classification shown in Figure A1

Note: TBT-containing self-polishing paints are included in the OECD table (see below), but are not mentioned here. Sources: OECD (2005: table 1.1), Takahashi (2009), Nurioglu et al. (2015).

Biocidal paints	Characteristics	Field of use
<p>Soluble matrix type</p> 	<ul style="list-style-type: none"> • The biocides are not bound in the matrix and diffuse through the paint layer to the water • Exponentially decreased release rate of the biocide (high initial release rate but eventual release rate too slow to prevent fouling) • The binding compound of the matrix dissolves slowly in water • Time after which the paint layer has to be renewed depends on the biocide used • Often need not be removed before next application on pleasure boats 	<ul style="list-style-type: none"> • Seawater • Freshwater (with copper as the most important active ingredient) • Pleasure boats.
<p>Insoluble matrix type</p> 	<ul style="list-style-type: none"> • Same characteristics as the soluble matrix type, except that the binding compound of the matrix does not dissolve in water • Needs to be removed before next application 	<ul style="list-style-type: none"> • Seawater • Freshwater (with copper as the most important active ingredient) • Pleasure boats
<p>Ablative or polishing paints</p> 	<ul style="list-style-type: none"> • Has the same leaching characteristics as the soluble and insoluble matrix types, except that this paint erodes by hydrolysis. This increases emissions due to diffusion, because of the shorter diffusion path • Usually need not be removed before next application on pleasure boats 	<ul style="list-style-type: none"> • Seawater • Freshwater (with copper as the most important active ingredient) • Fast motor boats and racing sailing boats.
<p>Self-polishing paints</p> 	<ul style="list-style-type: none"> • Acrylic co-polymers • Hydrolysable units lead to a progressive degradation of immersed binder and to initiation and control of erosion rate • Usually need not be removed before next application on pleasure boats 	<ul style="list-style-type: none"> • All kinds of boats

Annex 2. Authorised antifouling paints and coatings in the Netherlands

Table A2. Authorised antifouling paints and coatings in the Netherlands

Notes: P = professional use, NP = non-professional use (rows marked in yellow). Pleasure boats include boats sailing in freshwater and seawater. Marine vessels are commercial and military ships and include yachts > 24 m. Products authorised for these vessels may not be applied to boats used in freshwater. Freshwater vessels include commercial and recreational boats.

Source: Biocide PT21 category, www.ctgb.nl/toelatingen; accessed 16 May 2018.

Name	Registration number	Expiration date	Use	Ship type	Active substances
Altura 619	13535	1-12-2021	P	Marine ships	dicopper oxide
Antifouling Plus	15606	1-8-2021	P & NP	Recreational craft	dicopper oxide
Corsa 642	13554	1-1-2022	P	Marine ships	copper thiocyanat zinc pyrithione
Cruiser One	14532	1-8-2021	P & NP	Recreational craft	dicopper oxide
Cupron Plus	13536	1-12-2021	P & NP	Marine and freshwater ships	dicopper oxide
Ecoloflex SPC 100	14069	1-12-2020	P	Marine ships	dicopper oxide zinc pyrithione
Ecoloflex SPC 200	13400	1-12-2020	P	Marine ships	dicopper oxide zinc pyrithione
Ecoloflex SPC 600	13252	1-10-2019	P	Marine ships	dicopper oxide zinc pyrithione
Epifanes Copper-Cruise	14301	1-12-2021	P & NP	Marine and freshwater ships	dicopper oxide
Guardia	14388	1-12-2021	P & NP	Marine and freshwater ships	dicopper oxide
Hempel's Hard Racing Xtra 7666C	15529	1-8-2021	P & NP	Recreational craft	dicopper oxide
Hempel's Mille NCT 7173C	15528	1-8-2021	P & NP	Recreational craft	dicopper oxide
HEMPEL'S ANTIFOULING GLOBIC 9000 78902	15500	1-12-2027	P	Marine ships	dicopper oxide zinc pyrithione
Hempel's Antifouling Globic 9000 78952	14319	1-1-2024	P	Marine ships	dicopper oxide zinc pyrithione
Hempel's antifouling OLYMPIC 86951	13251	1-10-2019	P	Marine ships	dicopper oxide

Name	Registration number	Expiration date	Use	Ship type	Active substances
HEMPEL'S CLASSIC 71220	15010	1-8-2021	P & NP	Marine ships and recreational craft	dicopper oxide
Hempel's Mille NCT 7174C	15534	1-8-2021	P & NP	Recreational craft	copper thiocyanate
Hempel's Mille Xtra 7166C	15525	1-8-2021	P & NP	Recreational craft	dicopper oxide
Intercept 7000	14598	3-10-2024	P	Marine ships	dicopper oxide copper pyrrithione
Intercept 8000 LPP	14608	3-10-2024	P	Marine ships	dicopper oxide copper pyrrithione
Intersmooth 360 SPC	12601	9-9-9999	P	Marine ships	dicopper oxide zinc pyrrithione
Intersmooth 7460HS	13398	3-12-2020	P	Marine ships	dicopper oxide copper pyrrithione
Intersmooth 7465Si SPC	14223	1-1-2024	P	Marine ships	dicopper oxide copper pyrrithione
Interspeed 340	11858	1-11-2025	P	Marine ships	dicopper oxide zineb
Interspeed 6200	14299	1-1-2024	P	Marine ships	dicopper oxide zineb
Interspeed Extra	14533	1-8-2021	P & NP	Recreational craft	dicopper oxide zineb
Interswift 6600	14506	1-8-2024	P	Marine ships	dicopper oxide
Interswift 6800HS	13454	1-5-2021	P	Marine ships	dicopper oxide copper pyrrithione
Megayacht Imperial Antifouling	13163	1-1-2021	P	Marine ships	dicopper oxide copper pyrrithione
Micron	12842	1-11-2025	P	Marine ships	dicopper oxide zineb
Micron 99	15174	1-10-2026	P	Marine ships	dicopper oxide copper pyrrithione
Micron LZ	15401	1-8-2021	P & NP	Recreational craft	dicopper oxide
MICRON OPTIMA	13195	1-6-2019	P	Marine ships	dicopper oxide zinc pyrrithione
Nautical Antifouling	14646	1-8-2021	P & NP	Recreational craft	dicopper oxide
Nelfamar Cuprum-45	13641	1-5-2024	P	Marine ships	dicopper oxide
SCIROCCO NL	15027	1-12-2021	P & NP	Marine and freshwater ships	dicopper oxide

Name	Registration number	Expiration date	Use	Ship type	Active substances
Sea Grandprix 1000 L	15507	1-12-2027	P	Marine ships	dicopper oxide copper pyrithione
Sea Grandprix 2000	15512	1-12-2027	P	Marine ships	dicopper oxide copper pyrithione
Sea Grandprix 500	13090	1-7-2018	P	Marine ships	dicopper oxide copper pyrithione DCOIT
Sea Grandprix 660 HS	15513	1-12-2027	P	Marine ships	dicopper oxide DCOIT
Sea Grandprix Mark II	15506	1-12-2027	P	Marine ships	dicopper oxide copper pyrithione
SeaForce 90 (Spl)	13086	1-1-2021	P	Marine ships	dicopper oxide copper pyrithione
Seajet 023 Teichi	15006	1-12-2021	P & NP	Marine and freshwater ships	dicopper oxide
SeaQuantum Classic S	13084	1-1-2021	P	Marine ships	dicopper oxide copper pyrithione
SeaQuantum Plus S	13085	1-1-2021	P	Marine ships	dicopper oxide copper pyrithione
SeaQuantum Ultra S	13083	1-1-2021	P	Marine ships	dicopper oxide copper pyrithione
SEATENDER 10	12029	1-5-2024	P	Marine ships	dicopper oxide
Sigma Ecofleet 290 A	13412	1-2-2021	P	Marine ships	dicopper oxide DCOIT
Sigma Ecofleet 530	12985	1-9-2027	P	Marine ships	dicopper oxide DCOIT
Transocean Cleanship Antifouling 92.90	12578	1-5-2024	P	Marine ships	dicopper oxide
Trilux 33	15061	1-3-2026	P	Marine ships	copper thiocyanate zinc pyrithione
Uni-Pro 225	15568	1-8-2021	P & NP	Recreational craft	dicopper oxide

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