Review

Biofouling: lessons from nature

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Biofouling is generally undesirable for many applications. An overview of the medical, marine and industrial fields susceptible to fouling is presented. Two types of fouling include biofouling from organism colonization and inorganic fouling from non-living particles. Nature offers many solutions to control fouling through various physical and chemical control mechanisms. Examples include low drag, low adhesion, wettability (water repellency and attraction), microtexture, grooming, sloughing, various miscellaneous behaviours and chemical secretions. A survey of nature's flora and fauna was taken in order to discover new antifouling methods that could be mimicked for engineering applications. Antifouling methods currently employed, ranging from coatings to cleaning techniques, are described. New antifouling methods will presumably incorporate a combination of physical and chemical controls.

Keywords: biomimetics; biofouling; biofilm; antifouling; self-cleaning

1. Introduction

Inspired by the ingenious designs found throughout nature, researchers are reverse engineering the world's flora and fauna to solve technical challenges. Much attention is given to nature's structures, materials and surfaces in order to apply them to commercial applications. Copying nature's designs is called biomimicry or biological mimicking. Nature efficiently uses resources and incorporates novel methods to solve problems. In biomimicry, the goal is to understand lessons from nature and apply them in engineering applications. Several engineering designs are a direct result of biomimetic research. Examples include submarines inspired by the low drag shape of dolphins, 'self-cleaning' windows inspired by the superhydrophobic lotus leaf and wall-climbing robots inspired by adhesive gecko feet [1–8].

One engineering challenge solved in nature, but plaguing a variety of industries, is biological fouling, commonly referred to as biofouling. This is the accumulation of unwanted biological matter on surfaces, with biofilms created by

micro-organisms and macroscale biofouling (simply called macrofouling) created by macro-organisms. In addition to biofouling, inorganic fouling is composed of deposits from corrosion, crystallization, suspended particles, oil and ice. The term fouling describes both biofouling and inorganic fouling. The type and extent of fouling depend on the local environment, inorganic deposits and organisms; this varies significantly between medical, marine and industrial applications. In general, medical biofouling includes only the biofilm, whereas marine and industrial biofouling generally include a combination of biofilm, macrofouling and inorganic fouling [9–13].

Biofouling morphology is characterized by the thickness, density, structure, composition, bioadhesive strength and weight of fouling organisms. As biofouling ranges from micro-organisms to macro-organisms, a variety of measurement techniques are necessary to record the properties. Such properties are measured with weight scales as well as light, transmission electron, scanning electron (SEM), atomic force and fluorescence microscopy techniques [13–18].

For humans, biofouling poses significant health risks and financial losses in the medical, marine and industrial fields. Medical biofouling occurs in areas such as prosthetic implants, biosensors, catheters, dental implants and medical equipment. Problems include implant rejection, malfunction of biosensors and spread of infectious diseases [17,19–21]. Biofouling is commonly associated with marine environments where noticeable aquatic growth appears on ships and underwater structures. This increases ship hull drag, corrosion, fuel consumption and engine stress [9,12,22–24]. Industrial fouling occurs in areas such as power plants, water-treatment systems and food/beverage industries. Problems include pipe blockage, decreased membrane flux, contaminated water and reduced heat-exchanger efficiency [11,17,25].

Looking at nature for antifouling lessons reveals several examples of both physical and chemical control methods, and a combination thereof [3,8]. Physical controls include low drag, low adhesion, wettability, microtexture, grooming, sloughing and various miscellaneous behaviours; and chemical controls include various secretions. Fouling is both prevented and removed with the aforementioned physical and chemical controls. In an ambient environment, plants and insects employ these controls; and in the marine environment, plants, corals and fish employ them. Specific antifouling examples range from the lotus leaf [26–30] to shark skin [31–34].

Controlling biofouling is accomplished through a variety of ways in medical, marine and industrial applications. Common controls exist, such as low-drag and low-adhesion surfaces that reduce biofouling. In fluid flow, a low-drag surface will promote removal (washing away) of micro-organisms, while low-adhesion surfaces prevent micro-organism colonization through reduced adhesive strength. Furthermore, improving biocompatibility will reduce medical biofouling, as foulers will not target the implanted device [35–37].

Figure 1 shows an overview of this paper focusing on antifouling lessons from nature. To understand the importance of fouling, a review of fields susceptible to biofouling is included, with medical, marine and industrial examples. The relevant types of fouling are addressed with a description of biofouling and inorganic fouling. Biomimetics addresses the importance of surface textures and chemistries that influence the antifouling properties. A description of flora and fauna that exhibit antifouling properties are mentioned, along with the mechanisms at work.
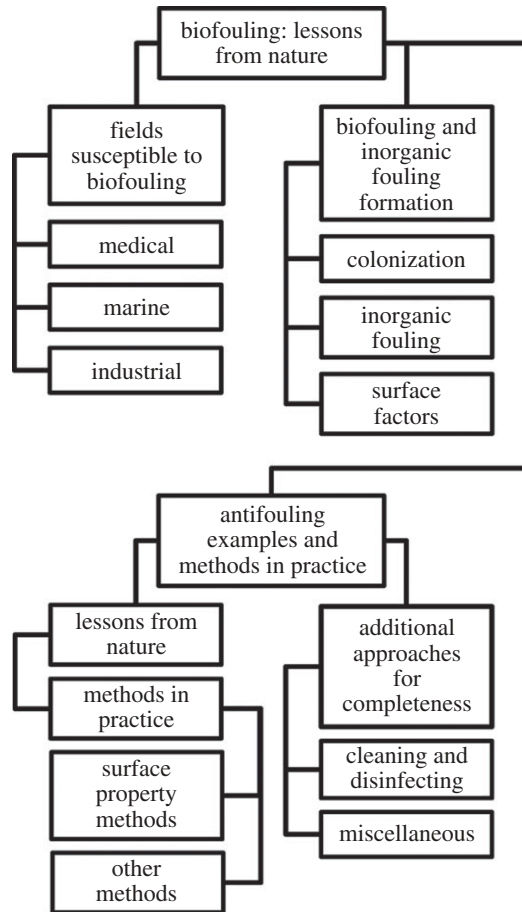
Figure 1. Overview of fields susceptible to biofouling, description of the fouling formation process and current antifouling strategies.

Current antifouling methods in practice are described, including surface textures, coatings, cleaning methods and experimental techniques. An outlook on new research of bioinspired antifouling surfaces is also presented.

2. Fields susceptible to biofouling

Fouling is prevalent in medical, marine and industrial fields, causing significant problems related to health risks, environmental impact and financial losses [11–13,19]. Table 1 outlines many examples in susceptible fields. Specific examples of biofouling hazards are described, along with the need for improved control methods.

(*a*) *Medical*

Areas susceptible to biofilm infection are shown in figure 2, highlighting catheter contamination, implant contamination and gum disease [17,19–21,52].

Table 1. Fields susceptible to biofouling, including common examples.

type	problems	source
medical		
orthopaedic implant	removal owing to infection	Smeltzer *et al.* [38]
respirator	ventilator-associated pneumonia	Thomas *et al.* [39]
contact lens	eye infection	Banerjee *et al.* [40]
catheter	urinary tract infections	O'May *et al.* [41]
haemodialysis	infectious break-outs	Pasmore & Marion [42]
teeth/dental implant	periodontal disease, gingivitis	Armellini *et al.* [43]
biosensor	failure from fibrous encapsulation	Yeh *et al.* [44]
marine		
ship hull	increased fuel consumption	Dobretsov [45]
ship engine	increased stress from extra drag	Jones [46]
marine platform	increased marine structure load/stress/fatigue	Jones [46]
metal	increased biocorrosion	Lebret *et al.* [47]
industrial		
membrane	reduced flux	Pangarkar *et al.* [48]
heat exchanger	reduced convection efficiency	Lebret *et al.* [47]
fluid flow	frictional loss in pipes	Nebot *et al.* [49]
drinking water	pathogens in potable water	Lebret *et al.* [47]
fuel	diesel fuel contamination	Morton [50]
food, paper and paint	food spoilage and worker health risks	Jass & Walker [51]
metal-cutting fluid	filter blockage and worker health risks	Morton [50]

As far as biofouling on artificial surfaces is concerned, more than 45 per cent of hospital-contracted infections are traced to biofilm-infected medical devices. For instance, catheters are the most commonly used medical device and second highest cause of infection [17,53]. Estimates show that 10 per cent of hospital patients will contract an infection from a clinical implant, such as a urethral catheter, tracheal tube or vascular catheter, with more than 5000 annual deaths owing to infections. Research shows that 9 per cent of 9000 patients using a ventilator in 1998 acquired ventilator-associated pneumonia, which increased the average hospital stay costs by $40 000 [17,21,54], making ventilator-associated pneumonia the most expensive nosocomial infection in United States hospitals [39]. Furthermore, approximately 8 per cent of orthopaedic implants develop complications owing to biofilm or biocompatibility issues and often require surgery [38].

Biofouling and biocompatibility are generally detrimental and often lead to medical device failure. Biocompatibility describes the compatibility of the device with the body, as foreign objects are naturally rejected (for example, causing fibrous encapsulation). Biofouling describes the adhesion of proteins or micro-organisms to the device (biofilm) and begins soon after implantation. In certain applications, however, the fibrous encapsulation is not harmful and can even be beneficial. For instance, encapsulation of devices such as pacemaker power
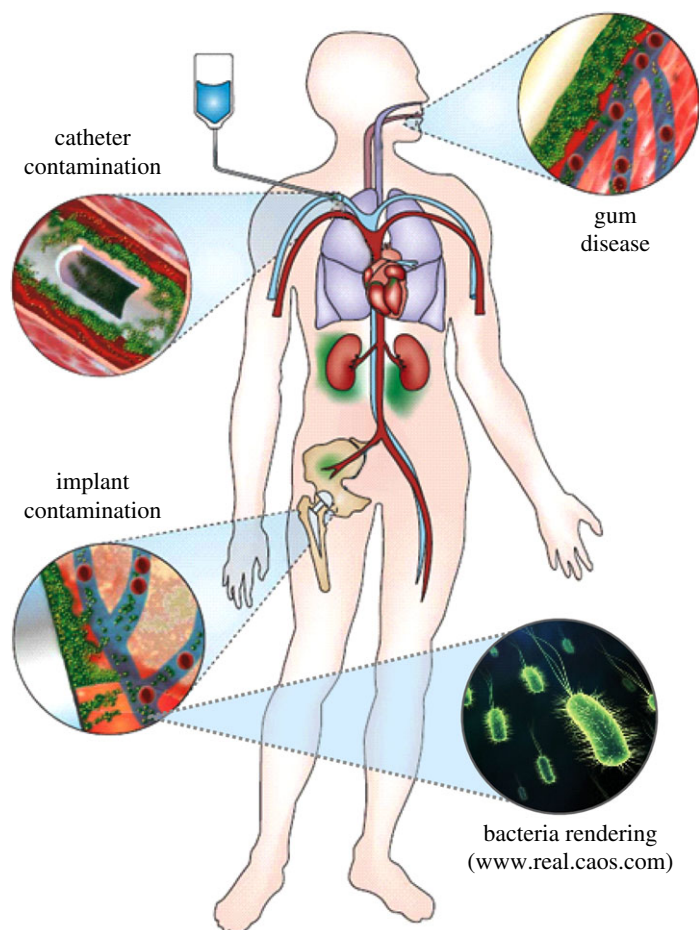
Figure 2. Schematic highlighting areas of the body susceptible to infectious biofilms. Adapted from P. Dirckx Center for Biofilm Engineering. (Online version in colour.)

wires help prevent unwanted movement within the body. Conversely, undesired encapsulation of devices such as biosensors and orthopaedics may cause sensor malfunction and prevent bone growth, respectively [19,20,55].

Treating biofilms on infected medical devices often requires surgical replacement, which increases the risk of mortality and antibody resistance. Infections caused by pathogenic *Staphylococcus aureus* (MRSA) bacteria are the worst because of its methicillin resistance [19,21]. Antibiotics are usually ineffective against biofilms, which leads to difficulties treating biofilm-induced medical conditions such as cystic fibrosis [56]. Furthermore, protein fouling on biological implants reduces efficiency and may lead to thrombosis (blood clots) [40].

Biofilms contain a diverse variety of micro-organisms such as gram-positive or gram-negative bacteria. Gram-positive include *E. faecalis, S. aureus, S. epidermidis and S. viridans* and the gram-negative include *E. coli,*
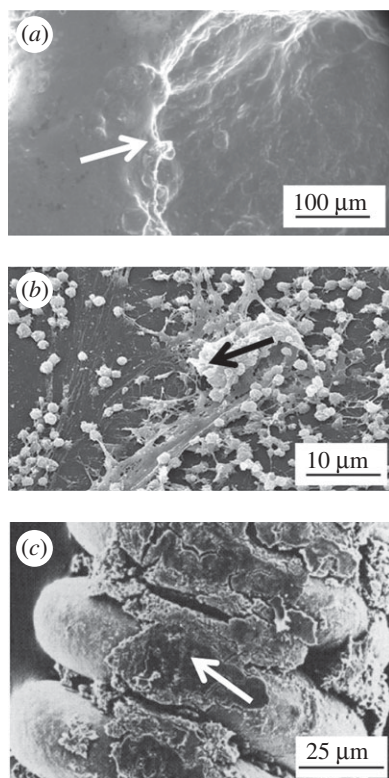
Figure 3. Medical device biofilm SEM examples. Such biofilms may lead to infections that require device removal as antibodies are often ineffective. (*a*) Ventilation tube removed from patient. Reproduced with permission from Trinidad *et al.* [18]. (*b*) Needleless connector. Adapted from Janice Carr. (*c*) Pacemaker wire removed from patient. Reproduced with permission from Marrie *et al.* [58].

K. pneumoniae, P. mirabilis and *P. aeruginosa.* Prevalent infection-causing micro-organisms include *P. aeruginosa, E. coli, S. aureus* and *S. epidermidis* [19,20,55,57].

Infectious biofilms in medical equipment such as haemodialysis machines can form, even with advanced purification systems. This microbial presence is especially detrimental to sick patients, and cleaning, descaling and disinfecting are difficult [42]. Examples of medical biofilms are shown in figure 3 with SEM images of a titanium ventilation tube, needleless connector and pacemaker wire. The ventilation tube was removed from a patient after three months owing to a foul smelling odour [18]. The needleless connector biofilm, found on the inner surface of the connector, increases the risk of bloodstream infections [57]. The pacemaker wire was removed from a patient who suffered from *S. aureus* bacteraemia (presence of bacteria in the blood) [14,58].

Medical devices affected by biofouling can be classified into two major categories: permanent and temporary devices. In general, a permanent device is implanted and intended for 'long-term' (non-disposable) use, whereas a temporary device is intended for 'short-term' (disposable) use.

(*b*) *Permanent implants*

Permanent implant devices include biosensors, heart valves, bone plates, fasteners, orthopaedic implants, dental implants, pacemakers, drug-delivery devices and ventilation tubes [19,20,54]. Immediately after surgery, the permanent implant is flooded with blood followed by adsorption of proteins onto the surface [2,59]. Such adsorption on a biosensor may lead to sensor 'blindness' [44], reduced lifespan and increased power consumption. Furthermore, biofouling causes problems with sensor stability and calibration [60]. Mechanical heart valve biofilms can lead to prosthetic valve endocarditis (tissue inflammation) from *S. epidermidis* and *S. aureus.* During implant surgery, such micro-organisms can enter the bloodstream by the surrounding skin or other devices [57].

Patients suffering from severe trauma often require bone plate and fastener implants (osteosynthesis) after a catastrophic injury. These medical implants are susceptible to biofilm formation because of the high concentration of micro-organisms such as *S. aureus* in the contaminated wound area, and an overall weakened immune system. When the plates or fasteners become infected by the biofilm, they are generally untreatable by antibiotics and require removal to control the infection [57,61,62].

Dental implants are a source of infection, especially when the socket is exposed during surgery. Dental plaque biofilm is a diverse collection of micro-organisms in the oral cavity, containing many species of bacteria such as *S. mutans.* Plaque grows on teeth, gums, the tongue and cheeks, leading to dental decay and periodontal disease. The micro-organisms living in saliva colonize tooth enamel, dental implants and cementum. Plaque can form inside teeth sockets where micro-organisms are protected from cleaning mechanisms such as chewing, saliva, mouth rinses and brushing. Problems occur when micro-organisms are not eliminated by the host defences [43,63,64].

(*c*) *Temporary implants*

Temporary implant devices include biosensors, catheters, drug-delivery devices, bone plates, fasteners, ventilation tubes, needleless connectors and ventilator tubes [19,20,54]. Perhaps, the most common biosensor is the single-use blood glucose monitoring device for diabetic patients. Such blood glucose sensors are relatively imprecise, inaccurate but also inexpensive [65]. Glucose diffuses from capillaries through the sensor membrane, which is semi-permeable, and acts as the interface between the enzymes and electrode. Failures occur from biocompatibility issues such as membrane biofouling, fibrous encapsulation, electrode passivation and biodegradation [60]. Membrane biofouling starts upon bodily contact when micro-organisms, proteins and other components adhere to the surface, impeding the sensor's diffusion ability. See figure 4 for an example showing the OneTouch blood glucose monitoring device and an implantable biosensor probe with a schematic of biofouling-induced failure points. Membrane biofouling and fibrous encapsulation prevents glucose from contacting the probe for accurate measurements [66,67].

Urinary catheter calcification from bacterial colonization may cause bladder stone formation and urinary tract infections [41]. Urinary catheter biofilms contain *S. epidermidis, E. faecalis, E. coli, P. mirabilis, P. aeruginosa, K. pneumoniae* and other gram-negative micro-organisms. Central venous

(*a*)

MEMS drug-delivery device
(photograph courtesy of Dana Lipp)

OneTouch
glucose
monitor
[60]

(*b*)

MiniMed
glucose
implantable
monitor
[60]

membrane

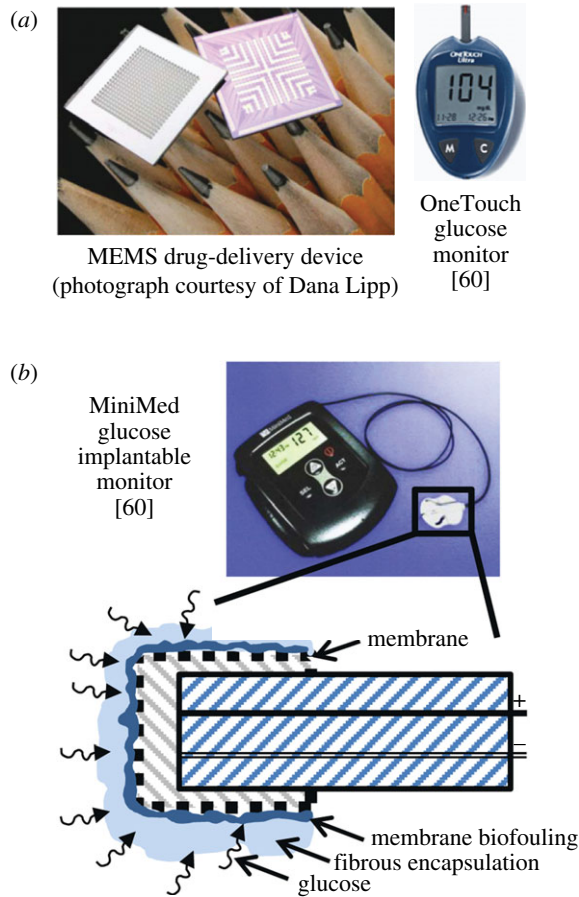membrane biofouling
fibrous encapsulation
glucose

Figure 4. (*a*) Biosensor product examples and biofouling. (*b*) Schematic of the implantable glucose biosensor probe illustrates biocompatibility and biofouling issues. (Online version in colour.)

catheter biofilms contain *S. epidermidis*, *S. aureus*, *Candida albicans*, *P. aeruginosa*, *K. pneumoniae* and *E. faecalis*, which originate from the patient's skin, device or healthcare workers [19,20,55,57].

Pulmonary, transdermal, intravenous and subcutaneous drug delivery through implanted devices are available for treating conditions such as brain tumours and prostate cancer. An example of the Micro Electromechanical System (MEMS) drug-delivery device is shown in figure 4. Drug-delivery devices are divided into passive and active categories, where drugs diffuse or degrade in the body at a constant rate. Micro- and nano-electromechanical devices help where long-term treatments with complex dosages are required. Advanced devices gather, use and communicate biological data to the healthcare workers [19,55,68,69]. Such devices often require biosensors, which limit the long-term operation owing to biofouling of electrode surfaces or membranes. An ideal implantable drug-delivery device is small, resists biofouling (for example, by protective reservoirs), allows liquid or solid drug delivery and is controllable by healthcare workers [68,69].
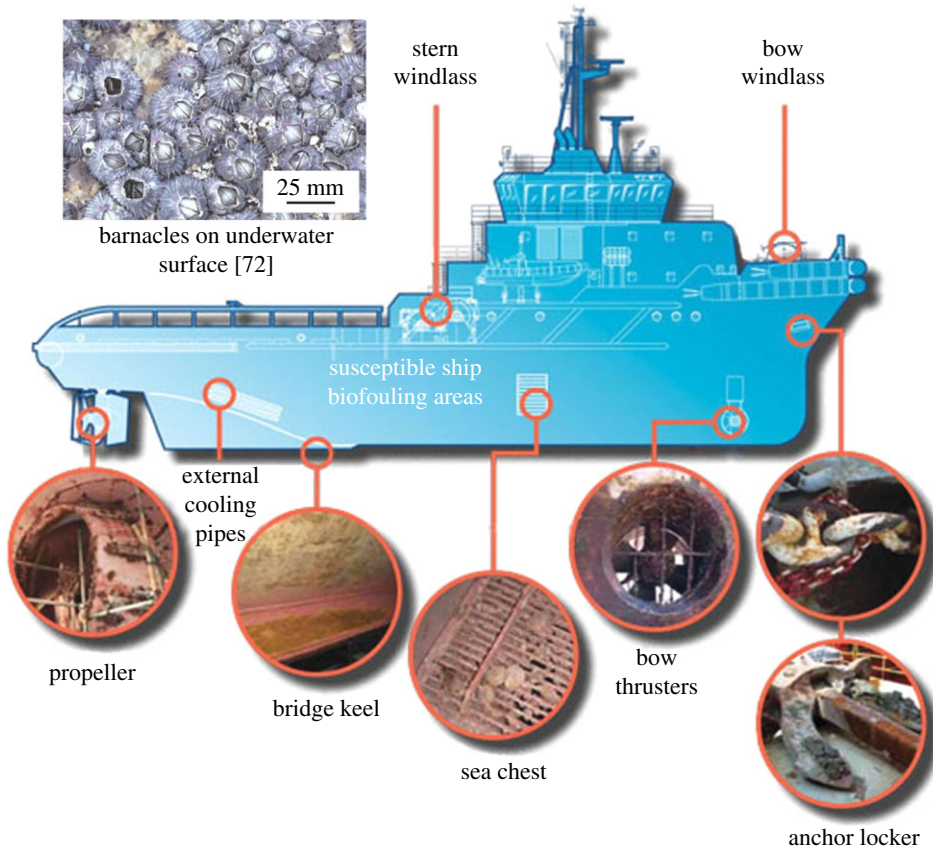
Figure 5. Marine biofouling examples. Areas susceptible to biofouling on a typical ship (middle) and the common hard-shelled barnacle (*Tetraclitella purpurescens*) (top left). Adapted from Mermaid Marine Australia, Ltd; photographs courtesy of Ashley Coutts, Cawthron Institute, John Polglaze, URS Australia and Helix ESG. (Online version in colour.)

(*d*) *Marine*

Perhaps, the most recognized form of biofouling is found in the marine environment. Biofouling colonizes ships, buoys, sonar devices, pontoons, offshore structures, oil installations, platforms, underwater cables, underwater acoustic instruments, seawater cooling systems and marinas. Issues include increased costs, reduced speed, environmental concerns, corrosion and safety hazards [9,10,12,13,22–24,70]. Areas with the best aeration, such as a ship's waterline, propeller and rudder blade experience the highest amount of fouling [47]. Common marine foulers are green algae *Ulva australis* and brown algae *Ectocarpus* [71]. Figure 5 illustrates the areas susceptible to biofouling on a typical petroleum ship and common hard-shelled barnacles (*Tetraclitella purpurescens*) [72].

Biofouling reduces ship speed owing to the extra drag, which increases fuel consumption and engine stress. In 1981, the US Navy consumed 18 million barrels of fuel, with 3.3 million attributed to biofouling losses [12,46]. A biofilm 1 mm thick can increase the ship hull friction by 80 per cent, which translates into a
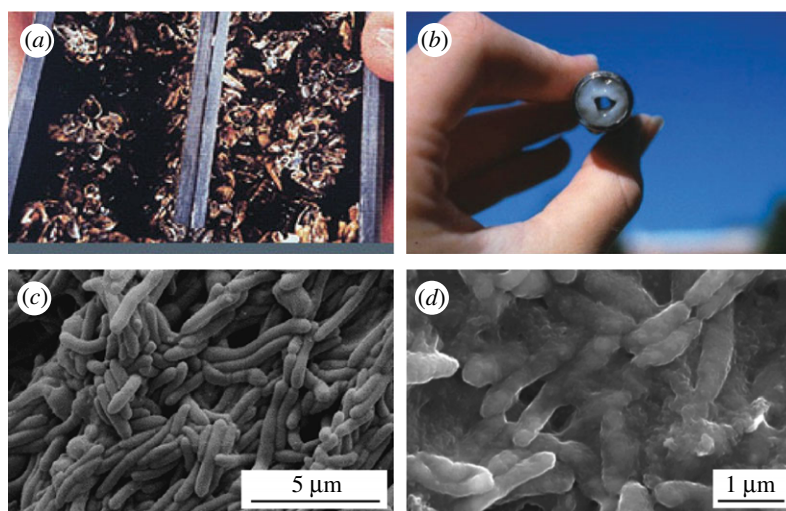
Figure 6. (*a*) Industrial biofouling examples. Zebra mussels (*Dreissena polymorpha*) clogging a power plant intake pipe (photograph courtesy of Peter Yates), (*b*) biofilm accumulation in a stainless steel tube (adapted from Cunningham *et al.* [76]), (*c*) biofilm (*B. cereus*) on dairy industry stainless steel plate (adapted from Simoes *et al.* [77]) and (*d*) biofilm (*P. aeruginosa*) on reverse osmosis membrane (adapted from Herzberg & Elimelech [78]). (Online version in colour.)

15 per cent loss in speed [73]. Furthermore, a 5 per cent increase in biofouling increases ship fuel consumption by 17 per cent, with a 14 per cent increase in greenhouse gases CO_2, NO_x and SO_2 emissions [45]. Foulers on ship hulls and ballast tanks can be transported worldwide and spread invasive non-native species. Biological corrosion can occur by acid-producing bacteria in the biofilm [12,13]. Biofouling alga on structures and walkways create a slippery coating, leading to increased safety risks. Extra loading owing to biofouling can damage fishing nets and sink buoys [46].

(*e*) Industrial

Industrial fouling affects applications ranging from nuclear power plants to food production [11,17,25]. Biofilms increase friction, energy needs and pipe pressure drops, as well as decrease heat-transfer efficiency [74]. Often nuclear power plant condenser cooling tubes suffer from biofouling-induced corrosion and blockage [49]. Biofilms can also harbour dangerous pathogenic micro-organisms in potable water supplies [47]. Most water supplies, even stainless steel pipes with ultrapure water, are susceptible to biofilms. Fungi initiated by biofilms can grow, causing poor taste and odour problems [75]. Figure 6 shows such biofouling examples with Zebra mussels (*Dreissena polymorpha*) clogging a power plant intake pipe (www.marinebiotech.org), biofilm accumulation in a stainless steel tube [76], biofilm (*B. cereus*) on a dairy industry stainless steel plate [77] and biofilm (*P. aeruginosa*) on a reverse osmosis membrane [78].

Membranes are used for various purposes, including desalination and water purification. Membrane biofouling occurs in applications such as reverse osmosis, nano/microfiltration, clarification, virus removal and bioreactors. Removal of

salt from brackish water or seawater is effectively accomplished with reverse osmosis and nanofiltration, but fouling decreases flux and efficiency. Such fouling originates from deposits of organic material, iron, phosphorus and micro-organisms that lead to detrimental increases in osmotic pressure and hydraulic resistance [48,78–80].

3. Biofouling and inorganic fouling formation

The genesis of biofouling formation occurs when micro-organisms make a transition from free-floating planktonic to stationary sessile lifestyles, thus forming a biofilm. They adhere to one another and a hard surface with an adhesive called the extracellular polymeric substance (EPS). The biofilm continues to grow and become more diverse by attracting more micro-organisms through chemical 'messages'. The general principles of biofilm formation and factors leading to the settlement on hard surfaces are similar in medical, marine and industrial applications [9,11,12,17,56,81,82]. Described in the following section are biofouling colonization, bioadhesion, inorganic fouling and hard substrate surface factors affecting settlement. Owing to similarities of biofouling applications, marine fouling is detailed to illustrate various attributes affecting formation.

(a) Colonization

Colonization is the process of biofouling organisms collecting and growing on a surface. In the marine environment, this usually starts with the formation of a biofilm that attracts larger macrofoulers [12,13,81,82]. For instance, tubeworms prefer settling on biofilms, but bryozoans and barnacles do not require a biofilm [33]. Figure 7 illustrates the five-stage colonization process, which includes initial attachment, irreversible attachment, initial growth, final growth and dispersion. Initial attachment starts the colonization process, which begins within days to a few weeks. The biofilm covered surface then attracts other organisms that may have been previously deterred. Initial attachment of micro-organisms is reversible, but once they secrete the EPS, the bond becomes irreversible. This permanent attachment allows initial growth, final growth and dispersion [12,56,81,82]. Figure 7 also shows a biofilm cross section highlighting the EPS morphology.

Underwater environments are ideal for biofouling as currents deliver nutrients and carry away wastes, promoting colonization by planktonic and sessile organisms. Biofouling growth rates depend on the organism, substrate, flow velocity, shear stress and temperature [12,46,83]. Organism transportation to a surface is either passive from the current or active from the propagule, juvenile or adult organism. Active mechanisms include electrostatic repulsion, Brownian motion, turbulent pulsations and cell outgrowths [12,33].

As far as the tenacity of the biofouling is concerned, bioadhesion plays an important role [12,56,81,82]. Bioadhesion is the adhesion strength of biofouling on a hard surface. This depends on the organism type, substrate and separating fluid [84] owing to influences of electrostatic forces and surface wettability [85–89]. Biofilm bioadhesion is a two-stage process, starting with the initial attachment and then the irreversible attachment. Initial attachment is controlled by a
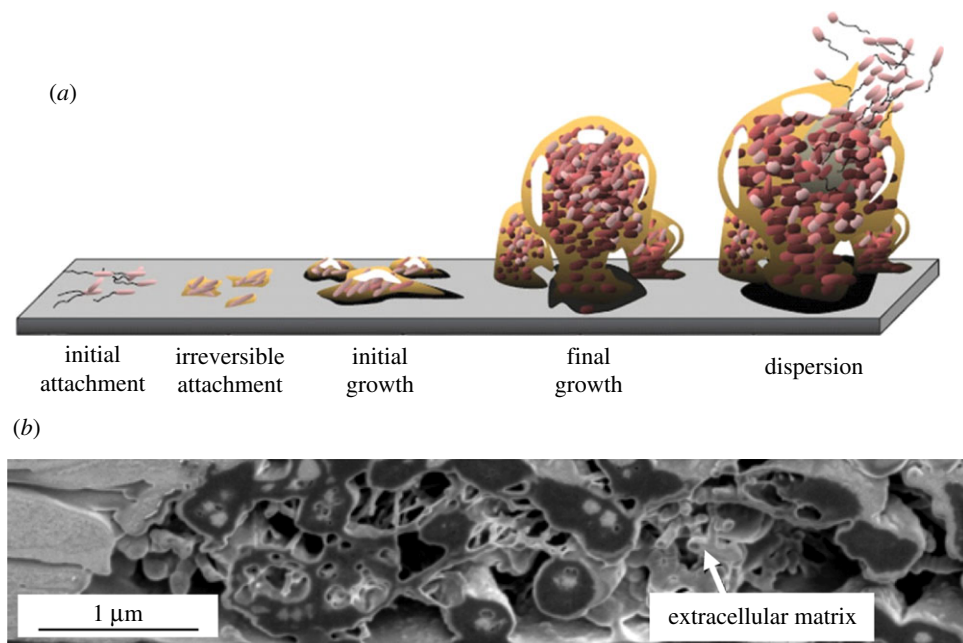
Figure 7. Biofilm development process and cross-section example. (*a*) Schematic illustrates the five-stage colonization process (adapted from D. Davis) and (*b*) SEM of biofilm cross section highlighting the EPS morphology (adapted from Andy Blankemeier). (Online version in colour.)

physical adhesion between the micro-organism and the substrate. Also known as adsorption, the initial colonists attach to a surface through weak, reversible van der Waals bonds, which are slightly stronger than electrostatic repulsive forces. Irreversible attachment is accomplished with secretion of the EPS, which exhibits a sponge-like matrix. This adhesive permanently binds the micro-organisms to one another and collectively to the surface [12,81,90].

(*b*) *Inorganic fouling*

Inorganic fouling composed of non-living particles may form in addition to or independent of biofouling. Particles originate from corrosion, crystallization, suspended particles, oil and ice. For instance, salts from aqueous solutions crystallize and deposit on surfaces. Other deposits may result from minerals found in water such as magnesium, calcium and barium [11,17,25].

Types of inorganic fouling include particulate, freeze and gas stream particulate. Particulate fouling occurs when suspended solid particles deposit onto a heat-transfer surface [91]. Deposition of crystals from freeze fouling occurs in locations such as cold region oil pipelines when waxy hydrocarbons contact cold pipe walls. Gas stream particulate fouling occurs in gas lines, reactors, combustion chambers and heat exchangers. This includes mineral, organic and inorganic particles, which are common in oil or gas combustion systems [92].
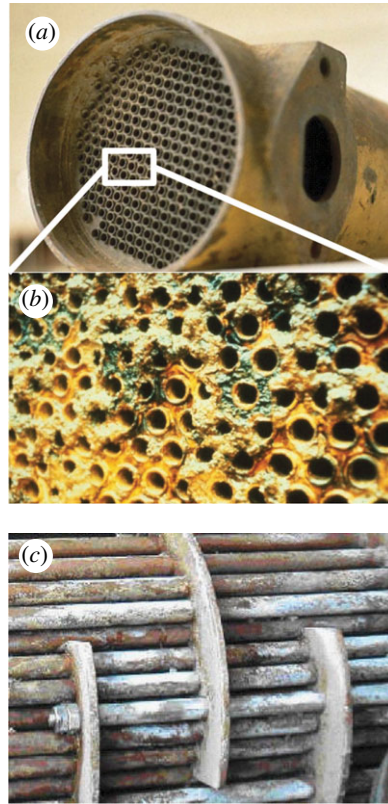
heat exchanger tubing with
crystallization (photograph courtesy of
H&C Heat Transfer Solutions, Inc)

Figure 8. Inorganic fouling examples. (*a*) Inside of a clean nuclear power plant heat exchanger tube compared with (*b*) a fouled tube with corrosion deposits. (*c*) Calcium carbonate crystallization fouling on the outside of a heat exchanger. Adapted from Cunningham *et al.* [76]. (Online version in colour.)

Biofouling may initiate inorganic fouling, where biocorrosion causes the formation of corrosion particles. Such fouling is prevalent in boilers, cooling condensers, desalination plants, food-processing equipment, geothermal plants and oil production equipment [93]. Heat exchangers can develop hard deposits called 'scale' or more porous deposits such as 'sludge' [94]. Figure 8 shows inorganic fouling by comparing the inside of a clean nuclear power plant heat exchanger tube with a similar tube covered in corrosion deposits [76]. Also shown is calcium carbonate crystallization fouling on the outside of a heat exchanger (www.hcheattransfer.com).

(*c*) *Surface factors*

Biofouling and inorganic fouling depend on the surface factors such as wettability, microtexture, colour and contours [10,12,13,59,82]. For instance, bryozoan and mussel larvae prefer hydrophobic surfaces [73]; hydroids, bryozoans

and ascidians prefer microtextured surfaces; larvae, sponges, barnacles, ascidians and molluscs prefer light-coloured surfaces; barnacles prefer convex contours; and calcareous sponges prefer concave contours [12].

Surface wettability influences fouler colonization, which ranges from water-fearing superhydrophobic to water-loving superhydrophilic surfaces [10,12,13,59,82,95,166]. A hydrophobic surface exhibits low wettability and low surface energy, whereas a hydrophilic surface exhibits high wettability and high surface energy. Water droplets on a hydrophobic surface will 'bead up', while droplets on a hydrophilic surface will spread out evenly. The preface 'super' indicates higher tendencies in either direction, such as superhydrophobic and superhydrophilic. The degree of wettability is determined by contact angle measurements, where contact angles less than 10° are superhydrophilic and over 150° are superhydrophobic. Figure 9a shows the contact angles for superhydrophilic, hydrophilic, hydrophobic and superhydrophobic surfaces as well as photographs of water droplets in the Cassie–Baxter, and Wenzel regimes, highlighting the air pocket effect.

Close examination of the liquid–solid–air interface reveals that the Wenzel regime does not contain an air pocket, unlike the Cassie–Baxter regime. This difference, owing to surface roughness, influences the surface wettability as the air pocket affords a larger contact angle θ, which relates to wettability [28]. Equations (3.1)–(3.3) describe the Wenzel equation (no air pockets), where θ is the contact angle, θ_f the contact angle of the droplet on the solid surface, R_f the roughness factor, A_F the flat solid–liquid contact area and A_{SL} the projection of the solid–liquid area. Equation (3.3) describes the Cassie–Baxter equation (with air pockets), where f_{SL} is the fractional solid–liquid contact area [95]. Furthermore, the contact angle hysteresis (CAH) is the difference between the advancing (downhill side) and receding (uphill side) contact angles, which is low for Cassie–Baxter and high for Wenzel regimes. As the CAH increases, so does the adhesion strength, which explains the deformed shape of a water droplet adhered to a vertical window [28].

Wenzel regime:

$$\cos\theta = R_f \cos\theta_f, \tag{3.1}$$

where

$$R_f = \frac{A_{SL}}{A_F}. \tag{3.2}$$

Cassie–Baxter regime:

$$\cos\theta = R_f f_{SL} \cos\theta_f - 1 + f_{SL}. \tag{3.3}$$

Low-adhesive, superhydrophobic surfaces promote contaminant removal with the application of liquid, through an action simply called 'self-cleaning'. The schematic in figure 9b illustrates the self-cleaning action of a water droplet on a low-adhesive, superhydrophobic surface. On an incline, the water droplet slides past the particles on the hydrophilic surface, while the water droplet rolls and collects particles on the superhydrophobic surface (www.hk-phy.org). Also shown are droplets of water and mercury, each collecting contaminants on lotus (*Nelumbo nucifera*) and taro (*Colocasia esculenta*) leaves, respectively [26,28].
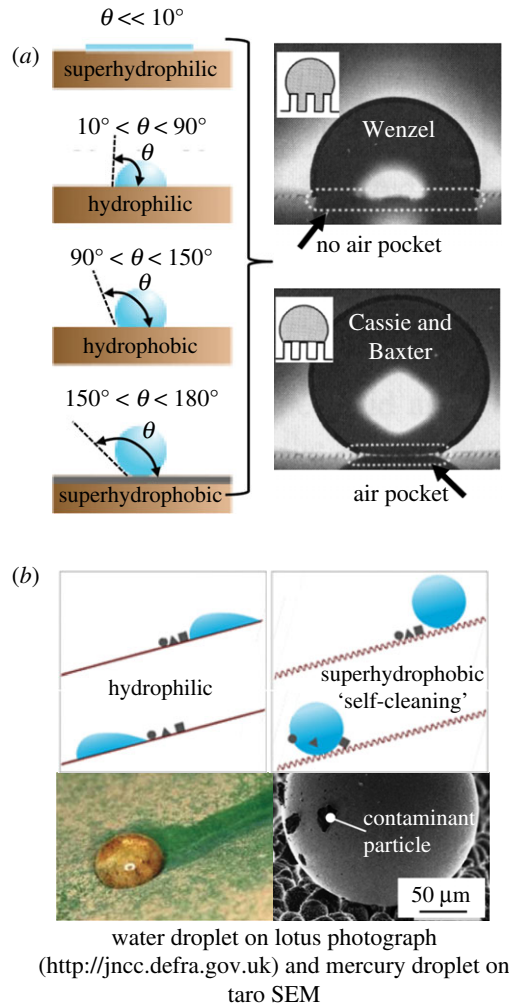
Figure 9. Various parameters describing wettability and self-cleaning. (*a*) Schematic shows droplet contact angles (left) and photographs of droplet regimes (right). Adapted from Nosonovsky & Bhushan [28]. (*b*) Schematic shows the self-cleaning effect (top) and superhydrophobic examples (bottom). Adapted from Barthlott & Neinhuis [26]. (Online version in colour.)

Antifouling, superhydrophilic surfaces attract water to form an evenly distributed water layer, which can confuse and disrupt micro-organism settlement [96]. In general though, micro-organisms prefer to colonize hydrophilic surfaces, although some actually prefer hydrophobic surfaces. For example, *Ulva linza* prefer hydrophobic surfaces, whereas *Balanus Amphitrite* prefer hydrophilic surfaces. Furthermore, micro-organisms such as *Ulva linza* attach more easily to hydrophobic surfaces, but experience decreased adhesive strength [88]. Additionally, the sheeting action of sliding liquid on a superhydrophilic surface can promote self-cleaning, where the liquid helps collect and remove fouling (www.ppg.com).
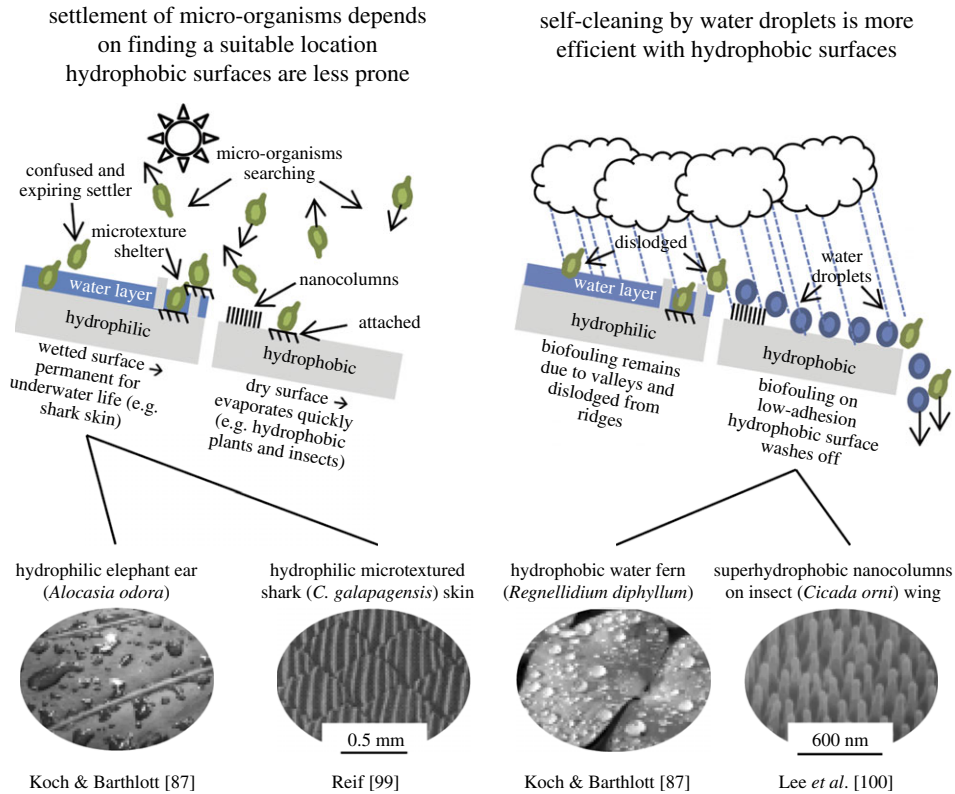
Figure 10. Schematic shows surface topography antifouling mechanisms demonstrating wettability and texture properties that influence micro-organism settlement and colonization. (Online version in colour.)

Surface microtexture influences organisms such as hydroids, bryozoans and ascidians that seek shelter against strong currents by settling in grooves, pits, cracks and crevices [10,12]. Micro-organisms prefer to settle in areas slightly larger than themselves for maximum protection and surface area contact with the substrate. Fewer attachment points between the micro-organism and substrate translate into lower bioadhesive strength [97]. Bioadhesion is also affected by the effectiveness of EPS flowing into crevices formed by surface roughness, which depends on the adhesive viscosity. Furthermore, when adhesive contacts only the surface asperity peaks or tops of microtexture ridges, the force applied to break bonds is significantly reduced [98].

Figure 10 demonstrates physical control antifouling mechanisms affecting micro-organism settlement and colonization. Micro-organisms search for an ideal site to settle, which can depend on parameters such as wettability and texture [88,86]. During the search process, micro-organisms will settle, move on or expire in the process. In general, biofouling on superhydrophobic surfaces wash off more easily (self-cleaning) when compared with superhydrophilic surfaces. Images show a variety of examples found in nature, including the hydrophilic elephant

Table 2. Flora antifouling lessons from nature.

type	mechanism	source
lotus (*Nelumbo nucifera*), taro (*Colocasia esculenta*)	superhydrophobic self-cleaning surface	Barthlott & Neinhuis [26]; Nosonovsky & Bhushan [28]
jewelweed (*Impatiens capensis*)	hydrophobic surface	Valdes [102]
water fern (*Salvinia*)	superhydrophobic surface	Koch *et al.* [103]
eelgrass (*Zostera marina*)	zosteric acid secretions	Callow & Callow [70]
lady mantle (*Alchemilla mollis*)	hydrophobic surface	Lee *et al.* [104]
broccoli (*Brassica oleracea*)	superhydrophobic surface	Lee *et al.* [104]
red seaweed (*Delisea pulchra*)	bacteria message manipulation	De Nys & Steinberg [105]
coralline algae (*Porphyridium purpureum*)	shading, chemical secretion, and shedding/sloughing	Scardino [88]
seaweed (*Ulva lactuca*)	chemical secretions	Rao *et al.* [106]
Indian cress (*Tropaeolum majus*)	hydrophobic surface	Barthlott & Neinhuis [26]

ear (*Alocasia odora*) [87], microtextured shark skin (*Carcharhinus galapagensis*) [99], hydrophobic water fern (*Regnellidium diphyllum*) [87] and superhydrophobic nanocolumns on an insect wing (*Cicada orni*) [100].

4. Antifouling examples and methods in practice

When considering antifouling methods, many strategies exist in nature and industry, including physical and chemical controls. Owing to the complex nature of fouling organisms, nature often uses a combination of physical and chemical controls. Industry mimics this approach through various antifouling technologies [9–13,19,33,55,101]. Described in detail are antifouling lessons from nature, antifouling mechanisms and current industry antifouling methods.

(a) Lessons from nature

Biofouling occurs throughout nature, but many examples of antifouling flora and fauna exist, as shown in tables 2 (flora) and 3 (fauna). These tables include a variety of both land-based and underwater examples. Antifouling mechanisms for each are included to demonstrate the wide variety of techniques that could be mimicked. Common mechanisms include low drag, low adhesion, wettability, microtexture, grooming, sloughing, various miscellaneous behaviours and chemical secretions [3,8,10,13,27,33,82,115].

Low-drag, fast-swimming shark skin is antifouling because of its riblet microtexture, flexion of scales and a mucous layer. The skin contains scales called dermal denticles, which are covered by specially sized and spaced riblets oriented

Table 3. Fauna antifouling lessons from nature.

type	mechanism	source
human		
red blood cell	phospholipid bilayer membrane	Cui & Wan [80]
cornea	eyelid wiper and chemical secretions	Menton [107]
birds		
dove (*Zenaida*), pigeon (*Columba*), duck (*Anas*)	superhydrophobic feathers	Bhushan [3]
insects		
dragonfly (*Libellula*), damselfly (*Ischnura*), mayfly (*Hexagenia*), lacewing (*Notiobiella*)	hydrophobic wax-covered wings	Bar-Cohen [8]
soybean aphid (*Aphis glycines*)	hydrophobic mushroom-like spines	Bar-Cohen [8]
butterfly (*Polyommatus icarus*), Cicadae (*Cicada orni*)	superhydrophobic wings	Feng & Jiang [86]
molluscs and crustaceans		
blue mussel (*Mytilus edulis*), *Mytilus galloprovincialis*, *Perna perna*, Pteria penguin	microtexture and filter feeding	Ralston & Swain [33]; Scardino [88]
crab (*Cancer pagurus*), crawfish (*Orconectes*), lobster (*Homarus*)	microtexture and self-grooming	Bers & Wahl [108]; Yen [109]
corals		
Gorgonian sea fans (*Pseudopteragorgia america* and *Pseudopteragorgia acerosa*)	microtexture, surface energy, sloughing and mucus	Guenther & de Nys [110]; Scardino [88]
marine mammals		
pilot whale (*Globicephala melas*), common dolphin (*Delphinus delphis*)	microtexture, surface energy and enzymes	Baum *et al.* [111]; Meyer & Seegers [112]
echinoderms		
brittle star (*Ophiura texturata*), sea urchin (*Diadema*)	sloughing and mucous	Scardino [88]
fish		
shark (*Squalus acanthias*)	low drag, riblets, flexion of scales and mucous	Kesel & Liedert [32]; Scardino [88]
dogfish (*Scyliorhinus canicula*) egg case	parallel ridge microtexture surface	Davenport [113]
fish (*Micropterus*) scales	hierarchical scale structure	Liu *et al.* [114]
stonefish (*Synanceja horribilis*)	skin sloughing	Ralston & Swain [33]

parallel to the swimming direction (figure 11). Low drag is achieved by the riblets lifting and constraining the naturally occurring fluid vortices, which reduces the transfer of momentum and total shear stress. When the vortices are pinned just
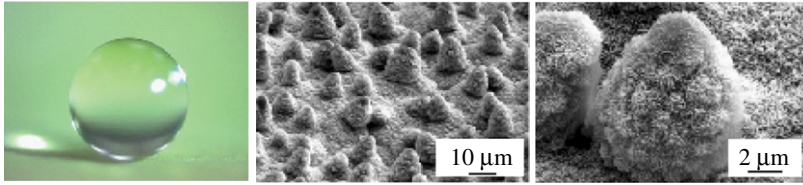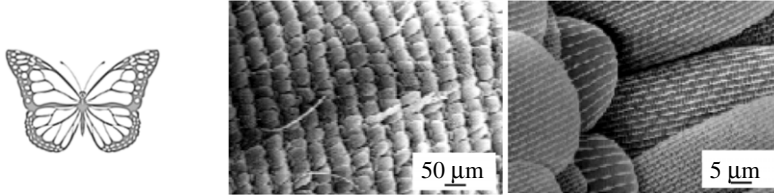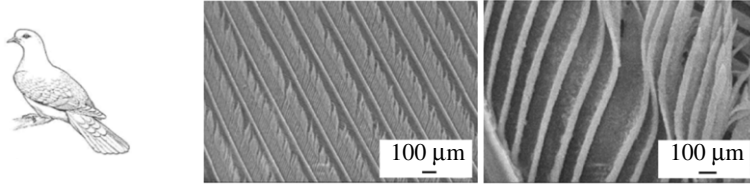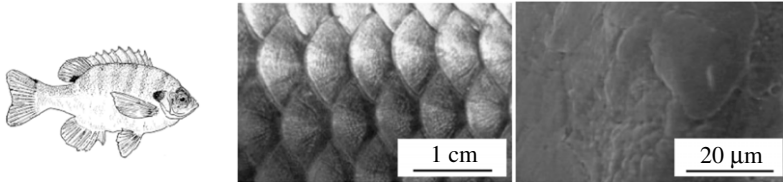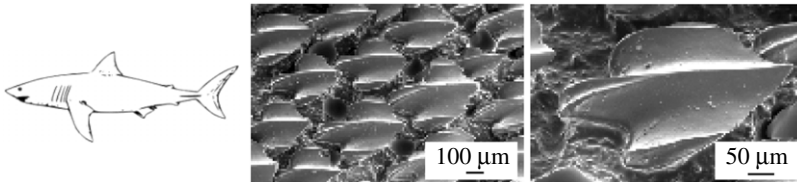
examples of self-cleaning surfaces

superhydrophobic lotus (*N. nucifera*) leaf (reproduced with permission from Bhushan *et al.* [5])

superhydrophobic butterfly (*P. lcarus*) wings (adapted from W. Barthlott)

superhydrophobic pigeon (*Columba*) feathers (reproduced with permission from Bormashenko *et al.* [115])

superoleophobic fish (*Micropterus*) scales (reproduced with permission from Liu *et al.* [114])

low-drag shark (*S. acanthias*) skin (reproduced with permission from Jung & Bhushan [95])

Figure 11. Antifouling examples from nature using wettability properties. Water promotes self-cleaning on low-adhesion superhydrophobic surfaces, as shown in the lotus, butterfly and pigeon examples. Also shown are fish scales, which are superoleophobic when submerged. Shark skin is antifouling owing to a combination of features including low drag, riblets, flexion of scales and mucous layers. (Online version in colour.)

above the riblet tips, the cross-stream movement and entanglement of stream-wise vortices are limited, thus reducing the transfer of momentum. The total shear stress is reduced as the vortices only contact the small riblet tips, when compared with the total surface area. Lower drag also allows the water layer next to the skin to move faster, which reduces micro-organism settlement time and helps wash

them away [34,99,116,117]. In addition to low drag, shark skin microtexture deters certain micro-organisms, as they prefer particular groove widths and depths for settlement. As a result of these mechanisms, micro-organisms have difficulty adhering to and colonizing shark skin [31–34].

Desirable wettability properties include low-adhesive superhydrophobic and superoleophobic self-cleaning surfaces that resist fouling as water washes away the contaminating particles [27,95]. Figure 11 shows superhydrophobic examples with the lotus leaf, butterfly wings and pigeon feathers as well as a superoleophobic example with fish scales. Submerged fish scales are oil resistant because of their hierarchical structure, which consists of 4–5 mm diameter scales covered by papillae 100–300 µm long and 30–40 µm wide [114]. Other superhydrophobic examples include broccoli, lady mantle and the insect cicada [100,104].

Certain microtextured surfaces resist biofouling as organisms seek ideal surface features for settlement, and may be deterred if no suitable surface is found. The barnacle *Cypris* larvae are deterred by microtextured surfaces if the features are of the same size or slightly smaller than juveniles. The mussel *Mytilus* deters foulers with a micro-hair-covered surface, and the dogfish shark egg case deters foulers with a microtextured surface [33,108,113]. Also, the pilot whale (*Globicephala melas*) and the common dolphin (*Delphinus delphis*) deter biofouling with microtextured skin [111,112].

Grooming is the physical removal of biofouling from the host, which effectively controls slow- and fast-growing biofouling. Decapods and crustaceans groom other creatures with special brush structures for removing foulers from gills and appendages. Echinoderms and bryozoans use special structures called pedicellaria to groom macroepibionts, while crayfish depend on *Branchiobdellid annelids* to feed on foulers in their gills.

Sloughing is the slow shedding of the outermost layer of an organism, which effectively controls slow-growing biofouling. This method is employed by organisms such as crustaceans, stonefish *S. horribilis* and seaweed [33].

Miscellaneous antifouling behaviours include any physical action that prevents or removes fouling. Such behaviours include activities such as burrowing, hiding in the dark, flexing and mechanical cleaning. These may be used in conjunction with antifouling mechanisms such as low drag, low adhesion, wettability, microtexture, grooming, sloughing and chemical secretions. Burrowing scrapes off foulers, and hiding in the dark inhibits algae formation [118]. Algae prevent biofouling by flexing and bending, unlike rigid foulers such as barnacles and tubeworms [119]. Figure 12 illustrates a mechanical cleaning example combining wiping with chemical secretion, as demonstrated in the human eye via the lachrymal gland-secreting tears, puncta collecting tears and eyelid wiping the cornea [107].

Chemical secretion methods range from preventing to removing biofouling. Figure 12 shows the red seaweed (*Delisea pulchra*), which uses a halogenated furanone to manipulate colonizing bacteria 'attraction' messages [109]. Other chemical examples include snails that leave a predatory mucous trail, antimicrobial coral egg shells [120], mucus on shark skin [33] and antifouling chemicals produced by the bacteria *Roseobacter gallaeciensis* [121]. Furthermore, blood cell protein adsorption and cell adhesion are inhibited with phosphorylcholine [55].
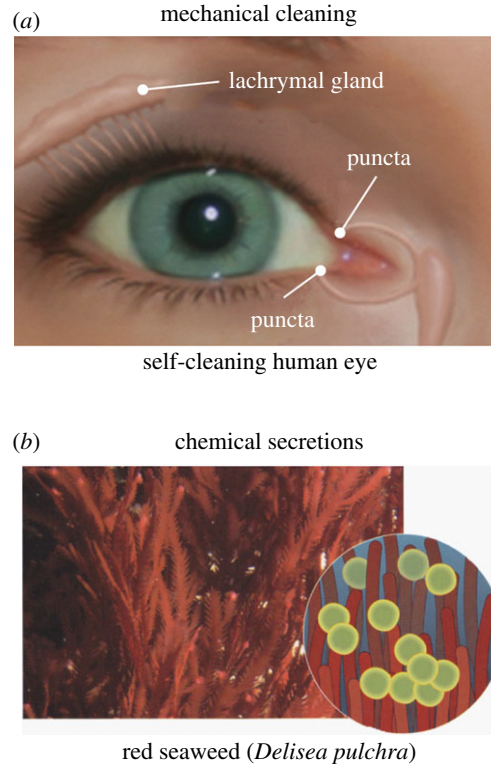
(*a*) mechanical cleaning

self-cleaning human eye

(*b*) chemical secretions

red seaweed (*Delisea pulchra*)

Figure 12. Antifouling examples from nature using mechanical cleaning and chemical secretions. (*a*) Human eye combines wiping with chemical secretions to clean the cornea (adapted from John Nyquist). (*b*) Red seaweed using a halogenated furanone to manipulate colonizing bacteria 'attraction' messages (adapted from Yen [109]). (Online version in colour.)

(i) *Methods in practice*

Several bioinspired antifouling methods in practice benefit or could potentially benefit medical, marine and industrial applications. These include mimicking nature's physical and chemical control methods, such as low-drag, low-adhesion, wettability and microtextured surface properties, as well as grooming, sloughing, various miscellaneous behaviours and chemical secretions [2,8,28,33]. Coatings are perhaps the most common method of biofouling control, and examples are shown in table 4 [13,20].

Surface property methods. Low-drag surfaces provide antifouling benefits, and drag reduction is demonstrated by saw tooth, scalloped and bullnose shark skin inspired riblets. Laboratory experiments show that such microtextures can reduce drag by up to 9.9 per cent, with an optimized relationship between the blade thickness and spacing [131,117]. Both two-dimensional and three-dimensional riblets have been studied for their effectiveness in drag reduction, but no significant improvement is observed with three-dimensional versus two-dimensional riblets [132]. Styles of riblets include aligned segmented blade [133], offset segmented blade, offset three-dimensional blade [134] and three-dimensional

Table 4. Antifouling coatings.

type	mechanism	source
medical		
metal	toxic silver or zinc-coated surface	Dror *et al.* [122]
hydroxyapatite	toxic coating for osteosynthesis applications	Montali [61]
antiseptic	toxic coating with chlorhexidine and/or chloroxylenol	Montali [61]
antibodies	toxic coating with antibiotics	Montali [61]
PEG	SAMS hydrophilic surface deters protein adsorption and adhesion	Emmenegger *et al.* [123]
oligoethylene glycol	SAMS hydrophilic surface deters fibrinogen adsorption	Emmenegger *et al.* [123]
zwitterionic polymers	hydrophilic surface deters protein adsorption and reduces bioadhesion	Emmenegger *et al.* [123]
fluoropolymer and fluorosilane	films increase biocompatibility for implantable devices to reduce protein adsorption	Lee *et al.* [100]
marine/industrial		
metal coating	toxic copper or silver-coated surfaces	Railkin [12]; Zodrow *et al.* [124]
silicone elastomer	low surface energy promotes low bioadhesion	Callow & Callow [70]
self-polishing copolymer	self-polishing paint with copper, tin, zinc or biocides released during vessel movement	Abarzua *et al.* [125]
hydrogels	hydrophilic surface confuses settlers	Lewis [126]
biological	deterrents include bacteria, algae and invertebrates	Abarzua *et al.* [125]
enzymes	lowers bioadhesion and lyses bacteria	Olsen *et al.* [127]
hormones	promotes premature metamorphosis of larva	Fischer *et al.* [128]
short fibres	fibres or spikes confuse settlers	Lewis [126]
conductive paint	electrochemical disinfection process	Matsunaga *et al.* [129]
organo-metallic	toxic flexible metal surface	Willemsen [101]
plastic film	disposable film removed with attached biofouling	Fischer *et al.* [128]
photoactive film	self-cleaning film uses UV or visible radiation	Banerjee *et al.* [40]
cayenne pepper	deterrent pepper with silicone grease	Manov *et al.* [130]

shark skin replicas [135–137]. A riblet optimization review paper suggests that a blade riblet height divided by the spacing equalling 0.5 is optimal for drag reduction, regardless of riblet length [34].

Riblet-inspired drag-reducing products include the experimental 3M saw tooth riblets as well as the Speedo FastSkin fabric racing swimsuit. The 3M riblets are manufactured in polymer films and have been tested in various aerospace, marine and industrial applications [138–140]. Riblet technology has captured
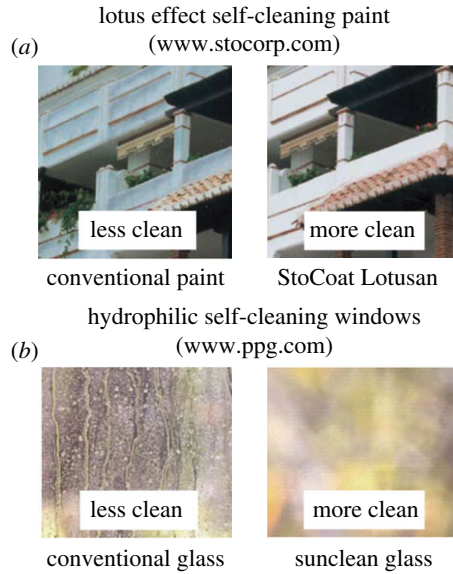
Figure 13. Effectiveness of self-cleaning antifouling coatings. (*a*) The improved cleanliness with Lotusan hydrophobic self-cleaning paint and (*b*) the improved clarity with the SunClean hydrophilic self-cleaning glass are demonstrated. (Online version in colour.)

the attention of the National Aeronautics and Space Administration (NASA), US Navy, Airbus, Boeing, as well as Olympic competitors. In the 1984 Los Angeles Olympics and 1987 America's Cup, riblets were applied to US boats, which presumably helped secure victories. The 2008 Beijing Olympics witnessed the benefit of the Speedo FastSkin swimsuit when American Michael Phelps set Olympic records and won several gold medals. Reducing fluid drag can also benefit wind turbine, microfluidics and oil pipeline industries [141–144].

Low-adhesive products include a variety of self-cleaning hydrophobic paints, roof tiles and fabrics, as well as self-cleaning hydrophilic windows and membranes. Examples are Lotusan paints by Sto (www.stocorp.com), Tegotop paints by Degussa (www.goldschmidt.com), Erlus Lotus roof tiles (www.erlus.com), NanoSphere fabrics by Schoeller Technologies (www.schoeller-textiles.com) and SunClean glass by PPG Industries (www.ppg.com). Self-cleaning is achieved with the hydrophobic Lotusan roll on and Tegotop spray paints that create a microstructure surface (www.stocorp.com; www.goldschmidt.com), hydrophobic Erlus Lotus roof tiles with an etched surface finish (www.erlus.com) and hydrophobic NanoSphere fabrics with integrated nanoparticles (www.schoeller-textiles.com). Self-cleaning hydrophilic SunClean glass with titanium dioxide uses the sheeting action of water to efficiently gather and remove contaminants (www.ppg.com). Figure 13 shows the improved cleanliness with Lotusan hydrophobic self-cleaning paints on concrete and stucco (www.stocorp.com), and better clarity with the SunClean hydrophilic self-cleaning glass (www.ppg.com).

Hydrophobic polymers and antimicrobials such as Nitrofurazone or silver-based hydrogel are examples of medical device coatings [53]. Select applications include catheters, endotracheal tubes [122] and orthopaedic hip
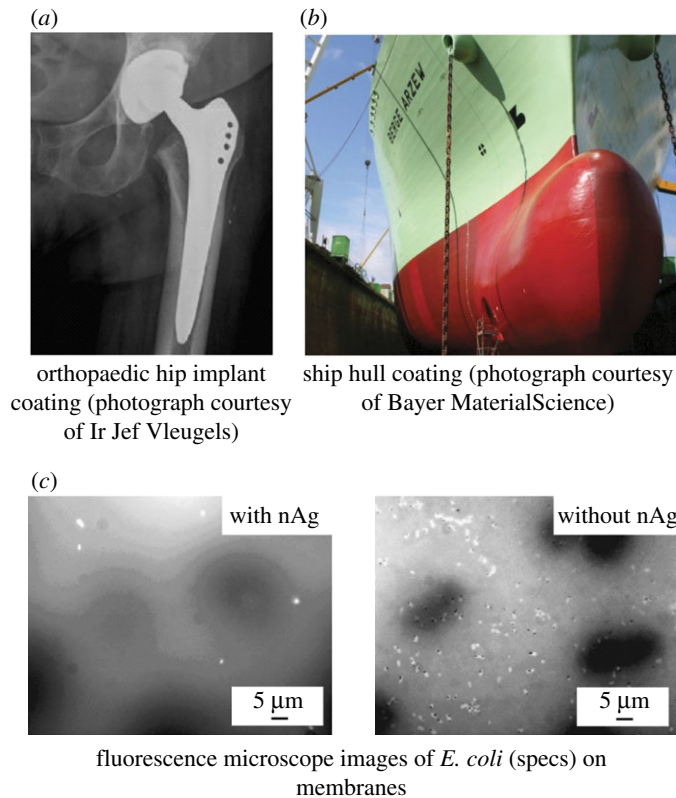
(a)

(b)

orthopaedic hip implant
coating (photograph courtesy
of Ir Jef Vleugels)

ship hull coating (photograph courtesy
of Bayer MaterialScience)

(c)

fluorescence microscope images of *E. coli* (specs) on
membranes

Figure 14. Medical, marine and industrial antifouling coating examples. (*a*) Orthopaedic hip implants are covered with a biocompatible coating designed to control biofouling, wear rate and promote bone growth. (*b*) Marine foul-release organic tin-free hull coating called 'Green Ocean Coating Heavy Duty' minimizes manual cleaning. (*c*) Polysulphone ultrafiltration membrane treated with silver nanoparticles (nAg) shows the antifouling benefit with fewer *E. coli* attached (adapted from Zodrow *et al.* [124]). (Online version in colour.)

implants. Hydrophobic surfaces reduce protein bioadhesion, and antimicrobial surfaces reduce ambient micro-organisms [56]. Surfaces with superhydrophilic polyethylene glycol (PEG) or polyethylene oxide show less protein adsorption and bioadhesion [98,145]. Other coating examples include self-assembled monolayers (SAMs), which are desirable as they coat the surface with a molecularly thick biocompatible film. This is especially important for applications such as Biomedical Micro/Nano Electromechanical Systems (BioMEMS/NEMS) [35–37,146]. Figure 14 shows an orthopaedic hip implant covered with a biocompatible coating designed to control biofouling, wear rate and promote bone growth [147,148].

In 2008, the International Maritime Organization banned tributyltin coatings because of their harmful effects on the surrounding marine environment. As a result, efforts are underway exploring environmental-friendly methods such as new non-toxic antifouling paints and foul-release coatings [10,12,13,149]. Marine foul-release coatings are non-toxic hydrophobic surfaces that promote

self-cleaning. Nano/microtextured surfaces control surface energy, charge, conductivity, porosity, roughness, wettability and friction [150]. Hydrophobic materials such as fluoropolymers and silicone elastomers are non-toxic, adhesion resistant, environmental friendly and easy to clean [151]. Siloxane elastomers provide a combination of lower elastic modulus and lower surface energy, creating a hydrophobic, low-stick surface. Silicone foul-release coatings are used for some quick moving boats, but degrade over time [98,152]. Figure 14 shows a foul-release organic tin-free hull coating called 'Green Ocean Coating Heavy Duty' by Advanced Marine Coatings, whose smoothness and hardness reduce cleaning cycles (www.bayermaterialscience.com).

Industrial heat-exchanger applications use SAMs to reduce bioadhesive strength between foulers and a heated surface, using low surface energy hydrophobic properties. Materials such as silicon can withstand temperatures up to 200°C, while materials such as hexadecyl disulphide can withstand up to 225°C. Furthermore, SAMs offer corrosion protection by limiting the oxygen and water diffusion at the substrate surface. This technique could be widely used for heat exchangers, but needs long-term durability testing [153].

Hydrophilic red blood cell plasma membranes are inspiring research to improve medical device and other synthetic membranes [80]. For instance, Advanced Hydro applies hydrophilic polymer coatings to water purification and filtration membranes, and results show a 30–50% reduction in fouling (www.advancedhydro.net). Clean Membranes use a 'smart-comb' copolymer in ultrafiltration membranes to provide antifouling and increased permeability (www.cleanmembranes.com). Researchers at the University of California Los Angeles combine superhydrophilic and antimicrobial nanoparticles in a polyamide thin-film coating for antifouling of reverse osmosis membranes (www1.cnsi.ucla.edu). Furthermore, studies show success using titanium dioxide (TiO_2) nanoparticles as a thin film on reverse osmosis membranes to control biofouling owing to the photocatalytic effects that eliminate bacteria [154]. Similarly, ultrafiltration membranes impregnated with antimicrobial and hydrophilic silver nanoparticles (nAg) show the antifouling benefit. Figure 14 compares nAg-treated and untreated polysulphone ultrafiltration membranes, showing fewer *E. coli* attached to the nAg membrane [124].

A microtexture film with riblet-inspired antifouling properties includes the Sharklet AF, which operates on the principle that micro-organisms are deterred from hydrophobic surfaces and crevices slightly smaller than themselves. Research suggests that appropriately sized topographies prevent colonization by various micro-organisms including *Ulva* spores and *Balanus Amphitrite* cyprids [31,155]. Figure 15 demonstrates the experimental Sharklet urinary catheter compared with Galapagos shark (*Carcharhinus galapagensis*) skin and the antifouling effectiveness of Sharklet AF with *Ulva* settlement on various surface topographies [31].

Other methods. Grooming and sloughing methods to control biofouling are used in many applications. For instance, the US Navy sponsored the development of a ship hull cleaning tool called the Bio-inspired Underwater Grooming robot (www.onr.navy.mil). This robot cleans a ship hull similar to a groomer on a host organism. Surface renewal in self-polishing paints mimics the actions of sloughing prevalent in nature. Current commercially available biocidal self-polishing paints are considered low maintenance, effective and repairable. Such paint types include
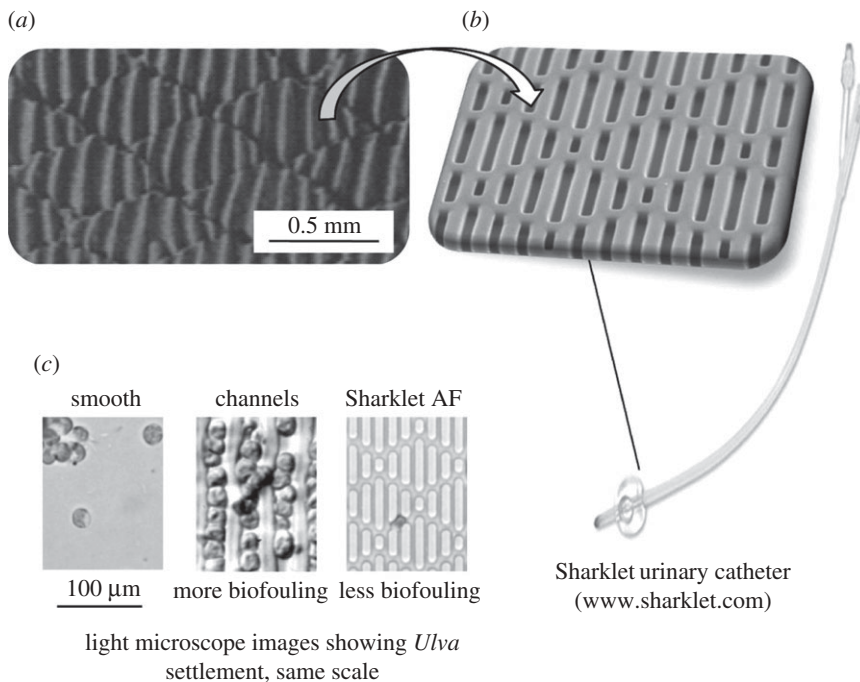
(*a*)

(*b*)

0.5 mm

(*c*)

smooth   channels   Sharklet AF

100 μm   more biofouling   less biofouling

light microscope images showing *Ulva*
settlement, same scale

Sharklet urinary catheter
(www.sharklet.com)

Figure 15. Biomimetic antifouling examples. Inspired by (*a*) nature's antifouling Galapagos shark (*Carcharhinus galapagensis*) skin (adapted from Reif [99]), researchers are developing (*b*) a Sharklet antifouling urinary catheter. (*c*) Experiments demonstrate the Sharklet AF antifouling effectiveness with *Ulva* settlement on various topographies (adapted from Carman *et al.* [31]).

biocidal-free association (released from resinous matrix) and ablative (bonded in soluble matrix that eventually peels off) [125]. Self-polishing copolymer paints contain antifouling toxins that erode over time, shedding the attached biofouling and continually exposing fresh toxins. However, biofouling is the most difficult to control in ports because of the lack of movement and higher concentration of bacteria from pollution and stagnant water [12,156]. Self-polishing paints without biocides are not very effective as the rate of removal is too slow to control fouler growth.

Behaviour antifouling methods include freshwater rinsing for ships. Researchers found that a fouled ship in saltwater being moved into freshwater (such as the Panama Canal) for 9 days and then back to saltwater removed 90 per cent of biofouling [33].

Chemical control antifouling examples include low-adhesive surfaces using zosteric acid extracted from eelgrass (*Zostera marina*) and polymers from sea urchin and killer whales [70]. Antifouling coatings include bioinspired dopamine from mussels [109] and natural enzyme [127] additives. Additionally, researchers have studied antifouling coatings with metabolites from micro-organisms, living bacteria and dopamine [33]. So-called living paints contain inhibitory bacteria to reduce biofouling, as demonstrated by incorporation of *Pseudoalteromonas tunicate* into hydrogels [105].

Table 5. Biofouling cleaning/disinfecting techniques.

type	mechanism	source
medical		
chemicals	toxic disinfectants (e.g. chlorine, alcohol)	Okochi *et al.* [160]
wet heat	steam autoclave sterilization	Life Science Outsourcing, Inc. [159]
dry heat	hot dry air sterilization	Life Science Outsourcing, Inc. [159]
vibrations	ultrasonic alcohol bath sterilization	Railkin [12]
plasma	cool plasma targets biofilms inside teeth	Dunham [161]
gamma rays	radiation exposure sterilization	Life Science Outsourcing, Inc. [159]
ethylene oxide	toxic gas sterilizes plastics, optics, electronics	Life Science Outsourcing, Inc. [159]
marine/industrial		
air bubbles	toxic air bubbles with dissolved kerosene	Railkin [12]
mechanical	manual scraping or with rotary tool removal	Cristiani [162]
jet spray	pressurized water blasting removal	Cristiani [162]
air drying	toxic dry-docking or air drying	Cristiani [162]
explosives	explosion-induced removal	Fischer *et al.* [128]
pH level	toxic acidic/alkaline solutions	Cui & Wan [80]
phages	viruses target and infect bacteria	Simoes *et al.* [77]

(b) *Additional approaches for completeness*

(i) *Cleaning and disinfecting*

Physical cleaning and disinfecting chemically are often considered effective methods to remove biofouling, albeit most tedious [11,13,17,157–159]. Table 5 lists many examples of methods in practice from medical, marine and industrial fields. Most employ mechanical methods, such as manual scrubbing, to disrupt and remove the biofouling. Figure 16 illustrates common methods of cleaning and disinfection such as medical sterilization, chemical disinfection, high-pressure water spray, automatic brush scrubbing and membrane-cleaning techniques. Included are a steam sterilization medical autoclave, Listerine antiseptic mouth rinse, water spray on a low-adhesion ship hull, automatic brush washing system and microfiltration membrane using sonication, chemicals and water backwash. As discovered and reinforced throughout nature, a combination of methods to clean the membrane proved to be most effective [163].

Disinfection is commonly employed in dental applications with antiseptic mouth rinses such as Listerine. For example, the active ingredient chlorhexidine attacks and reduces dental biofilm in order to control plaque and gingivitis in the oral cavity [164]. The biofilm is reduced when the individual bacteria
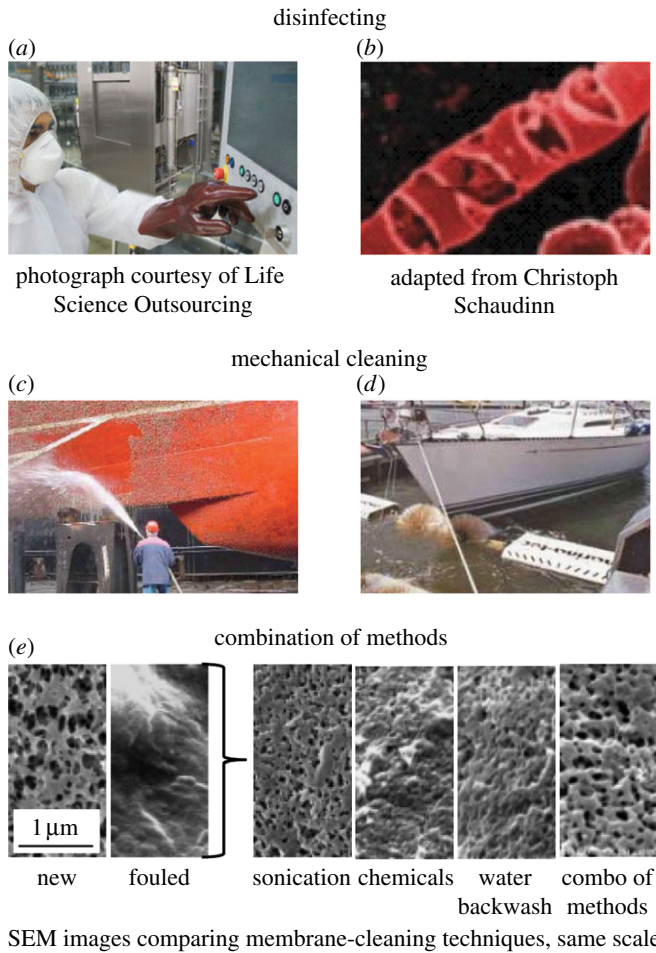
disinfecting

(*a*)

photograph courtesy of Life Science Outsourcing

(*b*)

adapted from Christoph Schaudinn

mechanical cleaning

(*c*)

(*d*)

(*e*)   combination of methods

1 μm

new   fouled   sonication chemicals water   combo of
                                        backwash methods

SEM images comparing membrane-cleaning techniques, same scale

Figure 16. Medical, marine and industrial biofouling cleaning examples. (*a*) Steam sterilization medical autoclave, (*b*) Listerine effect on bacteria, (*c*) water spray on a low-stick ship hull (adapted from Willemsen [101]), (*d*) automatic brush washing system (adapted from Willemsen [101]) and (*e*) microfiltration membrane using sonication, chemicals and water backwash (adapted from Lim & Bai [163]). (Online version in colour.)

walls rupture, as illustrated in figure 16 (www.jjdentalprofessional.com). Mouth rinses combined with brushing and flossing increase the effectiveness, as such 'mechanical methods' disrupt the biofilm [158].

(ii) *Miscellaneous*

Table 6 shows a variety of antifouling prevention methods. For instance, as shown in figure 17, a biosensor developed by NASA detects small amounts of bacteria, viruses and parasites to prevent the spread of disease. It can prevent biohazards in applications ranging from the Earth to the International Space Station. The sensor operates by implementing ultra-sensitive carbon nanotubes,

biosensor detects bacteria (photograph courtesy of
NASA Ames and Dominic Hart)

Figure 17. Biofouling prevention technique. Biosensor developed by NASA detects small amounts of bacteria, viruses and parasites to prevent the spread of disease. (Online version in colour.)

Table 6. Miscellaneous antifouling techniques.

type	mechanism	source
miscellaneous		
biosensor	detects presence of bacteria	www.earlywarninginc.com
UV-C	organism DNA manipulation inhibits reproduction	Lebret *et al.* [47]
filters	removal of micro-/macro-organisms	Lebret *et al.* [47]
active surface	cyclic parameters (e.g. varying temperature, charge, wettability, electrons, colour) deter settlement	Harder & Yee [96]
electricity	electric field/shear stress prevents bioadhesion	Yeh *et al.* [44]
surface charge	positive/negative charges deter settlement	Greer *et al.* [165]
responsive surface	changes in wettability (owing to light, temperature, electric field, solvents) inhibit settlement	Genzer & Efimenko [166]

which sends an electrical signal to determine the level of micro-organisms in a sample. Detecting the presence of pathogens can prevent an infectious outbreak before people become sick (www.earlywarninginc.com).

5. Summary and outlook

Biofouling is the accumulation of unwanted biological material on surfaces, as found in medical, marine and industrial applications. Biofouling can pose substantial health risks and financial losses, such as disease-spreading biofilms in hospitals and increased drag on ships. Biofouling composition includes organisms ranging from bacteria to barnacles, whereas inorganic fouling composition includes particles ranging from salt crystals to corrosion.

Generally, micro-organisms initially colonize a surface and form a biofilm. In marine and industrial applications, macrofouling and inorganic fouling usually accompany biofilms.

Nature's flora and fauna demonstrate a multitude of antifouling lessons that can be mimicked for engineering purposes. Many of nature's antifouling mechanisms have been studied to unlock their secrets, including examples such as self-cleaning lotus leaf and shark skin. Antifouling mechanisms include physical and chemical controls such as low drag, low adhesion, wettability, microtexture, grooming, sloughing, various miscellaneous behaviours and chemical secretions. Nature frequently uses a combination of methods in order to successfully prevent fouling. Examples of biomimetic methods in practice include shark skin inspired surface microtextures, as well as sloughing-inspired self-polishing paints.

Other antifouling approaches range from biocidal and self-cleaning coatings to various disinfecting techniques. For instance, medical devices use antimicrobial coatings to inhibit biofilm formation, ships use low-adhesion paints and power plants use chemical treatments. Medical cleaning is accomplished with sterilization and disinfecting chemicals, while marine and industrial cleaning primarily relies on high-pressure water jets or brush scrubbing.

Developing physical control non-toxic foul-release surfaces for medical, marine and industrial applications is particularly appealing. Approaches include creating antifouling surfaces with microtextured topographies, as well as with superhydrophobic or superhydrophilic wettability properties. Variables to consider and test include the antifouling physical and chemical control mechanisms found in nature. Research could focus on gleaning the best properties from each example and combining them to produce an effective antifouling surface resistant to a variety of foulers.

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