

Advances in Nonfouling Materials: Perspectives for the Food Industry

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ABSTRACT: Fouling of complex food components onto food-processing materials affects food quality, food safety, and operating efficiency. Developments in nonfouling and fouling-release materials for biomedical and marine applications enable the potential for adaptation to food applications; however, challenges remain. The purpose of this review is to present different strategies to prevent fouling and/or facilitate foulant removal with a critical point of view for an application of such materials on food-processing surfaces. Nonfouling, self-cleaning, and amphiphilic materials are reviewed, including an explanation of the mechanism of action, as well as inherent limitations of each technology. Perspectives on future research directions for the design of food processing surfaces with antifouling and/or fouling release properties are provided.

KEYWORDS: nonfouling material, fouling release, protein repellent, self-cleaning, food processing

INTRODUCTION

Fouling of food components onto food-processing surfaces (e.g., stainless steel, rubber gaskets, membranes, polymer or metal conveyor belts) reduces operating efficiency, shortens run times, and increases the likelihood of biofilm formation. As it pertains to the food industry, fouling can loosely be defined as the accumulation of minerals, proteins, and other food components on food-processing surfaces after prolonged submersion in liquid or semiliquid food products. In addition to providing a conditioning layer for the growth of pathogenic or spoilage biofilms,^{1,2} fouling of food-processing surfaces has a substantial impact on processing efficiency, productivity, and food quality. Fouling is a particular issue in heat exchangers, where wall heating effects exacerbate foulant deposition (Figure 1).³ As foulant builds up on the product side of a heat

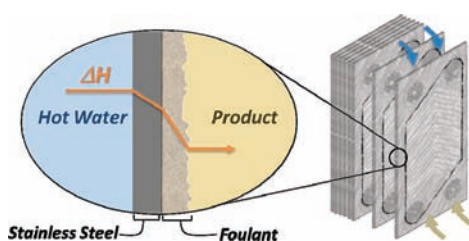


Figure 1. Fouling on plate heat exchanger. Mineral and complex (protein, carbohydrate, lipid) foulants build up on the product-contact side of stainless steel in a plate heat exchanger. As the thickness of the foulant layer increases, heat transfer and operational efficiencies decrease.

exchanger, thermal conductivity is reduced, increasing utility demands.⁴ Foulant buildup is similarly an issue in membrane processes. In both cases, eventually, foulant thickness increases to a point that fluid flow is significantly affected, increasing pump demand to maintain flow rate. Once fouling has been initiated, continued buildup of food components results in the eventual need for cleaning. In many cases, foulant can be removed only by shutting down production, dismantling the

unit, and manually cleaning the fouled equipment. In dairy processing, cleaning to remove foulant has been reported to be up to 15% of the total production time⁵ and accounts for up to 80% of total production costs,⁶ so the industrial economic impact of fouling on food-processing surfaces cannot be underestimated. A major challenge in the food industry is to avoid or minimize fouling caused by food components such as minerals and proteins during processing. This paper reviews recent advances in the design of nonfouling and self-cleaning materials. The following different approaches are described: protein-repellent surfaces, zwitterionic surfaces, stimuli-responsive polymers, the lotus effect, and amphiphilic materials. Finally, we critically evaluate challenges and opportunities toward possible applications of each approach to food processing.

Mechanisms of Fouling on Food-Processing Surfaces.

Despite the industry-wide impact of fouling on food-processing and -handling surfaces, the fundamental mechanisms by which fouling is initiated are not well understood. Several factors have been hypothesized to contribute to fouling in heat exchangers, including particulate deposition, protein content, mineral composition, and wall heating.⁷

According to Epstein,⁸ fouling mechanisms can be classified into five major categories,^{8–10} including precipitation, particulate, biofouling, corrosion, and chemical reaction fouling. It is unlikely that fouling is due to a single mechanism; rather, fouling likely involves a combination of several mechanisms occurring simultaneously. With regard to fouling by dairy products, two major classes of foulant are observed. Between 85 and 110 °C, a high protein content deposit forms, whereas at higher temperatures (110–140 °C) a higher mineral content deposit forms, consisting of calcium and phosphorus salts.¹¹

Received: November 18, 2011

Revised: January 25, 2012

Accepted: March 6, 2012

Published: March 6, 2012

Fouling is a time-dependent phenomenon. Five stages of fouling^{8–10} have been identified. During initiation, there is a delayed onset of fouling during which materials undergo surface conditioning and nucleation begins to initiate fouling. In the transport stage, there is mass transfer of additional foulant to the surface, which facilitates the attachment stage, in which foulant adheres to the surface via a range of interactions including electrostatic, hydrophobic, and surface nucleation. Often, there are also removal and aging stages in fouling. Removal may be a result of autoinitiated detachment or release of foulant from the material or by externally forces such as scouring, sloughing, or other mechanical agitation. In later stages of a fouled material, the fouled layer may age, particularly in a heated surface such as a heat exchanger. In this case, the nature of the foulant may change over time, influencing adhesion and cleanability characteristics. With regard to food processing, this may influence product quality by imparting a “cooked” flavor or sloughed off mineral deposits in the final product.

In the literature, fouling deposits caused by diverse food products have been studied, including coconut milk,¹² sugar cane juice,¹³ apple juice,¹⁴ cheese sauce,¹⁵ and, most commonly, milk.^{11,16–18} Numerous factors have been reported to influence the foulant deposition rate, adhesion strength, and chemical composition such as the operating conditions (temperature, flow, etc.), the nature of the processing surface (topography/roughness, chemical nature), and the composition of the processed fluid. It has been demonstrated that the composition of the fluid plays an important role in the chemical composition and deposition rate of fouling. Christian et al.¹⁸ showed that the addition of mineral salts, calcium and phosphate, to whey protein concentrate solution decreases the amount of deposit and changes its chemical composition, suggesting that fluctuation in fluid composition can significantly alter the content and nature of fouling. Therefore, understanding the conditions that promote fouling and being able to manipulate food-processing surfaces to prevent such fouling and/or facilitate foulant removal would have significant economic impact on the food-processing industry. Figure 2¹⁹ shows schematically three major strategies to design nonfouling surfaces. Most often, researchers seek to manipulate surface properties such as wettability (hydrophobic, hydrophilic) and topography.

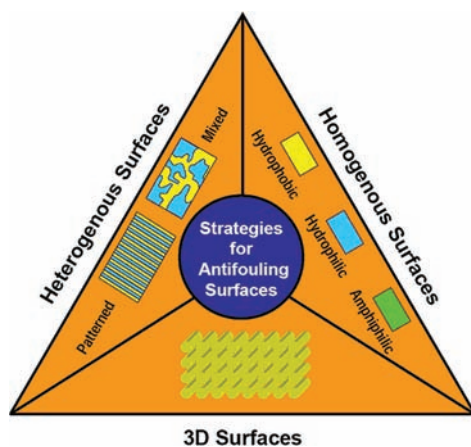


Figure 2. Approaches to the design of nonfouling materials.¹⁹ Reproduced with permission from ref 19 (<http://dx.doi.org/10.1039/b801491d>). Copyright 2008 The Royal Society of Chemistry.

Financial Impact of Fouling. Fouling is a complex and costly problem that affects many different sectors including the biomedical, marine, petrochemical, and food industries. The total financial impact of fouling was estimated in 2000 by Müller-Steinhagen²⁰ to be 0.25% of the gross national product (GNP) for industrialized countries such as the United States (\$7 billion) and up to 0.15% of the GNP for other countries. As it pertains to the food industry, about 80% of the total production cost in dairy processing has been attributed to fouling and cleaning of fouled process equipment.⁶ In the food industry, fouling is very severe and more expensive compared to other industries. Indeed, the unwanted deposits formed during food processing need to be cleaned on a daily basis or more often, for example, every 5–10 h, depending on the severity of the fouling, whereas such foulant removal is done once a year or less in the petrochemical industry. These frequent cleanings²¹ interrupt the production process and have significant economic and environmental impacts. Fouling can decrease permeate flux in filtration systems,²² reduce heat-transfer efficiency in heat exchangers,²³ and increase fluid frictional resistance in ultrafiltration, piping, or pasteurization²³ and lead to the formation and survival of pathogenic biofilms.²⁴ However, cleaning has its limitations and does not always remove all of the fouling deposits.²¹ For these reasons, there is substantial industrial and research interest in designing materials that reduce fouling of food-processing surfaces. As described in the sections that follow, two major approaches are considered toward this goal: the design of surfaces that resist the initiation and buildup of foulants (i.e., nonfouling materials) and the design of surfaces with fouling-release properties, in which the foulant is easily detached from the surface (i.e., “self-cleaning” materials).

■ NONFOULING MATERIALS

Protein-Repellent Surfaces. Whereas the exact conditions that promote initiation of fouling are not fully understood, fouling by food proteins is an important area of research toward the development of nonfouling materials. Hydrophobic surfaces (such as stainless steel and many food-contact polymers) can adsorb proteins via hydrophobic protein–surface interactions, and the adsorbed protein molecules can undergo conformational changes,²⁵ which can lead to irreversible fouling. A widespread approach to reduce protein fouling on hydrophobic surfaces is to modify the surface chemistry of such materials by the grafting or coating of hydrophilic polymers.

Among these hydrophilic polymers, poly(ethylene glycol) (PEG), also named poly(ethylene oxide) (PEO), is well-known for its protein-repellent, antifouling properties. In the literature, the antifouling properties of PEG are well documented.^{26–32} The ability of these antifouling polymers, and particularly PEG, to prevent nonspecific protein adsorption has been studied theoretically³³ by Jeon,^{34,35} Szleifer,^{36,37} and Halperin³⁸ for polymer brushes and by Prime^{39,40} and Grunze^{41,42} for self-assembled monolayers (SAMs). Jeon and others explained the resistance to protein adsorption of PEG brushes by a “steric and osmotic repulsion” mechanism^{34–38} (Figure 3), in which the compression of PEG chains during the approach of the protein toward the surface leads to steric repulsion, whereas the resistance of the hydrated polymer to release both bound and free water during compression creates an osmotic repulsion, that is, the “water barrier”. In Figure 3, protein adsorption onto a hydrated PEG brush disrupts the water molecules surrounding both protein and polymer chains (favorable

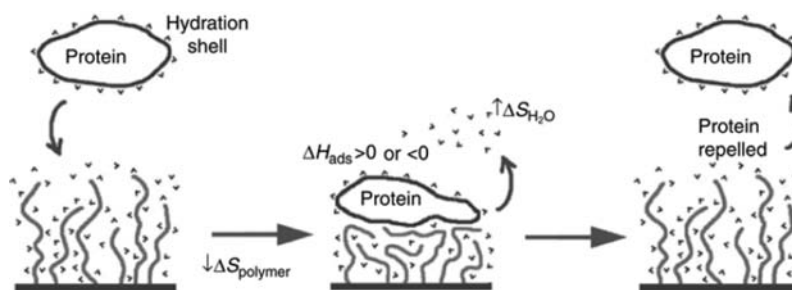


Figure 3. Proposed mechanism for preventing protein fouling by grafting a hydrophilic polymer such as polyethylene glycol. Polyethylene glycol swells with water to create an osmotic repulsion, that is, a “water barrier”. Reproduced with permission from ref 153. Copyright 2007 Springer Science+Business Media.

entropy gain: $\uparrow\Delta S_{\text{H}_2\text{O}}$) and compresses the polymer chains (unfavorable entropy loss: $\downarrow\Delta S_{\text{polymer}}$), leading to the repellency of the protein by the PEG brush (protein adsorption entropically unfavorable). In Figure 3, protein–polymer adsorption enthalpy is represented by the term “ ΔH_{ads} ”.

This model implies that to successfully impart nonfouling character, the PEG must be long polymer chains with a high surface coverage, in other words, a densely packed surface of a high molecular weight ($M_w \geq 2000$ g/mol) grafted polymer.^{34–38} However, Prime showed that oligo(ethylene glycol) (OEG) terminated SAMs of a few units presented good antifouling properties^{39,40} and attributed that observation to the fact that SAMs intrinsically result in surface coatings with much greater numbers of ethylene glycol chains per unit area than most chemical grafting methods due to improved density. Grunze emphasized the importance of the conformation of the OEG chain showing difference on the adsorption of fibrinogen protein, in which helical OEG was resistant to fibrinogen adsorption, whereas the trans conformation adsorbed fibrinogen.⁴¹

Thus, different important factors play a crucial role in the antifouling behavior of the PEGylated surfaces including polymer grafting density^{37,43,44} and temperature,^{43–45} and to date no theoretical model adequately describes their influence. McPherson showed that the greatest contribution to the prevention of protein adsorption by PEGylated surfaces is the surface density of the grafted polymer and that polymer molecular weight (M_w) (i.e., chain length) was less important.³⁷ A variation of the chain grafting density can affect the range and magnitude of the protein-repellent behavior of the grafted PEG.^{43,44} It has been reported that PEG grafting density can be influenced by inducing lowest critical solubility conditions during grafting. Lowest critical solubility (LCS) conditions are those at which the polymer chains take on a desolvated, collapsed form and are therefore more capable of packing more densely onto a surface. LCS conditions can be achieved by altering temperature, ionic strength, or PEG concentration. Kingshott^{46,47} reported LCS conditions of 60 °C and 0.6 M potassium sulfate.

A challenge in comparing reports of antifouling materials is that experimental conditions of the antifouling experiments vary widely. Specifically, one factor that seems to have an effect in certain cases is the temperature at which the tests of protein adsorption are conducted. Leckband⁴³ showed that a grafted PEG was unable to retain its antifouling properties against streptavidin above 35 °C, whereas Norde⁴⁴ and Schwendel⁴⁵ presented different results with bovine serum albumin (BSA) and human blood plasma and fibrinogen, respectively. They observed a retention of the protein resistance of the PEGylated

surfaces at a wide range of temperatures (between 22 and 38 °C⁴⁴ or >0 and 85 °C⁴⁵).

Different architectures of PEGylated surfaces have shown antifouling properties: linear (brushes),^{26,27} branched (comb-like polymers with PEGylated side chains),^{30,31} and hyperbranched (dendrimer).^{28,29} Several approaches have been used to attach PEG on surfaces including physical adsorption,⁴⁸ self-assembled monolayers,⁴⁰ grafting methods,^{27,49} and plasma polymerization or immobilization.^{50–53} The drawback of SAMs is their reported instability due to their molecular scale thickness compared to covalent attachment of PEG that is permanent and leads to irreversible grafting. Two common grafting methods, “grafting-to” and “grafting-from”, are used to tether PEG onto a surface.⁵⁴ The “grafting-to” method consists of a coupling between a functionalized surface and polymer chain, which limits the density of the attached polymer chain (mushroom regime), whereas the “grafting-from” one is a polymerization from the surface, or surface-initiated polymerization (dense brush regime). Therefore, the “grafting-to” method is more convenient for practical applications, whereas the “grafting from” method leads to higher surface density with better control over chain length. Plasma polymerization or cross-linking can be also used to covalently attach PEG-like layers on a variety of substrates such as stainless steel⁵³ or poly(vinylidene fluoride) membrane.^{51,52}

The stability of PEGylated surfaces is an important parameter for long-term antifouling applications in food processing. Sharma⁵⁵ demonstrated that PEG-modified silicon surfaces retained their protein repulsive properties after at least 4 weeks of submersion in a PBS buffer (pH 7.4) at 37 °C, in 5% CO₂. It has further been reported that PEG can undergo oxidative degradation and form aldehydes and ethers in the presence of oxygen and elevated temperatures. This phenomenon, although not widely reported, can lead to a loss in protein repellency and may be preventable by the use of antioxidants.⁵⁶

Other hydrophilic polymer coatings have been reported to exhibit protein repellency as well, including polysaccharides,^{57,58} poly(vinyl alcohol),^{59,60} poly(hydroxypropyl methacrylate),⁶¹ dendritic polyglycerols^{62–64} and others.⁶⁵ According to Chapman,^{66,67} common characteristics for many antifouling polymers include hydrophilic nature, electrical neutrality, and hydrogen-bond acceptors (not donors). Indeed, research suggests that for the most part, fouling is worse on surfaces modified by polymers having terminal groups that are hydrogen donors (e.g., hydroxyls), and fouling is less severe when the same polymer is terminated with a non-hydrogen donor (e.g., methoxy termination). A notable exception is that of OEG, in which both hydroxy- and methoxy-terminated

ethylene glycol oligomers have been reported to resist fouling by fibrinogen (fib) and lysozyme (lys) to a similar degree.^{66,67}

PEGylated and other hydrophilic-modified surfaces present good antifouling properties with regard to protein repellency and may therefore be appropriate for applications in the food industry to reduce fouling and associated costs of frequent cleanings. Challenges toward commercial application include ensuring a good surface coverage as well as demonstrating the stability of such PEGylated surfaces at temperatures typically used in food processing. In applications where mineral, not protein, deposits are the predominant foulant, such hydrophilic-modified surfaces may not be sufficient.

Zwitterionic Surfaces. Previously, it has been shown that neutral hydrophilic polymers such as PEG can be used to prepare antifouling surfaces. However, another class of polymers, zwitterionic polymers, also presents good protein-repellent behavior and includes polymers incorporating phosphorylcholine,^{68–71} sulfobetaine,^{72–76} or carboxybetaine^{77–80} groups. According to IUPAC, a zwitterionic polymer is “an ampholytic polymer in which ionic groups of opposite sign are incorporated into the same pendant groups”.⁸¹ Several studies comparing zwitterionic and PEG/OEG coated surfaces have shown comparable results in their ability to reduce protein adsorption.^{69,72,74} Hydration of zwitterionic polymers plays an important role in the mechanism of protein repellency; the hydration layer generates repulsive force on the approaching proteins. Contrary to the PEG, the water molecules are bound electrostatically by ionic interactions, not hydrogen bonding.⁸²

As with PEG, the protein resistance depends on the surface grafting density and the chain length of the zwitterionic polymers.^{68,69,76,83,84} Feng et al.^{68,69} reported that increasing the graft density or the chain length of phosphorylcholine-based surface contributes to decreased adsorption of fibrinogen and that the graft density is a more important factor than graft chain length for protein resistance. The influence of environmental factors including temperature,^{72,73,77} pH,^{72,79,85,86} and ionic strength^{72,73,75,76,79,86} of the protein solution on the ability of zwitterionic polymers to prevent protein fouling has been investigated by different research teams. Chang et al.^{72,73} and Cheng et al.⁷⁷ have demonstrated the thermal stability of the antifouling behavior of sulfobetaine- and carboxybetaine-modified surfaces, respectively, from room temperature to 37 °C. In general, zwitterionic polymers impart high protein repellency in a wide range of ionic strengths and pH values. However, in certain cases, an increase in the amount of adsorbed protein can be observed at low ionic strength^{73,75,79,86} and low pH value.^{72,79,85,86} The pH can affect the net charge of both the protein and the surface and lead to electrostatic interactions between the polymer (whether or not it is zwitterionic) and the protein.^{72,79,86} Wu et al.⁸⁶ have studied the adsorption of BSA onto carboxybetaine, sulfobetaine, and cationic surfaces in a phosphate buffer solution (PBS, pH ~6.9) and an acidic solution (MES, pH~3.5). As a function of the pH, the protein can be negatively (pH ~6.9) or positively (pH ~3.5) charged, like the carboxybetaine surface, whereas sulfobetaine and cationic surfaces stay negatively and positively charged, respectively. Both zwitterionic polymers show low protein adsorption independent of changes in pH, although the sulfobetaine surface presented a slight increase of BSA adsorption at low pH compared to the carboxybetaine surface. This slight increase is explained by an electrostatic attraction between the opposite charges of the protein and the surface that is limited by strong steric hydration repulsion forces, unlike

the cationic surface, which exhibits strong adsorption of BSA at pH around 6.9.

Likewise, the presence and concentration of ionic salt in the protein solution has an electrostatic screening effect that leads to an effective decrease of the electrostatic interactions between the zwitterionic polymer and the protein, resulting in better protein repellency of the zwitterionic surface.^{73,75,76} At low ionic strength or in a salt-free environment, a slight increase of protein adsorption has been observed on carboxybetaine⁷⁹ and sulfobetaine^{73,75} surfaces due to the absence of or weak electrostatic screening effect of the ionic salt compared to conditions with a higher ionic strength. Zhang et al.⁷⁹ had shown that the length of the spacer group between the positive and negative groups of carboxybetaine influences the antifouling properties of the zwitterionic polymer. With long spacer groups such as propylene or pentene, the range of ionic strengths and pH values at which the zwitterionic polymer is highly protein resistant decreases, particularly at low ionic strength and low pH value.⁷⁹

Pseudozwitterionic systems have also demonstrated promising antifouling properties.^{73,87–90} Ampholytic systems with a pseudozwitterionic structure are achieved by the synthesis of mixed-charge copolymer brushes, imparting an overall charge neutrality and resulting in overall ionic character similar to that of a zwitterionic polymer. Such pseudozwitterionic systems indicate that the overall charge balance is an important factor for the protein resistance behavior of such systems.^{73,88,90} Chang et al.⁷³ have shown that the protein adsorption behavior of the mixed-charge poly(TMA-*co*-SA)-grafted surfaces (11-mercapto-*N,N,N*-trimethylammonium chloride, TMA; 11-mercaptoundecylsulfonic acid, SA) was different from that of a sulfobetaine-based zwitterionic polymer-grafted surface and presents a much higher protein adsorption at low ionic strengths.

Zwitterionic and pseudozwitterionic polymers could be used for their antifouling properties in the food industry. However, further research at higher temperatures and with food products that have a more complex composition than single protein solutions is needed to validate their possible applications in the food industry.

■ SELF-CLEANING MATERIALS

The most common approach to designing materials that mitigate fouling by food components is to develop surfaces that resist the initiation and attachment of fouling. An interesting alternative is to develop so-called “self-cleaning” materials that, once fouled, can be cleaned in situ by changing the flow rate or other processing conditions. Below, we describe two classes of self-cleaning materials: those that can modulate surface chemistry as a function of some external stimulus and in turn release foulants (i.e., stimuli-responsive polymers) and those that are easy to clean due to their chemically and/or topographically defined low surface energy (i.e., the lotus effect).

Stimuli-Responsive Polymers. Stimuli-responsive or “smart” polymers are defined as polymers that undergo dramatic physical or chemical changes in response to small changes in environmental conditions such as temperature, pH, ionic strength, or electrical potential.^{91,92} Among these “smart” polymers, thermo-responsive polymers presenting a reversible change of wettability induced by a temperature-dependent conformational transition between a highly solvated, randomly coiled form and a desolvated, collapsed form of the polymer

chains are promising for a controlled fouling release. The temperature at which this conformational transition occurs is referred to as the lower critical solubility temperature (LCST), which can be tailored by altering polymer chemistry by copolymerization of other monomers such as poly(*N*-isopropylacrylamide) (PNIPAAm) as described below. It may be possible to exploit this particular behavior inducing a volume change and a transition between hydrophilic and hydrophobic state of the polymer chains to promote fouling release.^{93,94}

One of the most studied examples of stimuli-responsive polymers is PNIPAAm, for which this transition phenomenon (reversible solubility changes) happens at a LCST of ~ 32 °C in aqueous solution.⁹⁵ PNIPAAm has been extensively studied mainly for biomedical applications such as drug delivery systems⁹¹ and cell culture dishes⁹⁶ because of its LCST close to physiological temperature (37 °C). Several studies have shown its potential as a fouling release agent of different kinds of proteins, bacteria, and cells.^{93,96–104}

The fouling release of proteins by PNIPAAm grafted surfaces as reported in the literature is of great interest. A general observation is that the adsorption of proteins (e.g., myoglobin,¹⁰⁰ hemoglobin,¹⁰⁰ cytochrome *c*,^{100,105} BSA,^{100,105,106} polyclonal anti-horse ferritin antibody (anti-Fe),¹⁰⁶ or fibrinogen (Fg)^{104,106}) is greater above the LCST than below it.^{100,104–106} This is explained by a more pronounced affinity of the protein to foul onto the more hydrophobic surface exhibited above the LCST (via hydrophobic interactions) compared to the hydrophilic surface exhibited below the LCST.

Just as temperatures above a polymer's LCST may promote protein fouling, temperatures below the LCST induce a polymer phase transition, which can lead to a decrease in the binding strength of proteins adsorbed onto surfaces modified with PNIPAAm.¹⁰⁶ It has been reported that the proteins can detach spontaneously from the surface^{100,106} upon this temperature-induced change in surface hydrophilicity. However, if proteins have irreversibly bound to the material through strong interactions, such temperature-induced modulations in surface hydrophilicity may not be sufficient to cause protein release.¹⁰⁶ Other studies suggest that the fouling release of adsorbed proteins can be simply performed by washing the "smart" surface with a solution below LCST, enabling repeated use of the self-cleaning stimuli-responsive material. Reversible protein adsorption may depend on other factors beyond just the conformational change of PNIPAAm, including the nature of the protein, the method of grafting used (chemical or plasma polymerization, grafting density, thickness), and the conditions used to assess fouling (temperature, time, etc.). Finally, some studies show that PNIPAAm also presents resistance to protein adsorption even above LCST in its more hydrophobic state;^{100,106} however, its effectiveness seems to depend on the thickness of the coating.^{102,104,107}

Food-processing temperatures are typically higher than those used to assess nonfouling character of stimuli-responsive polymers, and the chemical nature of the foulant is typically different from that used in the previously described work. It would therefore be interesting to investigate PNIPAAm-grafted surfaces in conditions closer to the ones used in the food industry (processing temperatures, food products such as milk and juice). Application of stimuli-responsive polymers as self-cleaning materials in the food industry therefore remains an emerging area of research.

Lotus Effect. Self-cleaning due to chemically and topographically induced water repellency, also known as the "lotus effect", naturally occurs on lotus leaves and many other plants.¹⁰⁸ What is interesting about the lotus leaf as it pertains to self-cleaning food-processing surfaces is its unique ability to readily remove surface contaminants by water droplets, which pick up dirt as they slide across the surface (Figure 4).

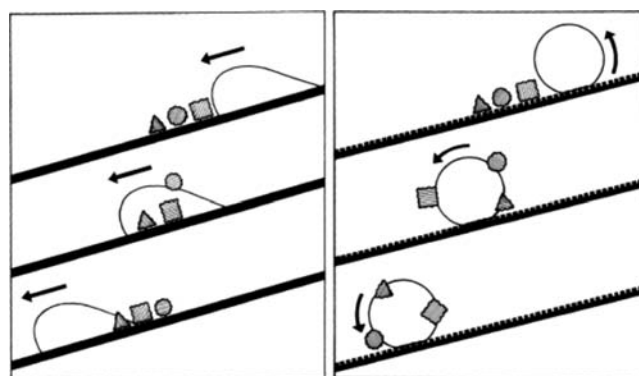


Figure 4. (Left) Movement of a water droplet across debris on a typical surface; (right) collection and removal of debris by water droplet on a superhydrophobic surface exhibiting the lotus effect. Reproduced with permission from ref 154. Copyright 1997 Springer Science+Business Media.

A superhydrophobic surface (i.e., one with a contact angle $>150^\circ$) must have a low contact angle hysteresis (advancing and receding contact angle of similar values) to be effectively self-cleaning.¹⁰⁹ Micro- and/or nanoscale topographical structures are typically necessary to obtain such a superhydrophobic surface, because the combination of the hydrophobic material chemistry with air entrapped between these structures results in greater hydrophobicity than the native, planar material. Consequently, hydrophobic surfaces (i.e., those with a contact angle $>90^\circ$) can become superhydrophobic by the introduction of such roughness. For example, a smooth polysiloxane surface exhibits a contact angle of 75° , whereas the contact angle on rough polysiloxane surface is 169° .¹¹⁰ In the case of lotus leaves, an alteration of the surface structure by removing nanoscale hair-like features while keeping the chemical composition unchanged leads to the loss of its self-cleaning property:¹¹¹ the contact angle decreases from 142° to 126° after removal of the nanoscale hairs. The lotus effect has been reproduced on artificial superhydrophobic surfaces.^{112–114} In the literature, a wide variety of techniques^{112,113} have been used to generate superhydrophobic surfaces involving chemical and/or physical methods such as lithography,^{115,116} the use of a template,¹¹⁷ and sol-gel¹¹⁸ methods. Adaptation of conventional lithography techniques to larger surface areas via roll-to-roll processing or block-copolymer templating would enable the potential for commercial adaptation of such lotus effect surfaces. Indeed, such superhydrophobic surfaces would have great potential if applied to food-processing surfaces because self-cleaning properties would enable rapid and facile cleaning of fouled surfaces.^{110,114,118}

Under static conditions, superhydrophobic surfaces have been reported to reduce the occurrence of marine biofouling.¹¹⁰ However, Zhang et al.¹¹⁰ reported that superhydrophobic materials can lose antifouling properties after long-term immersion in seawater. This phenomenon was explained as

Table 1. Examples of Structures of Precursors or Polymers of Amphiphilic Materials Studied for Their Antifouling and/or Fouling-Release Behaviors

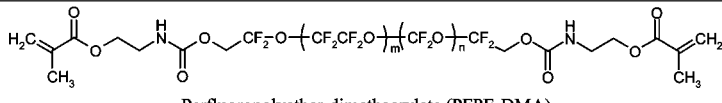


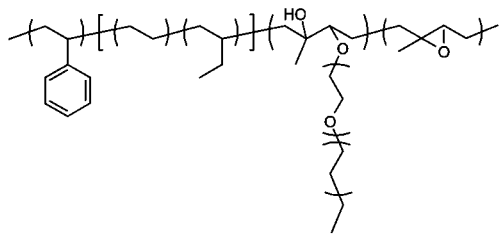
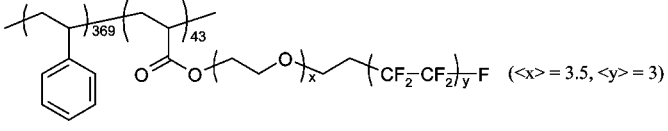
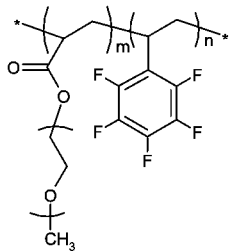
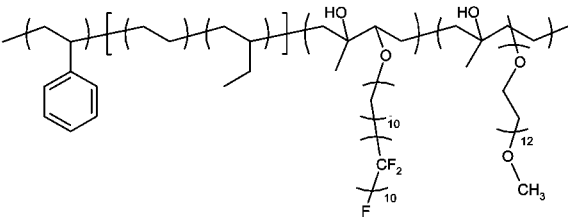
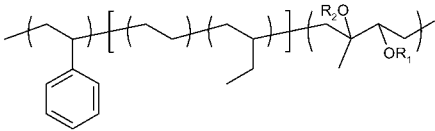
	Structure or precursor of amphiphilic copolymer /network :	Anti-fouling and/or fouling-release properties tested with:	Ref.
1	 <p>Perfluoropolyether-dimethacrylate (PFPE-DMA)</p>  <p>poly(ethylene glycol) monomethacrylate (PEG-MA) poly(ethylene glycol) dimethacrylate (PEG-DMA)</p>	<ul style="list-style-type: none"> <i>Ulva</i> spores/sporelings Juvenile barnacles 	136
2	 <p>1H,1H,2H,2H-perfluorodecyl acrylate, PFDA Diethyleneglycol dimethyl ether, DEGDME</p>	<ul style="list-style-type: none"> Human Serum albumin (HSA) Fibrinogen 	128
3		<ul style="list-style-type: none"> <i>Ulva</i> spores/sporelings Cells of the diatom <i>Navicula</i> 	137
4	 <p>polystyrene-<i>block</i>-poly(ethoxylated fluoroalkyl acrylate), PS-<i>b</i>-PAA-AMP</p>	BSA	129
5	 <p>poly[poly(ethylene glycol)methyl ether methacrylate]-<i>block</i>-poly(2,3,4,5,6-pentafluorostyrene), (P(PEGMA)-<i>b</i>-PPFS)</p>	<ul style="list-style-type: none"> Bovine serum albumin (BSA), a lectin protein from <i>Codium fragile</i> (CFL) and lipopolysaccharides from <i>Escherichia coli</i> (LPSE) Barnacle larvae 	130
6		<ul style="list-style-type: none"> <i>Ulva</i> spores/sporelings Cells of the diatom <i>Navicula</i> 	138
7	 <p>$R_1, R_2 = \text{H or } -\text{CH}_2\text{CH}_2(\text{OCH}_2\text{CH}_2)_x(\text{CF}_2\text{CF}_2)_y\text{F}$ with $x = 0-13$ and $y = 1-5$.</p>	<ul style="list-style-type: none"> <i>Ulva</i> spores/sporelings Cells of the diatom <i>Navicula</i> 	139

Table 1. continued

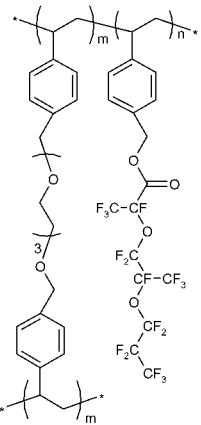
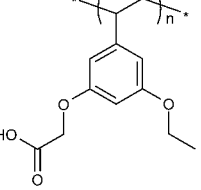
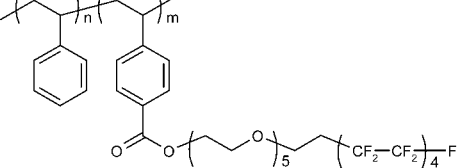
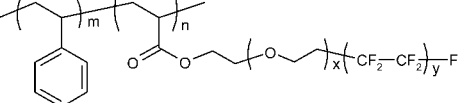
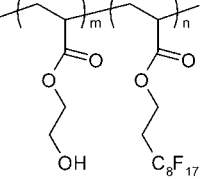
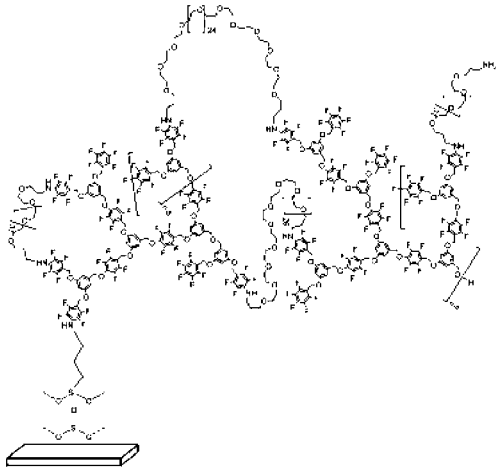
	Structure or precursor of amphiphilic copolymer /network :	Anti-fouling and/or fouling-release properties tested with:	Ref.
8	 <p>Structure of a block copolymer consisting of polystyrene blocks (m and n units) and a polyoxyethylene-polytetrafluoroethylene chain side-group.</p>	Cells of the diatom <i>Nitzschia</i> Bacteria <i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	140
9	 <p>Poly(3-alkoxy-5-carboxystyrene), C2 (ethoxy)</p>	BSA, Cytochrome C and Myoglobin	131
10	 <p>block copolymers of polystyrene, S, and polystyrene carrying an amphiphilic polyoxyethylene-polytetrafluoroethylene chain side-group, Sz</p> <p><i>S_nS_zm</i></p>	<i>Ulva linza</i> spores/sporelings Cells of the diatom <i>Navicula perminuta</i>	141
11	 <p>polystyrene-<i>block</i>-poly(ethoxylated fluoroalkyl acrylate)</p>	<i>Ulva</i> spores/sporelings Cells of the diatom <i>Navicula</i>	142
12	 <p>Random copolymer of 2-hydroxyethylmethacrylate (HEMA) and perfluorodecylacrylate (PFA), PHEMA-<i>r</i>-PFA</p>	BSA	132

Table 1. continued

	Structure or precursor of amphiphilic copolymer /network :	Anti-fouling and/or fouling-release properties tested with:	Ref.
13	 <p style="text-align: center;"><i>Reproduced with permission from</i>¹³⁴</p>	BSA, lectin from <i>Codium fragile</i> (CFL), lipopolysaccharides from <i>Escherichia coli</i> (LPSE) and <i>Salmonella minnesota</i> (LPSS) <i>Ulva</i> spores/sporelings	134

the disappearance of the air bubble layer due to pressure, organisms that displace the air, or the attachment of a conditioning layer of macromolecules that change the surface chemistry.

The water repellency of superhydrophobic surfaces prevents the penetration of protein solutions into the topographically defined air bubbles and can therefore limit the amount of protein adsorption. However, protein can act as a surfactant, allowing the protein solution to penetrate farther into the surface topography, leading to a greater surface area for protein adsorption.^{118–120} Furthermore, it is known that hydrophobic interactions play a dominant role in surface–protein interactions. Therefore, the contact angle of a droplet of protein solution on a topographically defined material likely exists somewhere between Wenzel's state (in which liquids penetrate the topographically defined structures) and Cassie's state (in which air bubbles dominate the gaps between topographically defined structures).¹²⁰ The presence of proteins in food products for which fouling is a concern presents a challenge in leveraging the lotus effect for food-processing surface design; however, the same challenge is present in biomedical^{121,122} and marine biofouling^{110,123,124} applications for which the lotus effect is of great research interest and has shown promise.

An interesting characteristic of the lotus effect is its behavior under shear stress. Koc et al.¹¹⁸ have studied the adsorption of BSA on superhydrophobic surfaces with roughness of various length scales (micro- and nanoscale) under static and shear flow conditions. Under static conditions, BSA adsorption was not reduced by using superhydrophobic surfaces compared to flat surfaces. However, under shear flow conditions, the adsorbed protein is almost completely removed from the superhydrophobic surfaces. The ability to readily remove foulant (such as adsorbed protein) by application of increased shear, which can be achieved by increasing fluid flow rate in a pipe or spraying a work table with a water hose, has great potential interest for the food industry. However, understanding the stability of this kind of surface under a continuous flow shear as well as the effectiveness of such materials after accumulation of contaminants is an area in need of research.

■ “AMBIGUOUS” SURFACES: AMPHIPHILIC MATERIALS

It has been demonstrated that hydrophobic coatings based on a polymer presenting a low surface energy and a low Young's modulus such as poly(dimethylsiloxane) (PDMS)¹²⁵ exhibit good fouling-release performances. On the other hand, hydrophilic surfaces based on PEG presented previously in this review have often been reported to resist protein adsorption. The development of new materials combining antifouling and fouling-release properties is of great interest and has led to the synthesis of amphiphilic coatings that are “ambiguous” surfaces including both hydrophobic (low surface energy) and hydrophilic components. Such amphiphilic materials have shown their ability to resist the adsorption of a variety of proteins^{126–134} and to facilitate the removal of microorganisms in marine applications (e.g., fouling of ship hulls).^{129,135–141}

Table 1 presents a summary of reported amphiphilic polymers for which antifouling and/or fouling-release properties have been tested. Different polymeric amphiphilic structures have been reported in the literature including homopolymer,⁷³ network,^{133–135,139} random,¹³¹ diblock,^{128,129,140,141} or triblock^{136–138} copolymers. The amphiphilic character can be given by the presence of hydrophobic and hydrophilic monomer units in the copolymer,^{127,129,131,135,137,139} or amphiphilic side chains on the polymer backbone.^{128,136,138,140,141} The hydrophobic part of amphiphilic materials is mostly fluorinated groups such as perfluoroalkyl. However, long perfluoroalkyl chains can degrade and lead to the formation perfluoroalkyl acids (PFAs), which have been demonstrated to have toxicological effects.^{142,143} For an application of amphiphilic coating in the food industry, it is of great importance to identify alternatives to long hydrophobic perfluoroalkyl moieties such as nontoxic fluorinated or alkyl segments. In the literature, there are few examples of fluorine-free hydrophobic components such as alkyl groups^{130,136} in amphiphilic materials.

Several studies^{130,131,133–137,140} have demonstrated the importance of an appropriate ratio between hydrophobic and hydrophilic parts to optimize the antifouling and/or fouling-release properties of amphiphilic materials. By varying the

composition of amphiphilic polymers, it has been established, for example, that PFPE/PEG-MA networks (Table 1, 1) with PEG content of 10% by weight,¹³⁵ HBFP/PEG networks (Table 1, 13) with PEG content of 45% by weight,¹³³ random copolymer PHEMA-*r*-PFA (Table 1, 12) with PFA content of 40% in mole,¹³¹ and poly(3-alkoxy-5-carboxystyrene) (Table 1, 12) with the alkoxy function corresponding to an ethoxy¹³⁰ displayed optimal antifouling and/or fouling-release performances against microorganisms and/or proteins tested (Table 1).

Young's modulus has been reported to have an influence on fouling-release properties as well, as studied by Chaudhury et al.¹²⁵ and Weiman et al.¹³⁸ This work reported a two-layer coating composed of a polystyrene-*block*-poly(ethylene-*ran*-butylene)-*block*-polystyrene (SEBS) bottom layer and a triblock copolymer with grafted ethoxylated fluoroalkyl amphiphilic side chains (Table 1, 7) top layer by using SEBS with two different Young's moduli (18 ± 0.3 and 1.2 ± 0.3 MPa). No significant difference in the density of settled *Ulva* spores was observed between the amphiphilic coatings on low- and high-modulus SEBS. However, whereas both amphiphilic coatings presented a high fouling release of sporelings, a lower impact pressure was needed to remove a higher percentage of sporelings from amphiphilic coating on the low-modulus SEBS. Manipulation of rheological properties of fouling-release coatings is a unique approach to improving the design of nonfouling materials for food industry applications.

The chemical incompatibility between hydrophobic and hydrophilic moieties can result in the directed formation of nano- or microdomains due to phase segregation, leading to complex topography of amphiphilic coatings. Well-defined morphologies have been observed as a function of the specific composition of the copolymer. For example, Martinelli et al.¹⁴⁰ synthesized block copolymers of polystyrene and polystyrene carrying an amphiphilic polyoxyethylene-polytetrafluoroethylene side chain (Table 1, 10), which presented a morphology with spherical (diameter of ~ 20 nm) or lying-down cylindrical (periodicity of 24–29 nm) domains. Cylindrical domains were also observed by Cho et al.¹³⁶ and Weinman et al.¹²⁸ for a triblock copolymer with grafted amphiphilic side chains composed of PEG and hydrocarbon moieties (Table 1, 3) and a block copolymer polystyrene-*block*-poly(ethoxylated fluoroalkyl acrylate) (PS-*b*-PAA-AMP) (Table 1, 4), respectively. Gan et al.¹³⁴ demonstrated that the size of phase-segregated surface domains of hyperbranched fluoropolymers (HBFP) cross-linked with PEG became smaller from the micro- to nanoscale as the coating thickness or the content of PEG decreased.

It has also been suggested that the length scale of the phase-segregated surface domains may disrupt the settlement of microorganisms and the adsorption of proteins. Using photolithography on silicon wafers, Finlay et al.¹⁴⁴ have designed patterned square surfaces alternating PEGylated and fluorinated stripes of the same width varying between 2 and 500 μm on either a PEG or fluorinated background. That is, the entire wafer was functionalized with either PEG or fluorinated surface chemistry onto which squares of alternating stripes were patterned covering 18% of the total wafer surface area. Their work demonstrated that *Ulva* spores could be effectively "confused" by amphiphilic surfaces presenting both hydrophobic and hydrophilic domains, thus diminishing spore settlement. The nature of the background and the width of the domains within each patterned square were shown to have an effect on the density of settled spores. In most cases,

fluorinated domains within patterned squares on a PEG wafer background exhibited a higher density of settled spores in comparison to fluorinated domains within patterned squares on a fluorinated wafer background. At a critical dimension (stripes $< 20 \mu\text{m}$) the *Ulva* spores avoided settlement on either of the regions, apparently unable to differentiate them, considering the patterned surface as pure PEG. Whereas spore settlement was disrupted by alternating domains of hydrophobic and hydrophilic character, this surface modification may not be suitable for protein repellency. Although protein resistance of the patterned surface was not thoroughly investigated, it is likely that the length scale that disrupts the settlement of *Ulva* spores is too large to have an impact on the adsorption of proteins. Indeed, fluorescent BSA was visibly adsorbed on the 2 μm fluorinated stripes on PEG background, the same surface chemistry that disrupted the settlement of *Ulva* spores. It was observed that BSA nevertheless adsorbed on the hydrophobic stripes on a PEG background. Such an approach may therefore be more suitable for preventing microorganism attachment and less suitable for strict protein repellency. However, it could be interesting to pursue research investigating alternating domains of nano dimensions, more in the range of protein hydrodynamic radii, to adapt such technologies to both microorganism and protein repellency. Block copolymers can self-organize by phase segregation to create nanoscale chemical patterns on surfaces.^{128,145–147} Indeed, nanopatterned surfaces created by such self-organizing block copolymers could be a promising approach for the development of food nonfouling surfaces because of the relative ease of application compared to lithographically defined patterns.

The behavior of amphiphilic coatings in aqueous solutions is of critical importance to their industrial application, be it food, medical, or marine. When exposed to water, amphiphilic coatings undergo surface reorganization^{127–129,131,133,135–138,140,141,147,148} at the film–water interface, leading to high water contact angle hysteresis. Hydrophobic segments are preferentially oriented at the polymer–air interface because of their low surface energy, but when the surface exposed to an aqueous solution, restructuring occurs in which the higher surface energy hydrophilic segments orient toward the polymer–water interface. As such, the topography and the morphology of amphiphilic coatings change after exposure to water.^{128,136,140} This phenomenon is reversible¹²⁷ when the surface dries. Krishnan et al.¹⁴¹ observed a two-phase reconstruction of the block copolymer polystyrene-*block*-poly(ethoxylated fluoroalkyl acrylate) after water exposure: initially, the surface becomes more hydrophilic by flipping of the amphiphilic side chains (Figure 5), and over a period of days, the polystyrene block migrates to the bulk of the film away from the surface.

Amphiphilic coatings can suffer from delamination under thermal and mechanical stresses or prolonged submersion in an aqueous environment, which can be a potential limitation for a food-processing application. Different strategies have been investigated to minimize or avoid delamination of coatings from the base material. Wang et al.¹³⁵ functionalized a glass substrate with *N*-(3-(trimethoxysilyl)propyl)acrylamide (TSPA). The silane functionality enabled covalent bonding to the glass, whereas the acrylamide functionality was available to copolymerize with the methacrylate functions of PFPE-DMA and PEG-MA or PEG-DMA, leading to a covalent bonding of PFPE/PEG films to the substrate (Figure 6a). Krishnan and others^{136–138,140,141} used a two-layer approach (Figure 6b) with

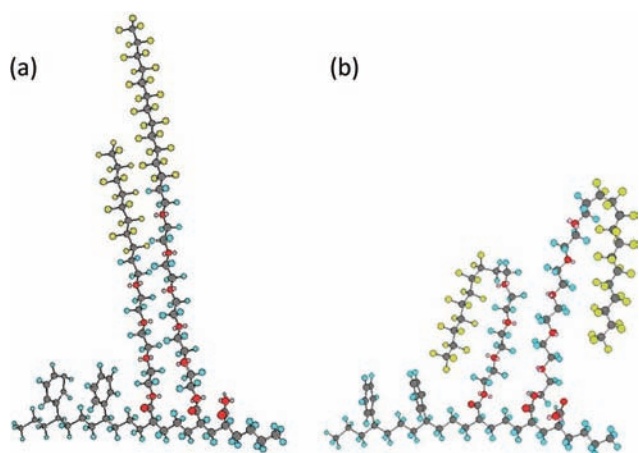


Figure 5. Proposed surface reorientation of block copolymer polystyrene-*block*-poly(ethoxylated fluoroalkyl acrylate) by flipping of the amphiphilic side chains when the surface is exposed from (left) air to (right) water. Reproduced from ref 141. Copyright 2006 American Chemical Society.

first a bottom layer covalently attached to the GPS-functionalized glass substrate ((3-glycidoxypropyl)-trimethylsilane, GPS) via the reaction of the epoxy groups of the GPS with the maleic anhydride (MA) groups of the SEBS-MA and second the amphiphilic top layer anchored to the bottom layer via an annealing process of the polystyrene domains present in the amphiphilic copolymer and the SEBS at the interface of the two layers. The use of plasma polymerization can also overcome the problem of delamination as the obtained polymer is covalently bonded to the substrate (e.g., PFDA-*co*-DEGDME¹²⁷). Continued research is needed to

demonstrate the successfulness of such strategies to mitigate delamination of nonfouling (amphiphilic and others) coatings in conditions typical of a food-processing plant (e.g., thermal extremes, mechanical abrasion, exposure to cleaners, and sanitizers).

Böhringer et al.^{149,150} have developed an amphiphilic surface that has topographically defined hydrophobic pillars with PEG domains at the top of the pillars. Despite the fact that the water-material interface occurs on the hydrophilic PEG regions (water contact angle of 32°), the pillar structure and associated air pockets impart overall hydrophobicity with a water contact angle of 137° (in Cassie's state). Kim et al.¹⁵¹ tested the adsorption of three different proteins (i.e., albumin (BSA), fibronectin (FN), and immunoglobulin (IgG)) on nanostructures of PEG pillars having a contact angle of 95° and observed that more proteins adsorbed onto the nanostructured PEG pillars than on bare PEG and that the proteins preferentially adsorbed on the tops of the pillars compared to the valleys. Topographically and chemically amphiphilic materials such as these represent a novel approach toward the design of nonfouling and, in particular, fouling-release materials.

CONCLUSIONS AND PERSPECTIVES

Advances in the design of nonfouling and fouling-release (aka self-cleaning) materials in biomedical and marine applications have paved the way for potential adaptation to preventing fouling in food processing. For application in the food industry, not only will the nonfouling and/or self-cleaning materials need appropriate food-contact approval status, but their mode of application will need to be economically practical. For example, biomimetic lotus-effect materials are often developed on the laboratory scale using conventional lithography techniques,

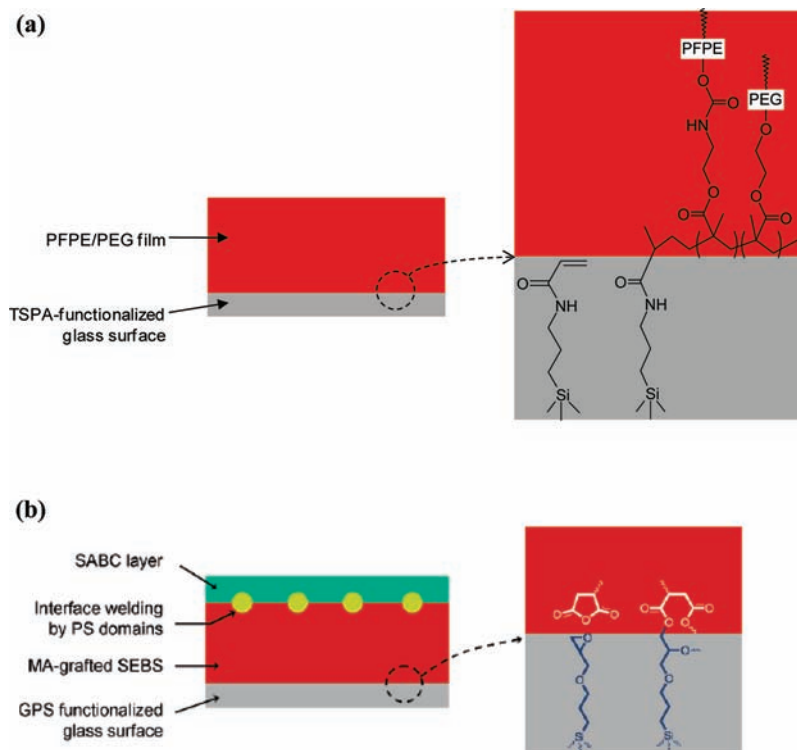


Figure 6. Schematic of attachment of amphiphilic coatings: (a) one-layer approach (adapted from ref 135; copyright 2011 American Chemical Society); (b) two-layer approach (reproduced from ref 155; copyright 2006 American Chemical Society).

which require the use of a cleanroom. Adaptation of nanoimprint lithography for roll-to-roll processing of larger scale materials supports such commercial applicability,¹⁵² as does the development of block copolymers, which can be applied across a large surface area to generate the desired surface chemistry and/or topography.^{128,129,136–138,140,141}

A challenge to identifying nonfouling coatings or surfaces for application in the food industry is that assessments for nonfouling materials are typically carried out using proteins and conditions less relevant to food processing. There remains a research need for demonstrating the performance of novel nonfouling and self-cleaning materials under conditions relevant in a food-processing environment. Specifically, materials are often evaluated using buffered solutions of a single fouling components (e.g., BSA in phosphate buffer). The effectiveness in the presence of complex food matrices, temperatures, and shear stresses typical in food processing will help to elucidate which materials show most promise for potential application in the food industry.

Whereas the focus of this review has been on food processing, there is potential application for nonfouling and self-cleaning materials in a range of food-contact material applications, including on the farm (dairy parlors, slaughterhouses), in the field (picking buckets, washing sinks, and packing tables), and in non-food-contact materials (conveyors, forklifts, air-handling systems). Improving cleanliness and sanitation of such food-contact as well as non-food-contact materials by the development of nonfouling and self-cleaning materials will help to support current Good Manufacturing Practices in maintaining a safe and high-quality food supply.

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Funding

This work was funded in part by USDA Special Grant 2010-34637-20985.

Notes

The authors declare no competing financial interest.

REFERENCES

- (1) Flint, S.; Palmer, J.; Bloemen, K.; Brooks, J.; Crawford, R. The growth of bacillus stearotherophilus on stainless steel. *J. Appl. Microbiol.* **2001**, *90* (2), 151–157.
- (2) Parkar, S. G.; Flint, S. H.; Brooks, J. D. Evaluation of the effect of cleaning regimes on biofilms of thermophilic bacilli on stainless steel. *J. Appl. Microbiol.* **2004**, *96* (1), 110–116.
- (3) Müller-Steinhagen, H.; Malayeri, M. R.; Watkinson, A. P. Heat exchanger fouling: environmental impacts. *Heat Transfer Eng.* **2009**, *30* (10/11), 773–776.
- (4) Malayeri, M. R.; Al-Janabi, A.; Müller-Steinhagen, H. Application of nano-modified surfaces for fouling mitigation. *Int. J. Energy Res.* **2009**, *33* (13), 1101–1113.
- (5) Mauermann, M.; Eschenhagen, U.; Bley, T.; Majschak, J.-P. Surface modifications – application potential for the reduction of cleaning costs in the food processing industry. *Trends Food Sci. Technol.* **2009**, *20* (Suppl.1), S9–S15.
- (6) van Asselt, A. J.; Vissers, M. M. M.; Smit, F.; De Jong, P. In *Heat Exchanger Fouling and Cleaning – Challenges and Opportunities*; Engineering Conferences International: Kloster Irsee, Germany, 2005.
- (7) Bansal, B.; Chen, X. D. A critical review of milk fouling in heat exchangers. *Compr. Rev. Food Sci. Food Saf.* **2006**, *5* (2), 27–33.
- (8) Epstein, N. Thinking about heat transfer fouling: a 5 × 5 matrix. *Heat Transfer Eng.* **1981**, *4* (1), 43–56.
- (9) Fryer, P. J.; Asteriadou, K. A prototype cleaning map: a classification of industrial cleaning processes. *Trends Food Sci. Technol.* **2009**, *20* (6–7), 255–262.
- (10) Minton, P. E. Fouling In *Handbook of Evaporation Technology*; William Andrew Publishing/Noyes: Norwich, NY, 1986; p 402.
- (11) Burton, H. Section G. Deposits from whole milk in heat treatment plant – a review and discussion. *J. Dairy Res.* **1968**, *35* (02), 317–330.
- (12) Narataruksa, P.; Pichitvittayakarn, W.; Heggs, P. J.; Tia, S. Fouling behavior of coconut milk at pasteurization temperatures. *Appl. Thermal Eng.* **2010**, *30* (11–12), 1387–1395.
- (13) Saha, N. K.; Balakrishnan, M.; Ulbricht, M. Fouling control in sugarcane juice ultrafiltration with surface modified polysulfone and polyethersulfone membranes. *Desalination* **2009**, *249* (3), 1124–1131.
- (14) Yazdanshenas, M.; Tabatabaee-Nezhad, S. A. R.; Soltanieh, M.; Roostaazad, R.; Khoshfetrat, A. B. Contribution of fouling and gel polarization during ultrafiltration of raw apple juice at industrial scale. *Desalination* **2010**, *258* (1–3), 194–200.
- (15) Li, L.; Singh, R. K.; Lee, J. H. Process conditions influence on characteristics of holding tube fouling due to cheese sauce. *Lebensm.-Wiss. -Technol.* **2004**, *37* (5), 565–572.
- (16) Premathilaka, S.; Hyland, M.; Chen, X.; Bansal, B. A study of the effects of surface chemistry on the initial deposition mechanisms of dairy fouling. *Food Bioprod. Process., Fouling, Cleaning Disinfection Food Process.* **2006**, *84* (4), 265–273.
- (17) Rosmaninho, R.; Santos, O.; Nylander, T.; Paulsson, M.; Beuf, M.; Benezech, T.; Yiantsios, S.; Andritsos, N.; Karabelas, A.; Rizzo, G.; Müller-Steinhagen, H.; Melo, L. F. Modified stainless steel surfaces targeted to reduce fouling – evaluation of fouling by milk components. *J. Food Eng.* **2007**, *80* (4), 1176–1187.
- (18) Christian, G. K.; Changani, S. D.; Fryer, P. J. The effect of adding minerals on fouling from whey protein concentrate: development of a model fouling fluid for a plate heat exchanger. *Food Bioprod. Process., Fouling, Cleaning Disinfection* **2002**, *80* (4), 231–239.
- (19) Krishnan, S.; Weinman, C. J.; Ober, C. K. Advances in polymers for anti-biofouling surfaces. *J. Mater. Chem.* **2008**, *18* (29), 3405–3413.
- (20) Müller-Steinhage, H. *Heat Exchanger Fouling: Mitigation and Cleaning Techniques*; Institution of Chemical Engineers: Essen, Rugby, Germany, 2000.
- (21) Ishiyama, E. M.; Paterson, W. R.; Ian Wilson, D. Optimum cleaning cycles for heat transfer equipment undergoing fouling and ageing. *Chem. Eng. Sci.* **2011**, *66* (4), 604–612.
- (22) Wei, J.; Helm, G. S.; Corner-Walker, N.; Hou, X. Characterization of a non-fouling ultrafiltration membrane. *Desalination, International Congress on Membranes and Membrane Processes* **2006**, *192* (1–3), 252–261.
- (23) Murthy, P. S.; Venkatesan, R. In *Marine and Industrial Biofouling*; Flemming, H.-C., Murthy, P. S., Venkatesan, R., Cooksey, K., Eds.; Springer: Berlin, Germany, 2009; Vol. 4, pp 65–101.
- (24) Chmielewski, R. A. N.; Frank, J. F. Biofilm formation and control in food processing facilities. *Compr. Rev. Food Sci. Food Saf.* **2003**, *2* (1), 22–32.
- (25) Roach, P.; Farrar, D.; Perry, C. C. Interpretation of protein adsorption: surface-induced conformational changes. *J. Am. Chem. Soc.* **2005**, *127* (22), 8168–8173.
- (26) Caro, A.; Humblot, V.; Méthivier, C.; Minier, M.; Salmain, M. L.; Pradier, C.-M. Grafting of lysozyme and/or poly(ethylene glycol) to prevent biofilm growth on stainless steel surfaces. *J. Phys. Chem. B* **2009**, *113* (7), 2101–2109.
- (27) Chen, H.; Zhang, Z.; Chen, Y.; Brook, M. A.; Sheardown, H. Protein repellent silicone surfaces by covalent immobilization of poly(ethylene oxide). *Biomaterials* **2005**, *26* (15), 2391–2399.
- (28) Dyer, M. A.; Ainslie, K. M.; Pishko, M. V. Protein adhesion on silicon-supported hyperbranched poly(ethylene glycol) and poly-(allylamine) thin films. *Langmuir* **2007**, *23* (13), 7018–7023.

- (29) Benhabbour, S. R.; Sheardown, H.; Adronov, A. Protein resistance of PEG-functionalized dendronized surfaces: effect of PEG molecular weight and dendron generation. *Macromolecules* **2008**, *41* (13), 4817–4823.
- (30) Kizhakkedathu, J. N.; Janzen, J.; Le, Y.; Kainthan, R. K.; Brooks, D. E. Poly(oligo(ethylene glycol)acrylamide) brushes by surface initiated polymerization: effect of macromonomer chain length on brush growth and protein adsorption from blood plasma. *Langmuir* **2009**, *25* (6), 3794–3801.
- (31) Zhang, F.; Kang, E. T.; Neoh, K. G.; Wang, P.; Tan, K. L. Surface modification of stainless steel by grafting of poly(ethylene glycol) for reduction in protein adsorption. *Biomaterials* **2001**, *22* (12), 1541–1548.
- (32) Harris, J. M. *Poly(ethylene glycol) Chemistry: Biotechnical and Biomedical Applications*; Plenum Press: New York, 1992.
- (33) Morra, M. On the molecular basis of fouling resistance. *J. Biomater. Sci. Polym. Ed.* **2000**, *11* (6), 547–569.
- (34) Jeon, S. I.; Lee, J. H.; Andrade, J. D.; De Gennes, P. G. Protein-surface interactions in the presence of polyethylene oxide: I. Simplified theory. *J. Colloid Interface Sci.* **1991**, *142* (1), 149–158.
- (35) Jeon, S. I.; Andrade, J. D. Protein-surface interactions in the presence of polyethylene oxide: II. Effect of protein size. *J. Colloid Interface Sci.* **1991**, *142* (1), 159–166.
- (36) Szleifer, I. Protein adsorption on surfaces with grafted polymers: a theoretical approach. *Biophys. J.* **1997**, *72* (2, Part 1), 595–612.
- (37) McPherson, T.; Kidane, A.; Szleifer, I.; Park, K. Prevention of protein adsorption by tethered poly(ethylene oxide) layers: experiments and single-chain mean-field analysis. *Langmuir* **1998**, *14* (1), 176–186.
- (38) Halperin, A. Polymer brushes that resist adsorption of model proteins: design parameters. *Langmuir* **1999**, *15* (7), 2525–2533.
- (39) Prime, K. L.; Whitesides, G. M. Self-assembled organic monolayers: model systems for studying adsorption of proteins at surfaces. *Science* **1991**, *252* (5009), 1164–1167.
- (40) Prime, K. L.; Whitesides, G. M. Adsorption of proteins onto surfaces containing end-attached oligo(ethylene oxide): a model system using self-assembled monolayers. *J. Am. Chem. Soc.* **1993**, *115* (23), 10714–10721.
- (41) Harder, P.; Grunze, M.; Dahint, R.; Whitesides, G. M.; Laibinis, P. E. Molecular conformation in oligo(ethylene glycol)-terminated self-assembled monolayers on gold and silver surfaces determines their ability to resist protein adsorption. *J. Phys. Chem. B* **1998**, *102* (2), 426–436.
- (42) Herrwerth, S.; Eck, W.; Reinhardt, S.; Grunze, M. Factors that determine the protein resistance of oligoether self-assembled monolayers- internal hydrophilicity, terminal hydrophilicity, and lateral packing density. *J. Am. Chem. Soc.* **2003**, *125* (31), 9359–9366.
- (43) Leckband, D.; Sheth, S.; Halpern, A. Grafted poly(ethylene oxide) brushes as nonfouling surface coatings. *J. Biomater. Sci. Polym. Ed.* **1999**, *10* (10), 1125.
- (44) Norde, W.; Gage, D. Interaction of bovine serum albumin and human blood plasma with PEO-tethered surfaces: influence of PEO chain length, grafting density, and temperature. *Langmuir* **2004**, *20* (10), 4162–4167.
- (45) Schwendel, D.; Dahint, R.; Herrwerth, S.; Schloerholz, M.; Eck, W.; Grunze, M. Temperature dependence of the protein resistance of poly- and oligo(ethylene glycol)-terminated alkanethiolate monolayers. *Langmuir* **2001**, *17* (19), 5717–5720.
- (46) Kingshott, P.; McArthur, S.; Thissen, H.; Castner, D. G.; Griesser, H. J. Ultrasensitive probing of the protein resistance of PEG surfaces by secondary ion mass spectrometry. *Biomaterials* **2002**, *23* (24), 4775–4785.
- (47) Kingshott, P.; Thissen, H.; Griesser, H. J. Effects of cloud-point grafting, chain length, and density of PEG layers on competitive adsorption of ocular proteins. *Biomaterials* **2002**, *23* (9), 2043–2056.
- (48) Maechling-Strasser, C.; Déjardin, P.; Galin, J. C.; Schmitt, A. Preadsorption of polymers on glass and silica to reduce fibrinogen adsorption. *J. Biomed. Mater. Res.* **1989**, *23* (12), 1385–1393.
- (49) Luo, N.; Hutchison, J. B.; Anseth, K. S.; Bowman, C. N. Surface-initiated photopolymerization of poly(ethylene glycol) methyl ether methacrylate on a diethyldithiocarbamate-mediated polymer substrate. *Macromolecules* **2002**, *35* (7), 2487–2493.
- (50) Wu, Y. J.; Timmons, R. B.; Jen, J. S.; Molock, F. E. Non-fouling surfaces produced by gas phase pulsed plasma polymerization of an ultra low molecular weight ethylene oxide containing monomer. *Colloids Surf., B* **2000**, *18* (3–4), 235–248.
- (51) Wang, P.; Tan, K. L.; Kang, E. T.; Neoh, K. G. Antifouling poly(vinylidene fluoride) microporous membranes prepared via plasma-induced surface grafting of poly(ethylene glycol). *J. Adhes. Sci. Technol.* **2002**, *16*, 111–127.
- (52) Wang, P.; Tan, K. L.; Kang, E. T.; Neoh, K. G. Plasma-induced immobilization of poly(ethylene glycol) onto poly(vinylidene fluoride) microporous membrane. *J. Membr. Sci.* **2002**, *195* (1), 103–114.
- (53) Dong, B.; Manolache, S.; Somers, E. B.; Lee Wong, A. C.; Denes, F. S. Generation of antifouling layers on stainless steel surfaces by plasma-enhanced crosslinking of poly(ethylene glycol). *J. Appl. Polym. Sci.* **2005**, *97* (2), 485–497.
- (54) Minko, S. In *Polymer Surfaces and Interfaces*; Stamm, M., Ed.; Springer: Berlin, Germany, 2008; pp 215–234.
- (55) Sharma, S.; Johnson, R. W.; Desai, T. A. Evaluation of the stability of nonfouling ultrathin poly(ethylene glycol) films for silicon-based microdevices. *Langmuir* **2003**, *20* (2), 348–356.
- (56) Mikhal'chuk, V. M.; Kryuk, T. V.; Petrenko, L. V.; Nelepova, O. A.; Nikolaevskii, A. N. Antioxidative stabilization of polyethylene glycol in aqueous solutions with herb phenols. *Russ. J. Appl. Chem.* **2004**, *77*, 131–135.
- (57) Morra, M.; Cassinelli, C. Non-fouling properties of polysaccharide-coated surfaces. *J. Biomater. Sci. Polym. Ed.* **1999**, *10* (10), 1107–1124.
- (58) McArthur, S. L.; McLean, K. M.; Kingshott, P.; St John, H. A. W.; Chatelier, R. C.; Griesser, H. J. Effect of polysaccharide structure on protein adsorption. *Colloids Surf. B* **2000**, *17* (1), 37–48.
- (59) Amanda, A.; Mallapragada, S. K. Comparison of protein fouling on heat-treated poly(vinyl alcohol), poly(ether sulfone) and regenerated cellulose membranes using diffuse reflectance infrared Fourier transform spectroscopy. *Biotechnol. Prog.* **2001**, *17* (5), 917–923.
- (60) Ma, X.; Su, Y.; Sun, Q.; Wang, Y.; Jiang, Z. Enhancing the antifouling property of polyethersulfone ultrafiltration membranes through surface adsorption-crosslinking of poly(vinyl alcohol). *J. Membr. Sci.* **2007**, *300* (1–2), 71–78.
- (61) Zhao, C.; Li, L.; Zheng, J. Achieving highly effective nonfouling performance for surface-grafted poly(HPMA) via atom transfer radical polymerization. *Langmuir* **2010**, *26* (22), 17375–17382.
- (62) Siegers, C.; Biesalski, M.; Haag, R. Self-assembled monolayers of dendritic polyglycerol derivatives on gold that resist the adsorption of proteins. *Chem.—Eur. J.* **2004**, *10* (11), 2831–2838.
- (63) Yeh, P.-Y. J.; Kainthan, R. K.; Zou, Y.; Chiao, M.; Kizhakkedathu, J. N. Self-assembled monothiol-terminated hyperbranched polyglycerols on a gold surface: a comparative study on the structure, morphology, and protein adsorption characteristics with linear poly(ethylene glycol)s. *Langmuir* **2008**, *24* (9), 4907–4916.
- (64) Vendra, V. K.; Wu, L.; Krishnan, S. Polymer thin films for biomedical applications In *Nanostructured Thin Films and Surfaces*; Kumar, C. S. S. R., Ed.; Wiley: Weinheim, Germany, 2010; Vol. 5, pp 1–51.
- (65) Zhou, M.; Liu, H.; Venkiteshwaran, A.; Kilduff, J.; Anderson, D. G.; Langer, R.; Belfort, G. High throughput discovery of new fouling-resistant surfaces. *J. Mater. Chem.* **2011**, *21* (3), 693–704.
- (66) Chapman, R. G.; Ostuni, E.; Takayama, S.; Holmlin, R. E.; Yan, L.; Whitesides, G. M. Surveying for surfaces that resist the adsorption of proteins. *J. Am. Chem. Soc.* **2000**, *122* (34), 8303–8304.
- (67) Ostuni, E.; Chapman, R. G.; Holmlin, R. E.; Takayama, S.; Whitesides, G. M. A survey of structure-property relationships of surfaces that resist the adsorption of protein. *Langmuir* **2001**, *17* (18), 5605–5620.

- (68) Feng, W.; Brash, J. L.; Zhu, S. Non-biofouling materials prepared by atom transfer radical polymerization grafting of 2-methacryloxyethyl phosphorylcholine: separate effects of graft density and chain length on protein repulsion. *Biomaterials* **2006**, *27* (6), 847–855.
- (69) Feng, W.; Zhu, S.; Ishihara, K.; Brash, J. L. Protein resistant surfaces: comparison of acrylate graft polymers bearing oligo-ethylene oxide and phosphorylcholine side chains. *Biointerphases* **2006**, *1* (1), 50–60.
- (70) Su, Y.; Li, C.; Zhao, W.; Shi, Q.; Wang, H.; Jiang, Z.; Zhu, S. Modification of polyethersulfone ultrafiltration membranes with phosphorylcholine copolymer can remarkably improve the antifouling and permeation properties. *J. Membr. Sci.* **2008**, *322* (1), 171–177.
- (71) Liu, P.-S.; Chen, Q.; Wu, S.-S.; Shen, J.; Lin, S.-C. Surface modification of cellulose membranes with zwitterionic polymers for resistance to protein adsorption and platelet adhesion. *J. Membr. Sci.* **2010**, *350* (1–2), 387–394.
- (72) Chang, Y.; Liao, S.-C.; Higuchi, A.; Ruaan, R.-C.; Chu, C.-W.; Chen, W.-Y. A highly stable nonbiofouling surface with well-packed grafted zwitterionic polysulfobetaine for plasma protein repulsion. *Langmuir* **2008**, *24* (10), 5453–5458.
- (73) Chang, Y.; Shu, S.-H.; Shih, Y.-J.; Chu, C.-W.; Ruaan, R.-C.; Chen, W.-Y. Hemocompatible mixed-charge copolymer brushes of pseudozwitterionic surfaces resistant to nonspecific plasma protein fouling. *Langmuir* **2009**, *26* (5), 3522–3530.
- (74) Nguyen, A. T.; Baggerman, J.; Paulusse, J. M. J.; van Rijn, C. J. M.; Zuilhof, H. Stable protein-repellent zwitterionic polymer brushes grafted from silicon nitride. *Langmuir* **2011**, *27* (6), 2587–2594.
- (75) Su, Y.-l.; Li, C. Controlled adsorption of bovine serum albumin on poly(acrylonitrile)-based zwitterionic membranes. *React. Funct. Polym.* **2008**, *68* (1), 161–168.
- (76) Yang, W.; Chen, S.; Cheng, G.; Vaisocherová, H.; Xue, H.; Li, W.; Zhang, J.; Jiang, S. Film thickness dependence of protein adsorption from blood serum and plasma onto poly(sulfobetaine)-grafted surfaces. *Langmuir* **2008**, *24* (17), 9211–9214.
- (77) Cheng, G.; Li, G.; Xue, H.; Chen, S.; Bryers, J. D.; Jiang, S. Zwitterionic carboxybetaine polymer surfaces and their resistance to long-term biofilm formation. *Biomaterials* **2009**, *30* (28), 5234–5240.
- (78) Gao, C.; Li, G.; Xue, H.; Yang, W.; Zhang, F.; Jiang, S. Functionalizable and ultra-low fouling zwitterionic surfaces via adhesive mussel mimetic linkages. *Biomaterials* **2010**, *31* (7), 1486–1492.
- (79) Zhang, Z.; Vaisocherová, H.; Cheng, G.; Yang, W.; Xue, H.; Jiang, S. Nonfouling behavior of polycarboxybetaine-grafted surfaces: structural and environmental effects. *Biomacromolecules* **2008**, *9* (10), 2686–2692.
- (80) Zhang, Q.; Zhang, S.; Dai, L.; Chen, X. Novel zwitterionic poly(arylene ether sulfone)s as antifouling membrane material. *J. Membr. Sci.* **2010**, *349* (1–2), 217–224.
- (81) Hess, M.; Jones, R. G.; Kahovec, J.; Kitayama, T.; Kratochvíl, P.; Kubisa, P.; Mormann, W.; Stepto, R. F. T.; Tabak, D.; Vohlidal, J.; Wilks, E. S. Terminology of polymers containing ionizable or ionic groups and of polymers containing ions (IUPAC Recommendations 2006). *Pure Appl. Chem.* **2006**, *78* (11), 2067–2074.
- (82) He, Y.; Hower, J.; Chen, S.; Bernards, M. T.; Chang, Y.; Jiang, S. Molecular simulation studies of protein interactions with zwitterionic phosphorylcholine self-assembled monolayers in the presence of water. *Langmuir* **2008**, *24* (18), 10358–10364.
- (83) Yang, Y.-F.; Li, Y.; Li, Q.-L.; Wan, L.-S.; Xu, Z.-K. Surface hydrophilization of microporous polypropylene membrane by grafting zwitterionic polymer for anti-biofouling. *J. Membr. Sci.* **2010**, *362* (1–2), 255–264.
- (84) Li, G.; Cheng, G.; Xue, H.; Chen, S.; Zhang, F.; Jiang, S. Ultra low fouling zwitterionic polymers with a biomimetic adhesive group. *Biomaterials* **2008**, *29* (35), 4592–4597.
- (85) Yu, H.; Cao, Y.; Kang, G.; Liu, J.; Li, M.; Yuan, Q. Enhancing antifouling property of polysulfone ultrafiltration membrane by grafting zwitterionic copolymer via UV-initiated polymerization. *J. Membr. Sci.* **2009**, *342* (1–2), 6–13.
- (86) Wu, L.; Jasinski, J.; Krishnan, S. Carboxybetaine, sulfobetaine, and cationic block copolymer coatings: a comparison of the surface properties and antibiofouling behavior. *J. Appl. Polym. Sci.* **2011**, DOI: 10.1002/app.35233.
- (87) Chen, S.; Jiang, S. A new avenue to nonfouling materials. *Adv. Mater.* **2008**, *20* (2), 335–338.
- (88) Bernards, M. T.; Cheng, G.; Zhang, Z.; Chen, S.; Jiang, S. Nonfouling polymer brushes via surface-initiated, two-component atom transfer radical polymerization. *Macromolecules* **2008**, *41* (12), 4216–4219.
- (89) Li, G.; Xue, H.; Gao, C.; Zhang, F.; Jiang, S. Nonfouling polyampholytes from an ion-pair comonomer with biomimetic adhesive groups. *Macromolecules* **2009**, *43* (1), 14–16.
- (90) Ekblad, T.; Andersson, O.; Tai, F.-I.; Ederth, T.; Liedberg, B. Lateral control of protein adsorption on charged polymer gradients. *Langmuir* **2009**, *25* (6), 3755–3762.
- (91) Gil, E. S.; Hudson, S. M. Stimuli-reponsive polymers and their bioconjugates. *Prog. Polym. Sci.* **2004**, *29* (12), 1173–1222.
- (92) Aguilar, M. R.; Elvira, C.; Gallardo, A.; Vázquez, B.; Román, J. S. Smart polymers and their applications as biomaterials In *Topics in Tissue Engineering*; N Ashammakhi, R. R. E. C., Ed.; Biomaterials and Tissue Engineering Group: York, U. K., 2007; Vol. 3, pp 1–27.
- (93) Banerjee, I.; Pangule, R. C.; Kane, R. S. Antifouling coatings: recent developments in the design of surfaces that prevent fouling by proteins, bacteria, and marine organisms. *Adv. Mater.* **2011**, *23* (6), 690–718.
- (94) Nath, N.; Hyun, J.; Ma, H.; Chilkoti, A. Surface engineering strategies for control of protein and cell interactions. *Surf. Sci., BIOSURF V: Funct. Polym. Surf. Biotechnol.* **2004**, *570* (1–2), 98–110.
- (95) Heskins, M.; Guillet, J. E. Solution properties of poly(*N*-isopropylacrylamide). *J. Macromol. Sci.: Part A—Chem.* **1968**, *2* (8), 1441–1455.
- (96) Kikuchi, A.; Okano, T. Nanostructured designs of biomedical materials: applications of cell sheet engineering to functional regenerative tissues and organs (Proceedings of the Eighth European Symposium on Controlled Drug Delivery). *J. Controlled Release* **2005**, *101* (1–3), 69–84.
- (97) Ista, L. K.; López, G. P. Lower critical solubility temperature materials as biofouling release agents. *J. Ind. Microbiol. Biotechnol.* **1998**, *20* (2), 121–125.
- (98) Ista, L. K.; Pérez-Luna, V. H.; López, G. P. Surface-grafted, environmentally sensitive polymers for biofilm release. *Appl. Environ. Microbiol.* **1999**, *65* (4), 1603–1609.
- (99) Ebara, M.; Yamato, M.; Hirose, M.; Aoyagi, T.; Kikuchi, A.; Sakai, K.; Okano, T. Copolymerization of 2-carboxyisopropylacrylamide with *N*-isopropylacrylamide accelerates cell detachment from grafted surfaces by reducing temperature. *Biomacromolecules* **2003**, *4* (2), 344–349.
- (100) Huber, D. L.; Manginell, R. P.; Samara, M. A.; Kim, B.-I.; Bunker, B. C. Programmed adsorption and release of proteins in a microfluidic device. *Science* **2003**, *301* (5631), 352–354.
- (101) Schmaljohann, D.; Oswald, J.; Jørgensen, B.; Nitschke, M.; Beyerlein, D.; Werner, C. Thermo-responsive PNiPAAm-g-PEG films for controlled cell detachment. *Biomacromolecules* **2003**, *4* (6), 1733–1739.
- (102) Akiyama, Y.; Kikuchi, A.; Yamato, M.; Okano, T. Ultrathin poly(*N*-isopropylacrylamide) grafted layer on polystyrene surfaces for cell adhesion/detachment control. *Langmuir* **2004**, *20* (13), 5506–5511.
- (103) Cole, M. A.; Voelcker, N. H.; Thissen, H.; Griesser, H. J. Stimuli-responsive interfaces and systems for the control of protein-surface and cell-surface interactions. *Biomaterials* **2009**, *30* (9), 1827–1850.
- (104) Yu, Q.; Zhang, Y.; Chen, H.; Zhou, F.; Wu, Z.; Huang, H.; Brash, J. L. Protein adsorption and cell adhesion/detachment behavior on dual-responsive silicon surfaces modified with poly(*N*-isopropylacrylamide)-block-polystyrene copolymer. *Langmuir* **2010**, *26* (11), 8582–8588.

- (105) Cunliffe, D.; de las Heras Alarcón, C.; Peters, V.; Smith, J. R.; Alexander, C. Thermoresponsive surface-grafted poly(*N*-isopropylacrylamide) copolymers: effect of phase transitions on protein and bacterial attachment. *Langmuir* **2003**, *19* (7), 2888–2899.
- (106) Cheng, X.; Canavan, H. E.; Graham, D. J.; Castner, D. G.; Ratner, B. D. Temperature dependent activity and structure of adsorbed proteins on plasma polymerized *N*-isopropyl acrylamide. *Biointerphases* **2006**, *1* (1), 61–72.
- (107) Wavhal, D. S.; Fisher, E. R. Membrane surface modification by plasma-induced polymerization of acrylamide for improved surface properties and reduced protein fouling. *Langmuir* **2002**, *19* (1), 79–85.
- (108) Karthick, B.; Maheshwari, R. Lotus-inspired nanotechnology applications. *Resonance* **2008**, *13* (12), 1141–1145.
- (109) Wang, S.; Jiang, L. Definition of superhydrophobic states. *Adv. Mater.* **2007**, *19* (21), 3423–3424.
- (110) Zhang, H.; Lamb, R.; Lewis, J. Engineering nanoscale roughness on hydrophobic surface – preliminary assessment of fouling behaviour. *Sci. Technol. Adv. Mater. Int. Conf. Nanotechnol. Environ. Prot. Pollut.* **2005**, *6* (3–4), 236–239.
- (111) Cheng, Y. T.; Rodak, D. E.; Wong, C. A.; Hayden, C. A. Effects of micro- and nano-structures on the self-cleaning behaviour of lotus leaves. *Nanotechnology* **2006**, *17*, 1359–1369.
- (112) Li, X.-M.; Reinhoudt, D.; Crego-Calama, M. What do we need for a superhydrophobic surface? A review on the recent progress in the preparation of superhydrophobic surfaces. *Chem. Soc. Rev.* **2007**, *36* (8), 1350–1368.
- (113) Zhang, X.; Shi, F.; Niu, J.; Jiang, Y.; Wang, Z. Superhydrophobic surfaces: from structural control to functional application. *J. Mater. Chem.* **2008**, *18* (6), 621–633.
- (114) Fürstner, R.; Barthlott, W.; Neinhuis, C.; Walzel, P. Wetting and self-cleaning properties of artificial superhydrophobic surfaces. *Langmuir* **2005**, *21* (3), 956–961.
- (115) Öner, D.; McCarthy, T. J. Ultrahydrophobic surfaces. Effects of topography length scales on wettability. *Langmuir* **2000**, *16* (20), 7777–7782.
- (116) Shiu, J.-Y.; Kuo, C.-W.; Chen, P.; Mou, C.-Y. Fabrication of tunable superhydrophobic surfaces by nanosphere lithography. *Chem. Mater.* **2004**, *16* (4), 561–564.
- (117) Liu, C. Rapid fabrication of microfluidic chip with three-dimensional structures using natural lotus leaf template. *Microfluid. Nanofluid.* **2010**, *9* (4), 923–931.
- (118) Koc, Y.; de Mello, A. J.; McHale, G.; Newton, M. I.; Roach, P.; Shirtcliffe, N. J. Nano-scale superhydrophobicity: suppression of protein adsorption and promotion of flow-induced detachment. *Lab Chip* **2008**, *8* (4), 582–586.
- (119) Roach, P.; Shirtcliffe, N. J.; Farrar, D.; Perry, C. C. Quantification of surface-bound proteins by fluorometric assay: comparison with quartz crystal microbalance and amido black assay. *J. Phys. Chem. B* **2006**, *110* (41), 20572–20579.
- (120) Choi, C.-H.; Kim, C.-J. C. Droplet evaporation of pure water and protein solution on nanostructured superhydrophobic surfaces of varying heights. *Langmuir* **2009**, *25* (13), 7561–7567.
- (121) Sun, T.; Tan, H.; Han, D.; Fu, Q.; Jiang, L. No platelet can adhere – largely improved blood compatibility on nanostructured superhydrophobic surfaces. *Small* **2005**, *1* (10), 959–963.
- (122) Rahmawan, Y.; Jang, K.-J.; Moon, M.-W.; Lee, K.-R.; Suh, K.-Y. Anti-biofouling coating by wrinkled, dual-roughness structures of diamond-like carbon (DLC). *Biochip J.* **2009**, *3* (2), 143–150.
- (123) Efimenko, K.; Finlay, J.; Callow, M. E.; Callow, J. A.; Genzer, J. Development and testing of hierarchically wrinkled coatings for marine antifouling. *ACS Appl. Mater. Interfaces* **2009**, *1* (5), 1031–1040.
- (124) Scardino, A. J.; Zhang, H.; Cookson, D. J.; Lamb, R. N.; Nys, R. d. The role of nano-roughness in antifouling. *Biofouling* **2009**, *25* (8), 757–767.
- (125) Chaudhury, M. K.; Finlay, J. A.; Chung, J. Y.; Callow, M. E.; Callow, J. A. The influence of elastic modulus and thickness on the release of the soft-fouling green alga *Ulva linza* (syn. *Enteromorpha linza*) from poly(dimethylsiloxane) (PDMS) model networks. *Biofouling* **2005**, *21* (1), 41–48.
- (126) Peng, J.; Su, Y.; Shi, Q.; Chen, W.; Jiang, Z. Protein fouling resistant membrane prepared by amphiphilic pegylated polyethersulfone. *Bioresour. Technol.* **2011**, *102* (3), 2289–2295.
- (127) Kumar, V.; Pulpytel, J.; Giudetti, G.; Rauscher, H.; Rossi, F.; Arefi-Khonsari, F. Amphiphilic copolymer coatings via plasma polymerisation process: switching and anti-biofouling characteristics. *Plasma Processes Polym.* **2011**, *8* (5), 373–385.
- (128) Weinman, C. J.; Gunari, N.; Krishnan, S.; Dong, R.; Paik, M. Y.; Sohn, K. E.; Walker, G. C.; Kramer, E. J.; Fischer, D. A.; Ober, C. K. Protein adsorption resistance of anti-biofouling block copolymers containing amphiphilic side chains. *Soft Matter* **2010**, *6* (14), 3237–3243.
- (129) Tan, B. H.; Hussain, H.; Chaw, K. C.; Dickinson, G. H.; Gudipati, C. S.; Birch, W. R.; Teo, S. L. M.; He, C.; Liu, Y.; Davis, T. P. Barnacle repellent nanostructured surfaces formed by the self-assembly of amphiphilic block copolymers. *Polym. Chem.* **2010**, *1* (3), 276–279.
- (130) Chen, Y.; Thayumanavan, S. Amphiphilicity in homopolymer surfaces reduces nonspecific protein adsorption. *Langmuir* **2009**, *25* (24), 13795–13799.
- (131) Baxamusa, S. H.; Gleason, K. K. Random copolymer films with molecular-scale compositional heterogeneities that interfere with protein adsorption. *Adv. Funct. Mater.* **2009**, *19* (21), 3489–3496.
- (132) Arifuzzaman, S.; Özçam, A. E.; Efimenko, K.; Fischer, D. A.; Genzer, J. Formation of surface-grafted polymeric amphiphilic coatings comprising ethylene glycol and fluorinated groups and their response to protein adsorption. *Biointerphases* **2009**, *4* (2), FA33–FA44.
- (133) Gudipati, C. S.; Finlay, J. A.; Callow, J. A.; Callow, M. E.; Wooley, K. L. The antifouling and fouling-release performance of hyperbranched fluoropolymer (HBFP)-poly(ethylene glycol) (PEG) composite coatings evaluated by adsorption of biomacromolecules and the green fouling alga *Ulva*. *Langmuir* **2005**, *21* (7), 3044–3053.
- (134) Gan, D.; Mueller, A.; Wooley, K. L. Amphiphilic and hydrophobic surface patterns generated from hyperbranched fluoropolymer/linear polymer networks: minimally adhesive coatings via the crosslinking of hyperbranched fluoropolymers. *J. Polym. Sci. A: Polym. Chem.* **2003**, *41* (22), 3531–3540.
- (135) Wang, Y.; Betts, D. E.; Finlay, J. A.; Brewer, L.; Callow, M. E.; Callow, J. A.; Wendt, D. E.; DeSimone, J. M. Photocurable amphiphilic perfluoropolyether/poly(ethylene glycol) networks for fouling-release coatings. *Macromolecules* **2011**, *44* (4), 878–885.
- (136) Cho, Y.; Sundaram, H. S.; Weinman, C. J.; Paik, M. Y.; Dimitriou, M. D.; Finlay, J. A.; Callow, M. E.; Callow, J. A.; Kramer, E. J.; Ober, C. K. Triblock copolymers with grafted fluorine-free, amphiphilic, non-ionic side chains for antifouling and fouling-release applications. *Macromolecules* **2011**, *44* (12), 4783–4792.
- (137) Park, D.; Weinman, C. J.; Finlay, J. A.; Fletcher, B. R.; Paik, M. Y.; Sundaram, H. S.; Dimitriou, M. D.; Sohn, K. E.; Callow, M. E.; Callow, J. A.; Handlin, D. L.; Willis, C. L.; Fischer, D. A.; Kramer, E. J.; Ober, C. K. Amphiphilic surface active triblock copolymers with mixed hydrophobic and hydrophilic side chains for tuned marine fouling-release properties. *Langmuir* **2010**, *26* (12), 9772–9781.
- (138) Weinman, C. J.; Finlay, J. A.; Park, D.; Paik, M. Y.; Krishnan, S.; Sundaram, H. S.; Dimitriou, M.; Sohn, K. E.; Callow, M. E.; Callow, J. A.; Handlin, D. L.; Willis, C. L.; Kramer, E. J.; Ober, C. K. ABC triblock surface active block copolymer with grafted ethoxylated fluoroalkyl amphiphilic side chains for marine antifouling/fouling-release applications. *Langmuir* **2009**, *25* (20), 12266–12274.
- (139) Feng, S.; Wang, Q.; Gao, Y.; Huang, Y.; Qing, F.-L. Synthesis and characterization of a novel amphiphilic copolymer capable as anti-biofouling coating material. *J. Appl. Polym. Sci.* **2009**, *114* (4), 2071–2078.
- (140) Martinelli, E.; Agostini, S.; Galli, G.; Chiellini, E.; Glisenti, A.; Pettitt, M. E.; Callow, M. E.; Callow, J. A.; Graf, K.; Bartels, F. W. Nanostructured films of amphiphilic fluorinated block copolymers for fouling release application. *Langmuir* **2008**, *24* (22), 13138–13147.
- (141) Krishnan, S.; Ayothi, R.; Hexemer, A.; Finlay, J. A.; Sohn, K. E.; Perry, R.; Ober, C. K.; Kramer, E. J.; Callow, M. E.; Callow, J. A.

Fischer, D. A. Anti-biofouling properties of comblike block copolymers with amphiphilic side chains. *Langmuir* **2006**, *22* (11), 5075–5086.

(142) Lau, C.; Anitole, K.; Hodes, C.; Lai, D.; Pfahles-Hutchens, A.; Seed, J. Perfluoroalkyl acids: a review of monitoring and toxicological findings. *Toxicol. Sci.* **2007**, *99* (2), 366–394.

(143) Houde, M.; Martin, J. W.; Letcher, R. J.; Solomon, K. R.; Muir, D. C. G. Biological monitoring of polyfluoroalkyl substances: a review. *Environ. Sci. Technol.* **2006**, *40* (11), 3463–3473.

(144) Finlay, J. A.; Krishnan, S.; Callow, M. E.; Callow, J. A.; Dong, R.; Asgill, N.; Wong, K.; Kramer, E. J.; Ober, C. K. Settlement of ulva zoospores on patterned fluorinated and PEGylated monolayer surfaces. *Langmuir* **2008**, *24* (2), 503–510.

(145) Grozea, C. M.; Gunari, N.; Finlay, J. A.; Grozea, D.; Callow, M. E.; Callow, J. A.; Lu, Z.-H.; Walker, G. C. Water-stable diblock polystyrene-block-poly(2-vinyl pyridine) and diblock polystyrene-block-poly(methyl methacrylate) cylindrical patterned surfaces inhibit settlement of zoospores of the green alga ulva. *Biomacromolecules* **2009**, *10* (4), 1004–1012.

(146) Kumar, N.; Hahn, J.-i. Nanoscale protein patterning using self-assembled diblock copolymers. *Langmuir* **2005**, *21* (15), 6652–6655.

(147) Krishnan, S.; Paik, M. Y.; Ober, C. K.; Martinelli, E.; Galli, G.; Sohn, K. E.; Kramer, E. J.; Fischer, D. A. NEXAFS depth profiling of surface segregation in block copolymer thin films. *Macromolecules* **2010**, *43* (10), 4733–4743.

(148) Delcroix, M. F.; Zuyderhoff, E. M.; Genet, M. J.; Dupont-Gillain, C. C. Optimization of cryo-XPS analyses for the study of thin films of a block copolymer (PS-PEO). *Surf. Interface Anal.* **2012**, *44* (2), 175–184.

(149) Shastry, A.; Goyal, S.; Ratner, B. D.; Böhringer, K. F. In *The 10th International Conference on Miniaturized Systems for Chemistry and Life Sciences*; Society for Chemistry and Micro-Nano Systems: Tokyo, Japan, 2006.

(150) White, A.; Shastry, A.; Simonovsky, F. I.; Ratner, B. D.; Böhringer, K. Derivatization of pillared silicon substrates using poly(ethylene glycol) and 1-dodecanethiol. *J. Undergrad. Res. Bioeng.* **2007**, *7* (1), 91–98.

(151) Kim, P.; Kim, D. H.; Kim, B.; Choi, S. K.; Lee, S. H.; Khademhosseini, A.; Langer, R.; Suh, K. Y. Fabrication of nanostructures of polyethylene glycol for applications to protein adsorption and cell adhesion. *Nanotechnology* **2005**, *16* (10), 2420–2426.

(152) Ahn, S. H.; Guo, L. J. Large-area roll-to-roll and roll-to-plate nanoimprint lithography: a step toward high-throughput application of continuous nanoimprinting. *ACS Nano* **2009**, *3* (8), 2304–2310.

(153) Gong, P.; Grainger, D. W. Nonfouling surfaces – a review of principles and applications for microarray capture assay designs In *Microarrays: Vol. 1: Synthesis Methods*; Rampal, J. B., Ed.; Humana Press: Totowa, NJ, 2007; Vol. 381, pp 59–92.

(154) Barthlott, W.; Neinhuis, C. Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta* **1997**, *202* (1), 1–8.

(155) Krishnan, S.; Wang, N.; Ober, C. K.; Finlay, J. A.; Callow, M. E.; Callow, J. A.; Hexemer, A.; Sohn, K. E.; Kramer, E. J.; Fischer, D. A. Comparison of the fouling release properties of hydrophobic fluorinated and hydrophilic PEGylated block copolymer surfaces: attachment strength of the diatom *navicula* and the green alga *ulva*. *Biomacromolecules* **2006**, *7* (5), 1449–1462.