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Review

Micro- and nanotechnologies in plankton research

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ABSTRACT

A better understanding of the vast range of plankton and their interactions with the marine environment would allow prediction of their large-scale impact on the marine ecosystem, and provide in-depth knowledge on pollution and climate change. Numerous technologies, especially lab-on-a-chip microsystems, are being used to this end. Marine biofouling is a global issue with significant economic consequences. Ecofriendly polymer nanotechnologies are being developed to combat marine biofouling. Furthermore, nanomaterials hold great potential for bioremediation and biofuel production. Excellent reviews covering focused topics in plankton research exist, with only a handful discussing both micro- and nanotechnologies. This work reviews both micro- and nanotechnologies applied to broad-ranging plankton research topics including flow cytometry, chemotaxis/toxicity assays, biofilm formation, marine antifouling/fouling-release surfaces and coatings, green energy, green nanomaterials, microalgae immobilization, and bioremediation. It is anticipated that developments in plankton research will see engineered exploitation of micro- and nanotechnologies. The current review is therefore intended to promote micro-/nanotechnology researchers to team up with limnologists/oceanographers, and develop novel strategies for understanding and green exploitation of the complex marine ecosystem.

Contents

Abbreviations: DMSP, dimethylsulfoniopropionate; DMS, dimethylsulfide; LOC, lab-on-a-chip; AF, antifouling; FR, fouling-release; TBT, tributyl tin; µF, microfluidic; CNTs, carbon nanotubes; TPE, thermoset polyester; PDMS, polydimethylsiloxane; PEGDMA, poly(ethylene glycol) dimethacrylate; PEGDMA-*co*-GMA, PEGDMA-*co*-glycidyl methacrylate; PEGDMA-*co*-HEMA, PEGDMA-*co*-hydroxyethyl methacrylate; LbL, layer-by-layer; NPs, nanoparticles; MFCs, microbial fuel cells; Au-NPs, gold nanoparticles; Ag-NPs, silver nanoparticles; L-DOPA, L-3,4-dihydroxyphenylalanine; mPEG, methoxy-terminated poly(ethylene glycol); SAMs, self-assembled monolayers; PNIPAAM, poly(*N*-isopropylacrylamide); WBPSUU, waterborne polysiloxane–urethane–ureas; PFPE, perfluoropolyethers; HBFP, hyperbranched fluoropolymer; NA, noradrenaline; SABCs, surface-active block copolymers; SEBS, styrene–ethylene/butylene–styrene; PS-b-P(EO-stat-AGE), polystyrene-block-poly[(ethylene oxide)-stat-(allyl glycidyl ether)]; fAGE, fluorocarbon-functionalized AGE; TEOS, tetraethylorthosilicate; APTES, aminopropyltriethoxysilane; C18, octadecyltrimethoxysilane; TDF, tetrahydrooctyltriethoxysilane; FFAs, free fatty acids; MMSNs, magnetic mesoporous silica nanomaterials; Fe-MSN, iron-NPs supported on mesoporous silica nanoparticles; BSA, bovine serum albumin.

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Introduction

The marine ecosystem is greatly dependent on the interactions between the plankton and their surrounding environment, as plankton constitute more than three-fourths of marine biomass (Erickson et al., 2011; Ramanathan et al., 2013). Phytoplankton, the base of the marine food cycle, is a key component in atmospheric carbon exchange and plays a key role in regulating the greenhouse effect (Erickson et al., 2011). Phytoplankton-produced dimethylsulfoniopropionate (DMSP) provides hunting cues to different species of marine invertebrates, fish, birds, and mammals. Also, it is well known that oceanic cycling of DMSP into volatile dimethylsulfide (DMS) is the major natural source of cloud-forming sulfur aerosols (Seymour et al., 2010). Therefore, characterizing phytoplankton population variations could potentially help us understand the effects of potential global warming (Hashemi et al., 2011b). A better understanding of the vast range of plankton and their interactions with the marine environment would allow prediction of large-scale impacts on marine ecosystem, and provide in-depth knowledge on pollution and climate change. Numerous technological developments including micro- and nanotechnologies have been made towards this end (Aravamudhan, 2007; Bahi, 2013; Berzano et al., 2012; Bhushan, 2011; Brayner et al., 2011; Carvalho et al., 2011; Dunahay et al., 1996; Erickson et al., 2011; Jonsson, 2012; Lard et al., 2010; Mills and Fones, 2012; Zhan et al., 2013).

Lab-on-a-chip (LOC) microsystems typically contain fluid transport components (Schaap et al., 2012a), and offer several advantages including miniaturization, onboard multi-functionality integration, high-throughput screening, mass-production, automation, and ability to mimic spatiotemporal microenvironments (Mohammed et al., 2009, 2008; Seymour et al., 2008). Numerous LOC systems are being used to gain a better understanding of marine organisms and their interactions with their microenvironments (Erickson et al., 2011; Kim et al., 2012; Rusconi et al., 2014; Schaap et al., 2012a). Nanotechnology, affecting almost all aspects of our life, is being applied for bioremediation, green energy (Pattarkine and Pattarkine, 2012; Trindade, 2011; Zhang et al., 2013), and green synthesis applications (Gordon et al., 2009; Parkinson and Gordon, 1999; Wang et al., 2013; Zhang et al., 2012).

Marine biofouling, a complex biochemical phenomenon, has global economic consequences including higher fuel consumption and corrosion (Callow and Callow, 2002; Detty et al., 2014; Graham and Cady, 2014). The marine biofilm communities do contain viruses, bacteria, fungi, algae, protozoa, barnacles and seaweeds (Whitehead and Verran, 2009), that are broadly classified as microfoulants (causing colonization) and macrofoulants (causing the hydrodynamic drag forces on ships) (Buskens et al., 2013; Salta et al., 2013b). Marine foulants produce bioadhesives that penetrate troughs in rough surfaces and form a secure mechanical lock during settlement/adhesion/colonization of surfaces (Lejars et al., 2012; Pettitt et al., 2004). Marine biofouling typically occurs in five stages (Fig. 1). Numerous antifouling (AF) and fouling-release (FR) technologies are being developed to combat marine biofouling (Abdolahi et al., 2014; Almeida et al., 2007; Cao et al., 2011; Chen et al., 2010; Delauney et al., 2010; D'Souza et al., 2010; Ekblad et al., 2008; Genzer and Efimenko, 2006; Kristensen et al., 2008; Long et al., 2010a,b; Magin et al., 2010; Murosaki et al., 2011; Schilp et al., 2009; Schmidt et al., 2004; Walker, 2012; Xiao et al., 2013).

Antifouling technologies can be broadly classified into chemical, physical, and biological categories (Cao et al., 2011). Tributyl tin (TBT) based paints were being used efficiently against marine biofouling until the TBT ban by the International Maritime Organization in 2008 (Detty et al., 2014) due to its detrimental consequences on the marine ecosystems. In the quest for TBT-alternatives, biomimetic microtopographical and hierarchical surfaces have been studied for AF applications (Graham and Cady, 2014; Müller et al., 2013; Myan et al., 2013; Salta et al., 2010; Scardino and de Nys, 2010). Lab-on-a-chip microsystems have been used in understanding the biofilm formation that leads to biofouling. Numerous polymers with engineered chemistries and nanotopographies have been developed for AF/FR applications (Banerjee et al., 2011; Detty et al., 2014; Lejars et al., 2012; Murosaki et al., 2011; Pagliaro et al., 2009; Yang et al., 2014).

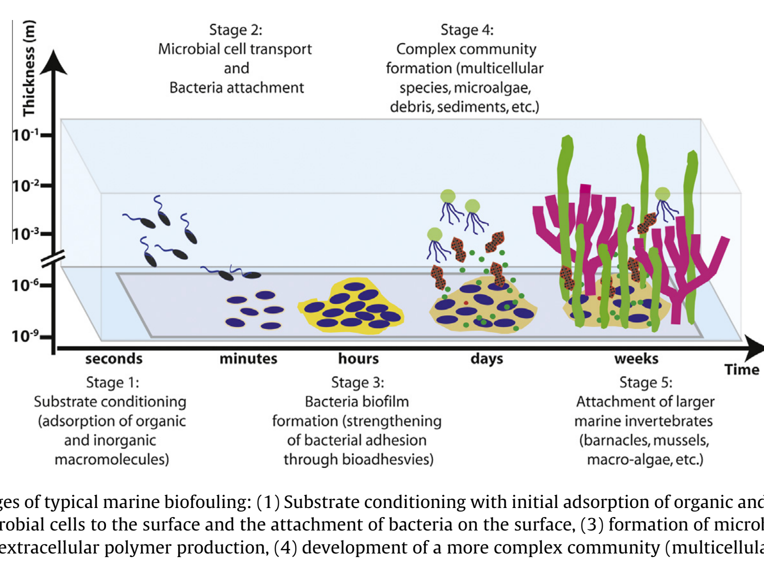

Fig. 1. Cartoon depicting the five stages of typical marine biofouling: (1) Substrate conditioning with initial adsorption of organic and inorganic macromolecules immediately after immersion, (2) transport of microbial cells to the surface and the attachment of bacteria on the surface, (3) formation of microbial biofilm by strengthening of bacterial adhesion to the substratum through extracellular polymer production, (4) development of a more complex community (multicellular species, microalgae, debris, sediments, etc.) on the surface, and (5) attachment of larger marine invertebrates (e.g., barnacles, mussels, macro-algae, etc.).

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