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Natural products: Potential and less explored source for antifouling compounds

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ABSTRACT

Development of microbial biofilms and the recruitment of propagules on the surfaces of man-made structures in the marine environment cause serious problems for the marine industries around the world. Current antifouling technology is based on the application of toxic substances that can be harmful to the natural environment. The ban of previously employed tributyltin coatings by international organizations further aggravated this issue. A bio-inspired approach to address this problem constitutes the use of natural products as antifouling agents. Natural products are the promising candidate for the development of non-toxic antifoulants. Extracts, partially purified and purified metabolites from plants, microbes and marine organisms are reported as active against micro and macrofouling organisms. However, still the number of microbes explored for antifouling compounds is very less. Among the microbial resources, actinobacteria, especially those which are from marine ecosystems are less explored for antifouling compounds. In this literature review, we described the antifouling activity of extracts and compounds from bacteria, fungi and actinobacteria. There is a great opportunity to isolate promising antifouling compounds from natural resources. However the joints efforts of biologists and natural product chemists is highly warranted.

Keywords: Marine biofouling, TBT, marine microbes; antifouling compounds

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INTRODUCTION

Biofouling

Marine biofouling is the undesired accumulation of organic molecules, microorganisms, plants, animals, and their by-products on an ocean-submerged surface. The accumulation of biological material on all surfaces immersed in biological fluids is a serious challenge for marine vessels, fresh water treatment and industrial plants [1]. In the 4th century B.C. Aristotle, the Greek Philosopher, had instructed that the barnacles coverage in ship hulls were the causative agent for slowing down of ships [2]. In the marine environment, natural and artificial surfaces, when contact with the marine water, are quickly colonized by microfoulers like bacteria, algae, protozoa and macrofoulers like barnacles, bryozoans and tubeworms [3, 4]. Now a days biofouling is an major biosecurity risk for the aquaculture industry, which includes direct impacts on cultured species (e.g. smothering, competition for space and food), deterioration of farm infrastructure (immersed structures such as cages, netting and pontoons) and effects on natural ecosystem functioning of adjacent areas [5, 6].

Mechanism of biofouling

The succession of fouling organisms is generally considered in five main stages [7]:

- In the first stage, when the surface immersed in the water, it immediately adsorbed by organic and inorganic macromolecules, forming the primary film;
- In the second stage, microbial cells are adhered on the surface and the immobilization of bacteria on the surface;
- Third stage, extracellular polymer (EPS) is produced after bacterial attachment on the substratum and forming a microbial film on the surface;
- Fourth stage corresponds to the development of a more complex community made up of multicellular species, microalgae, debris, sediments, etc. on the surface;
- Last stage is the attachment of larger marine invertebrates such as barnacles, mussels and macro-algae.

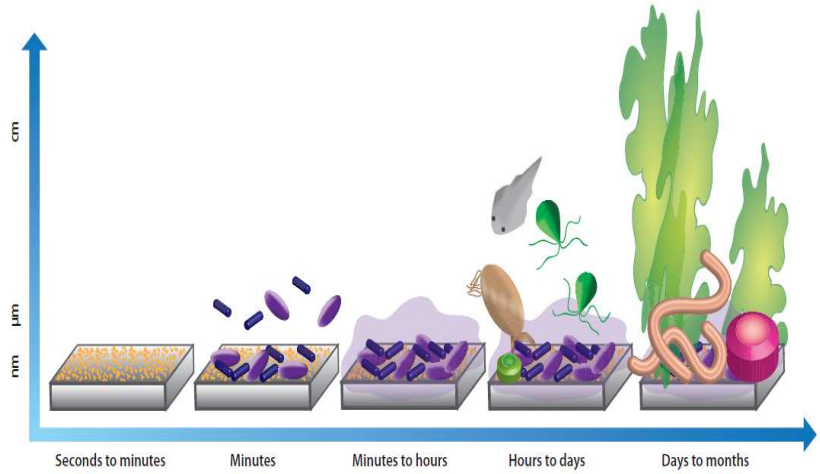

Figure 1. Schematic diagram of biofouling process [7]

Detrimental effects of biofouling

Fouling costs the shipping industry millions of dollars every year worldwide due to vessels being out of service in order to have fouling removed, costly repairs and man hours lost. The first obvious effect is the increase in the frictional drag, thus slowing down the vessel in the water and leading to increased fuel consumption to maintain the same speed. Additionally, engine equipments must have labour harder, increasing wear, stress and fatigue. These adverse effects will be significantly increase, when the ships route is via tropical/sub-tropical zones and lead to significant increase in the cost of maritime transportation, which in terms of tonnage as it handles about 90 % of the global exchange of goods. Another detrimental effect of biofouling on ship's hulls is the increased emissions of gas (CO_2, CO, SO_2 and NO_2) into the atmosphere correlated with the augmentation of fuel consumption. Considering that at a given time most vessels are relatively near shore, this implies that consequently the principal amount of gas emitted is along the coastline mainly in the Northern Hemisphere, along the West and East coast of the United States, in Northern Europe and in the North Pacific [8].

Another significant environmental damage which is linked to the colonisation of man-made surfaces is the species translocation from a geographical zone to another one during the ship voyage either falling off naturally in a new habitat or after the cleaning of the ship's hulls [9]. For example, Williams and Smith (2007) [10] estimated that 277 species of algae have been introduced in new environment with a total of 408 introductions. Among these, only 60 % of the introduction vectors are known and 77 species were reported to be introduced by ship hull transport. Marine macro algae are a significant component of marine alien taxa [11] and invasions can result in an alteration of the environment through modification of the habitat, or competition with indigenous species, resulting in important ecological (competition with native biota, effect on higher trophic level), evolutionary (change of ecosystem processes, genetic effects), economic and societal (cost of loss of ecosystem functions, impacts on environmental amenity and on human health, management costs) impacts [12, 13].

Biofouling on vessels increases hull roughness and hydrodynamic drag, which leads to decreases in speed and maneuverability, an increase in fossil fuel consumption and as a result increased emission of greenhouse gases. The

estimated costs due to fouling for the US Navy fleet, which represents only one-half of 1% of the world fleet in terms of number of ships, is between $180 million and $260 million per year [14].

Antifouling strategies

Mariners from ancient times were aware of the problems resulting from boring and other fouling organisms. Copper has been in general use by the British Navy since 1780 to control biofouling. However, copper binds to sulphur-containing cell constituents, leading to a variety of responses associated with heavy metal toxicity. The major types of toxic antifouling paints in use today are soluble matrix paints, also known as conventional paints, ablative paints (modern versions of conventional paints) and self-polishing systems. The majority of antifouling paints are pigmented with copper, usually as cuprous oxide (Cu_2O). The self-polishing copolymer (SPC) paints, introduced in 1974, were so called to indicate the 'polishing' effect as the polymer dissolves away during normal vessel operation, releasing tributyltin (TBT). TBT kills settling fouling organisms and, at the same time, the surface becomes smoother. Being very lipid soluble, it is rapidly taken up by the cells, where it inhibits energy transfer processes in respiration and photosynthesis. The SPC system was extremely successful, but TBT was shown to effect non-target organisms, including a number of shellfish, at levels much lower than ever envisaged. The most sensitive invertebrate species, the dog whelk, *Nucella lapillus*, exhibits imposex (imposition of male sexual characters on the female) at concentrations below 1 ng/l, and its disappearance from rocky shores in areas of high boating activity has been attributed to the presence of TBT from antifouling paints. TBT is now prohibited in many parts of the world and it is anticipated that the International Maritime Organisation (IMO) will impose a worldwide ban on the use of TBT-containing paints on any type of vessel from January 2003.

Furthermore, the discharge of copper from antifouling paints is currently under scrutiny, especially in California. The impact of TBT on the aquatic environment has also led to an increase in the regulations affecting the use of all other antifouling biocides, and only a few are now employed. Most commonly used are Sea-Nine 211 (an isothiazolone), zinc pyrithione (an anti-dandruff fungicide) and Irgarol 1051 (a triazine herbicide). All of these compounds are used mainly as co-biocides to copper, especially to increase efficacy against algae. In the current climate, registration of new active ingredients for use in antifouling paints is a very costly and protracted business. Increasing regulatory, environmental and product safety standards have all increased the cost and time required to develop a new antifoulant. Thus, there is intense research activity to seek novel, environmentally benign methods of fouling control. Figure 1 shows the strategies of antifouling compounds generation.

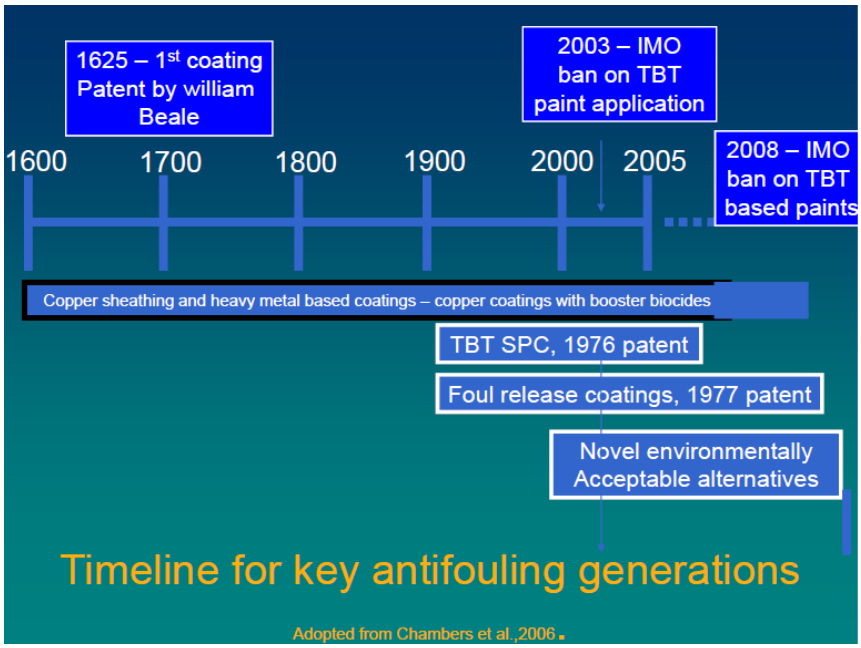

Figure 1a. Strategies of antifouling compounds

Natural product antifoulants

Toxic effects of tin and copper antifouling compounds have highlighted the need of new environmentally friendly antifouling coatings [15]. Marine natural products from microbes can be a better replacements for the chemicals commonly used in antifouling coatings [16]. Many sessile marine animals are free from biofouling and produce metabolites that demonstrate antifouling properties, presumably as a means of protection from colonisation by fouling organisms or to reduce competition for space in highly competitive environments [17].

For the past 40 years, several physical, mechanical, chemical and biological methods used for the prevention of marine biofouling have been tested [18]. Recently biogenic compounds produced by the microorganisms, especially marine microbes are most promising against of marine fouling. Many marine organisms microalgae and marine invertebrates produced biogenic agents with antibacterial, antifungal, antialgal, antiprotozoan, larvaicidal and molluscidal properties to defend themselves against settlement in the marine environment. Some of these secondary metabolites possess potent antifouling activity also [16], but their antifouling activity under laboratory and field conditions are unknown.

Natural product antifoulants (NPAs) are globally accepted and one of the most promising environmentally benign option to control marine biofouling. Secondary metabolites of marine organisms play a vital role to control the fouling. Sessile soft-bodied marine organisms are having inherent antifouling property, i.e. they produce secondary metabolites as a chemical means of warfare, protection from predation, competition for space, prevention of over growth/biofouling, combat poisoning and fight infections. Natural product antifoulants are mainly isolated from bryozoans, ascidians, sponges, soft corals, mangroves, seaweeds and bacteria. They are mainly comes under the chemical classes of terpenoids, steroids, carotenoids, phenolics, furanones, alkaloids, peptides and lactones. Phyletic distribution of 160 reviewed marine species from which potential antifouling natural products extracted. Of the 160 potential NPAs, 76% are from sponges, algae and cnidarians [19].

A recent review by Qian et al., [20] covered 214 antifouling marine natural compounds and 23 of their synthetic analogs, which were discovered and/or synthesized from mid-2009 to August 2014. The antifouling (AF) compounds reported have medium to high bioactivity (with a threshold of EC50 < 15.0 mg ml^{-1}). Among these compounds, 82 natural compounds were identified as new structures. All the compounds are marine-derived, demonstrating that marine organisms are prolific and promising sources of natural products that may be developed as environmentally friendly antifoulants.

Antifouling compounds from plants

In the 1980s, terrestrial plants were explored as a source of AF compounds [21], but were superseded by investigations on marine organisms in the 1990s. Recently, terrestrial natural products, pharmaceuticals and enzymes have been recognized as important sources of non-toxic antifoulants. When compared to microorganisms and marine organisms, reports on antifouling compounds from plants are very few, which may be an alternate source naturally available.

From several thousand years plants have been used in traditional medicine. Around 80% of the world's people depend on traditional medicine for their primary health care needs, according to the World Health Organization (WHO) [22]. India has more than one fourth (8000) of the World's known medicinal plant species (30,000), of which 90% are found in forests. A enormous amount of many novel biological active compounds are produced by plant species, as very few plants species have been thoroughly investigated for their medicinal properties. Thus, there is a renewing interest in phytomedicine during last decade and now many medicinal plant species are being screened for pharmacological activities [23]. A studied highlighted the promising antifouling activity of an active compound from *A. paniculata* plant extracts showed against marine fouling bacteria [24].

Recent years marine aquatic plants have been explored to overcome the antifouling problems. The potent AF compounds such as brominated furanones and elatol are identified from seaweeds [25], this group of plants has been actively explored for AF compounds [26,27, 28, 29, 30, 31, 32]. Antifouling activity of Seagrasses and mangrove plants have also been evaluated and the development of applications containing zosteric acid, a seagrass metabolite, as a non-toxic antifoulant has been attempted [33]. Three meroditerpenoids 16–18 isolated from the brown alga *Halidrys siliquosa* inhibited settlement of cyprids of *B. amphitrite* [34]. Floridoside , isolated from the red alga *Grateloupia turuturu*, showed potent anti-barnacle activity,but was non-toxic to nauplii, whereas co-occurring isethionic acid was less active, but more toxic [35]. A mixture of compounds inhibited Noctanoyl homoserine

lactone-mediated QS, showed inhibitory activity [36].A compound Luteolin-40-glucuronide isolated from the seagrass *Enhalus acoroides*, was a potent less toxic inhibitor of settlement of *B. neritina* larvae [37].

Eleven flavonoids were isolated from the leaves of the halophyte *Apocynum venetum*. Among them, the isolation of plumbocatechin A, 8-O-methylretusin and kaempferol 3-O-(600-O-acetyl)-b-D-galactopyranoside was reported for the first time from this plant. In addition, the antifouling activities of these compounds against the marine fouling bacteria, *Bacillus thuringiensis, Pseudoalteromonas elyakovii* and *Pseudomonas aeruginosa*, have been evaluated [38].

The use of modified tannin from black wattle tree used as an antifouling pigment and its formulated in antifouling coating exposure in a marine environment for 7 months. Water contact angle analysis showed the hydrophilic characteristic of the tannin antifouling coating surface. Immersion tests at Badalona Port in the Mediterranean Sea shows the high antifouling efficiency of the TAN coating, comparable to commercial paint, until 7 months. The use of natural black wattle tannin, without its complexation with metals, can eliminate the release of metals and other toxic biocides to the marine environment [39].

Antifouling compounds from Microbes

Bacteria

A variety of conditions (culture media, inocula, incubation temperatures) are employed in antifouling tests with marine bacteria. *Shewanella algae* was selected as model organism to evaluate the effect of these parameters on bacterial growth, biofilm formation, the activity of model antifoulants, and the development and nanomechanical properties of the biofilms. All the parameters significantly affected the ability of *S. algae* to grow and form biofilms, as well as the activity of antifouling molecules. A detailed study has been carried out in order to establish a biofilm model for further assays. The morphology and nanomechanics of *S. algae* biofilms were markedly influenced by the nutritional environments in which they were developed. As strategies for biofilm formation inhibition and biofilm detachment are of particular interest in antifouling research, the present findings also highlight the need for a careful selection of the assay conditions.

Two compounds, 2-hydroxymyristic acid (HMA) and cis-9-oleic acid (COA), were isolated from a chloroform extract of the marine bacterium, *Shewanella oneidensis* SCH0402. In a spectrophotometer based chemotaxis assay, HMA completely eliminated the optical density (OD) of *Alteromonas marina* SCH0401 and *Bacillus atrophaeus* SCH0408, motile, fouling bacteria, at 100 and 1000 lg ml–1, respectively. COA similarly decreased the OD of *A. marina* and *B. atrophaeus* by 100% at 1000 lg ml^{-1}. The commercially available, highly toxic anti-fouling compound, tributyltin oxide (TBTO) never reduced the OD of the target bacteria by 100% even at higher concentration. Instead, all the test bacterial cells were killed at higher than 1000 lg ml^{-1} of concentration. Both HMA and COA inhibited germination of *Ulva pertusa* spores completely at 10 and 100 lg ml^{-1}, respectively, while TBTO inhibited germination at 0.01 lg ml^{-1}. However, in field assays, both HMA and COA showed antifouling activities as potent as TBTO against a wide range of fouling organisms, including micro- and macro-algae, barnacles, and mussels. The average fouling coverage on the surface of the control panel was 93 ± 6% after 1.5 years but no fouling was observed on the surface of the test panel onto which each compound was applied separately. Thus, bacterial repellent compounds can be used as substitutes for potent toxic anti-fouling compounds, resulting in higher standards of environmental safety without loss of anti-fouling performance [40].

Bernbom et al., 2011 [41] carried out a study to determine if marine bacteria from danish coastal waters produce antifouling compounds and if antifouling bacteria could be ascribed to specific niches or seasons. We further assess if antibacterial effect is a good proxy for antifouling activity. We isolated 110 bacteria with anti-*Vibrio* activity from different sample types and locations during a 1-year sampling from Danish coastal waters. The strains were identified as *Pseudoalteromonas*, *Phaeobacter*, and *Vibrio naceae* based on phenotypic tests and partial 16S rRNA gene sequence similarity. The numbers of bioactive bacteria were significantly higher in warmer than in colder months. While some species were isolated at all sampling locations, others were niche specific. We repeatedly isolated *Phaeobacter gallaeciensis* at surfaces from one site and *Pseudoalteromonas tunicate* at two others.

Twenty-two strains, representing the major taxonomic groups, different seasons, and isolation strategies, were tested for antiadhesive effect against the marine biofilm-forming bacterium *Pseudoalteromonas* sp. strain S91 and zoospores of the green alga *Ulva australis*. The antiadhesive effects were assessed by quantifying the number of strain S91 or *Ulva* spores attaching to a preformed biofilm of each of the 22 strains. The strongest antifouling

activity was found in *Pseudoalteromonas* strains. Biofilms of *Pseudoalteromonas piscicida*, *Pseudoalteromonas tunicata*, and *Pseudoalteromonas ulvae* prevented *Pseudoalteromonas* S91 from attaching to steel surfaces. *P. piscicida* killed S91 bacteria in the suspension cultures, whereas *P. tunicata* and *P. ulvae* did not; however, they did prevent adhesion by nonbactericidal mechanism(s). Seven *Pseudoalteromonas* species, including *P. piscicida* and *P. tunicata*, reduced the number of settling *Ulva* zoospores to less than 10% of the number settling on control surfaces. The antifouling *alpP* gene was detected only in *P. tunicata* strains (with purple and yellow pigmentation), so other compounds/mechanisms must be present in the other *Pseudoalteromonas* strains with antifouling activity.

Fungi

Qi et al., [42] investigated the antifouling secondary metabolites from marine-derived fungi, we used bioassay guided column chromatography techniques, such as HPLC, to separate and purify compounds from *Cladosporium* sp. F14. Extensive spectral analyses including 1D NMR spectra and MS were employed for structure elucidation of the compounds. Antilarval activity of the compounds was evaluated in settlement inhibition assays with laboratory reared *Balanus amphitrite* and *Bugula neritina* larvae, while antibacterial activity was assessed with disc diffusion bioassay on growth inhibition of six marine bacterial species. In total, nine compounds were obtained. Among them, 3-phenyl-2-propenoic acid, cyclo-(Phe-Pro) and cyclo- (Val-Pro) had various antibacterial activities against three fouling bacteria, furthermore, 3-phenyl-2-propenoic acid and bis(2-ethylhexyl)phthalate effectively inhibited larval settlement of *B. neritina* and *B. amphitrite* larvae, respectively,indicating that the two compounds are potential natural antifouling agents.

Fungus, *Aureobasidium pullulans*, was isolated from marine biofilm and identified. A bioassay-guided fractionation procedure was developed to isolate and purify antifouling compounds from *A. pullulans* HN. The procedure was fermentation broth—aeration and addition of sodium thiosulfate–graduated pH and liquid–liquid extraction—SPE purification—GC–MS analysis. Firstly, the fermentation broth was tested for its toxicity. Then it was treated with aeration and addition of sodium thiosulfate, and its toxicity was almost not changed. Lastly, antifouling compounds were extracted at different pH, the extract had high toxicity at pH 2 but almost no toxicity at pH 10, which suggested the toxicants should be fatty acids. The EC_{50} of the extract against *Skeletonema costatum* was 90.9 μg ml^{-1}, and its LC_{50} against *Balanus amphitrete* larvae was 22.2 μg ml^{-1}. After purified by HLB SPE column, the EC_{50} of the extract against *S. costatum* was 49.4 μg ml^{-1}. The myristic and palmitic acids were found as the main toxicants by GC–MS [43].

Three new 14-membered resorcylic acid lactones, cochliomycins D–F, 1–3, and eight known analogues, 4–11, were isolated from the sea anemone-derived fungus *Cochliobolus lunatus*. Compounds 1–4 are diastereomers differing from each other by the absolute configurations of the 4′,5′-diol chiral centers. The absolute configurations of 1–4 were established by the CD exciton chirality method and TDDFT ECD calculations. In antifouling assays, 1, 3–6, and 6a exhibited potent antifouling activities against the larval settlement of the barnacle *Balanus amphitrite* at nontoxic concentrations, with EC50 values ranging from 1.82 to 22.5 μg/mL. Noticeably, fungicide whole-plant assays indicated that 6 showed excellent activity on the *Plasmopara viticola* preventative test at 6 ppm and concentration-dependent activity on the Phytophthora infestans preventative application at 200, 60, and 20 ppm. Preliminary structure–activity relationships are also discussed [44].

Actinobacteria

Actinomycetes are the well recognized as the richest source of bioactive compounds including clinically useful antibiotics, anti cancer agents and cell function modulators and hence of high pharmacological and commercial interest [45]. They are widely distributed in various normal and extreme ecosystems, due to their unparalleled ability to degrade wide range of complex substrates and withstand extreme physico-chemical conditions [46]. Based on the hypothesis “poorly researched habitats can offer better prospects for discovering new natural products”, actinomycetes from such habitats are currently in focus of considerable scientific interest [47]. Marine covers more than 70% of the earth’s surface which contains prevalent space for living microorganisms especially actinomycetes. Actinomycetes are a large group of bacteria producing novel secondary metabolites especially antibiotics. These Gram positive high GC bacteria are widely distributed in soils, but can be found in different marine environments like surface sea water, lower or abyssal depth of coastal to offshore region, and other general oceanic area [48, 49]. The increasing numbers of literatures on novel metabolites and the diversity of marine actinomycetes strongly support the view that the marine environment is a significant source for the search and discovery of both diversity and secondary metabolites [50,51]. *Actinomyces, Actinopolyspora, Micromonospora, Micropolyspora, Nocardia,*

Rhodococcus, Salinispora, Serinicoccus, Streptomyces, Streptosporangium, Streptoverticillium, and *Solwaraspora* are the major actinobacterial genera were reported from marine sediments [48, 52, 53].

Nowadays, the number of discovery of new metabolites from terrestrial actinomycetes has been decreased. On the other hand, there is an increase in the rate of reisolation of known compounds [54]. Therefore, thorough the examination of new groups of actinomycetes based on unexplored habitations as sources of fresh bioactive secondary metabolites proves crucial.

Many novel actinobacteria were isolated from marine environments which produced novel secondary metabolites with different biological activities were recently reported [55, 56,57, 58, 59]. In India also, there are many reports on bioprospecting of actinobacteria from marine ecosystems with special reference to antimicrobial and enzymatic activities [60,61, 62]. The reports stated that, more than 41 species of actinobacteria which are mainly comes under the genera Streptomyces, Nocardia, Micromonospora and Actinopolyspora are isolated from Indian marine ecosystems. In this regard, antifouling compound diketopiperazine was reported from deep sea bacterium *Streptomyces fungicidicus* [63]. Marine derived *Streptomyces albus* inhibited the *Vibrio* biofilm formation [24]. Five structurally similar compounds from the crude extract of a marine *Streptomyces* strain contain antifouling activities against major fouling organisms [64]. However bioprospecting of actinobacteria from Indian marine ecosystems with special reference to antifouling compounds are very few [65, 66, 67].

Overall, marine actinobacteria could provide a source of biologically active metabolites for the antifouling industry and other biotechnological applications. With the improvement of isolation and cultivation techniques and the availability of molecular tools for uncultivable strains, it may be possible to detect more isolates, to identify more novel antifouling compounds and to engineer ‘‘environmentally friendly’’ biotechnologies against biofouling.

Enzymes as an antifoulants

Over the last few decades, attention of research centers in the search for new bioactive substances, such as enzymes and biocides to be used in major sectors of the world economy, including the agricultural, chemical, food, textile, pharmaceutical, bioenergy and cosmetic industries. Especially industrial enzymes value was nearly US$ 4.8 billion in global market in the year 2013 and it is expected to reach US$ 7.1 billion by 2018 according to BCC Research (BCC Research 2014)[68]. Besides their economic value, microbial enzymes are applied in technologies employing eco-friendly processes [69].

Some of the novel enzymes explored for antifouling activity include oxidoreductases, transferases, hydrolases, lyases, isomerases ligases etc [27,45,70]. Quorum sensing an important factor in biofim formation. N -acyl homoserine lactones (AHL) is reported play an vital role in quorum sensing and repelling zoospores of *Ulva sp* [3]. AHL acylases is also potential for broad antifouling activity in addition to several proteases, glycosylases and oxido reductases acylase. Spore adhesion strength and settlement of *Ulva* zoospores the settlement of *Balanus amphitrite* cyprid larvae has been shown to be significantly highly inhibited by serine-protease at laboratory and field level experiments by incorporating in paints [45, 71,70].

Nano particles as an antifoulants:

Marine natural products, like seaweeds [72], sponges [73] and mangrove plants [74], have the ability to reduce metallic silver to AgNPs. The biogenic AgNPs have a wide range of applications like antibacterial [75] and antifungal agents [76].Poly-phenols, proteins and other active phytochemical in the seaweeds have the ability to reduce and stabilize noble metals like silver, gold, platinum, and lead [77]. The application of metal nanoparticles to prevent marine biofouling is inadequate. Though biofouling occurs in any material immersed in natural seawater, there is a substrate-specific variation in fouling load [78]. The most commonly used material in the seawater includes, concrete for the building of marine structures, mild steel in power plant cooling systems, PVC and stainless steel, in oceanographic research equipment, aquaculture cages, and ship hulls, wood are highly subjected to fouling communities and cause severe technical problems and environmental issues.

A novel eco-friendly antifouling product against marine biofouling is the need of the hour. The application of biogenic AgNPs as an effective anti-micro-fouling agent against marine biofilm consortia has not been reported elsewhere in the literature barring the work of Inbakandan et al., [73] and V Ramkumar et al., [79]. In nature, biofilm is composed of varieties of bacteria, belonging to both gram-positive and gram-negative bacteria. The growth of gram-negative bacteria was more profoundly inhibited by the AgNPs than that of the gram-positive

bacteria [80]. Inbakandan et al., [73] demonstrated the species-to-species variation in the antibacterial activity of AgNPs synthesized from sponges.

Actinobacteria - mediated synthesis of silver nanoparticles (AgNPs) is a reliable, eco-friendly and important aspect of nanobiotechnology. In this study, aqueous silver ions, which were exposed to an actinobacterial biomass of *Streptomyces naganishii* (MA7), were reduced to form stable AgNPs under optimized conditions. The microbially synthesized AgNPs were characterized by UV-Vis spectroscopy, Fourier transform infrared (FT-IR) spectroscopy, X-ray diffraction (XRD), selected area electron diffraction (SAED), energy dispersive X-ray spectroscopy (EDX), scanning electron microscopy (SEM), atomic force microscopy (AFM) and high- resolution transmission electron microscopy (HR-TEM). The size (5-50 nm) and shape (spherical) of the AgNPs were determined. The biosynthesised AgNPs exhibited good bactericidal, anti-biofouling, antioxidant and cytotoxic effects with regards to the HeLa cell line [81].

Among the eleven seaweeds studied, the yield of AgNPs synthesized by *U.lactuca* was high and exhibited excellent micro-fouling activities. The biogenic AgNPs coated on PVC coupons exposed for 45 days in natural seawater, which has inhibited the micro-fouling. The application of biogenic AgNPs as an effective anti-foulant against consortia of marine biofilms has not been reported elsewhere in the literature [82].

CONCLUSION

This review highlights the impacts of biofouling and potential of NPAs as alternatives to TBT-based antifouling coatings. Considering that marine microbes remain the largest untapped source of natural products. Judicious and gainful utilization microbes from marine ecosystems lead to the isolation of novel natural product antifoulants. There is a great opportunity to isolate promising antifouling compounds from natural resources. However the joints efforts of biologists and natural product chemists is highly warranted.

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