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Review

Natural antifouling compound production by microbes associated with marine macroorganisms — A review

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ABSTRACT

In the marine environment, all hard surfaces including marine macroorganims are colonized by microorganisms mainly from the surrounding environment. The microorganisms associated with marine macroorganisms offer tremendous potential for exploitation of bioactive metabolites. Biofouling is a continuous problem in marine sectors which needs huge economy for control and cleaning processes. Biotechnological way for searching natural product antifouling compounds gained momentum in recent years because of the environmental pollution associated with the use of toxic chemicals to control biofouling. While, natural product based antifoulants from marine organisms particularly sponges and corals attained significance due to their activities in field assays, collection of larger amount of organisms from the sea is not a viable one. The microorganisms associated with sponges, corals, ascidians, seaweeds and seagrasses showed strong antimicrobial and also antifouling activities. This review highlights the advances in natural product antifoulants research from microbes associated with marine organisms.

Contents

1. Introduction

Biofouling (accumulation of organisms) is a common problem on man-made objects submerged in the marine waters throughout the world. The biofouling growth on a substratum in the aquatic environment is a complex process (Fig. 1) with initial biofilm formation (consisting of microbes and microalgae) followed by settlement of invertebrate larvae and algal spores [1,2]. Biofouling assemblage in marine environment is made up of thousands of marine organisms such as bacteria, fungi, phytoplankton, polychaetes, barnacles, molluscs, ascidians and algae (Fig. 2). Biofouling on submerged surfaces in the marine environment has considerable ecological and economical importance particularly serious implications for shipping, offshore aquaculture and coastal industries [3,4,5]. The effects are mainly due to the loss of productivity in aquaculture [6] or increased costs of fuel to shipping as well as the costs associated with ongoing prevention, management and control [7,8].

Due to the economic significance of the problem in the marine waters, various control strategies are adopted by the marine sectors

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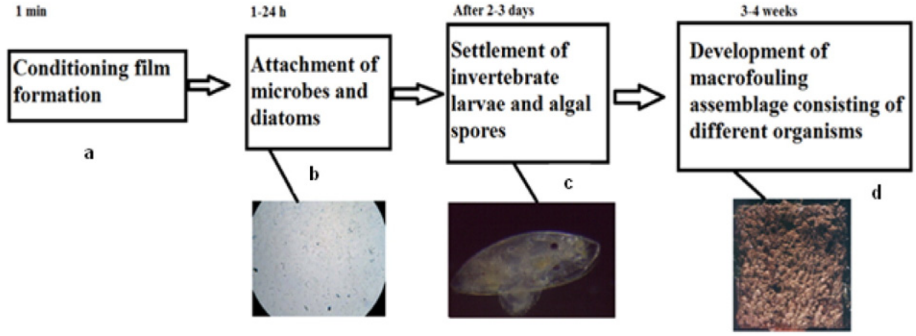

Fig. 1. Progression of biofouling development on hard substratum submerged in tropical coastal waters.

(Fig. 3). Tributyltin (TBT) containing antifouling paints were widely used in the commercial vessels to control biofouling [9,10]. However, use of TBT caused environmental problems as it is more toxic to non-target marine organisms [11,12,13,14]. Due to the environmental concern over the use of TBT, the International Maritime Organization and Marine Environment Protection Committee banned the application of TBT for marine applications from January 1, 2008 [5]. After the ban of TBT containing antifoulants, copper paints are used as an alternative despite the higher toxicity of copper to the marine environment [15]. In addition, many other compounds are also commonly used as antifouling biocides [16,17] which include irgarol 1051 diuron, dichloroflumid, chlorothalonil, zine, pyrithione, pyridine and zineb [10]. Some of these antifouling compounds are now under strict regulations in various regions due to the possible effects on marine ecosystems. Natural products are suggested as an alternative to toxic biocides in the antifouling paints for controlling biofouling. In a previous review by Qian et al. [10] have highlighted the recent progress in natural product antifouling research which consists of both marine and terrestrial sources. Recently, Qian et al. [18] reported another comprehensive review on the antifouling activities of natural products from marine sources and their synthectic analogs. Another review by Dobretsov et al. [19] reported the progress of biofouling inhibitory activities of marine microorganisms. However, antifouling activities of marine microbes associated with living surfaces are not reviewed comprehensively. The aim of this review was to expand our knowledge on current status of antifouling research from marine microbes associated with macroorganisms.

2. Eco-friendly antifoulants from marine organisms

After the ban of TBT based antifouling paints and environmental concerns associated with other toxic biocides, there is a growing need for the effective eco-friendly antifoulants for marine applications [20,21]. Research interest on natural product antifoulants has been increased in the recent years that was evident from the growing number publications [21,22]. In nature, many marine sessile organisms

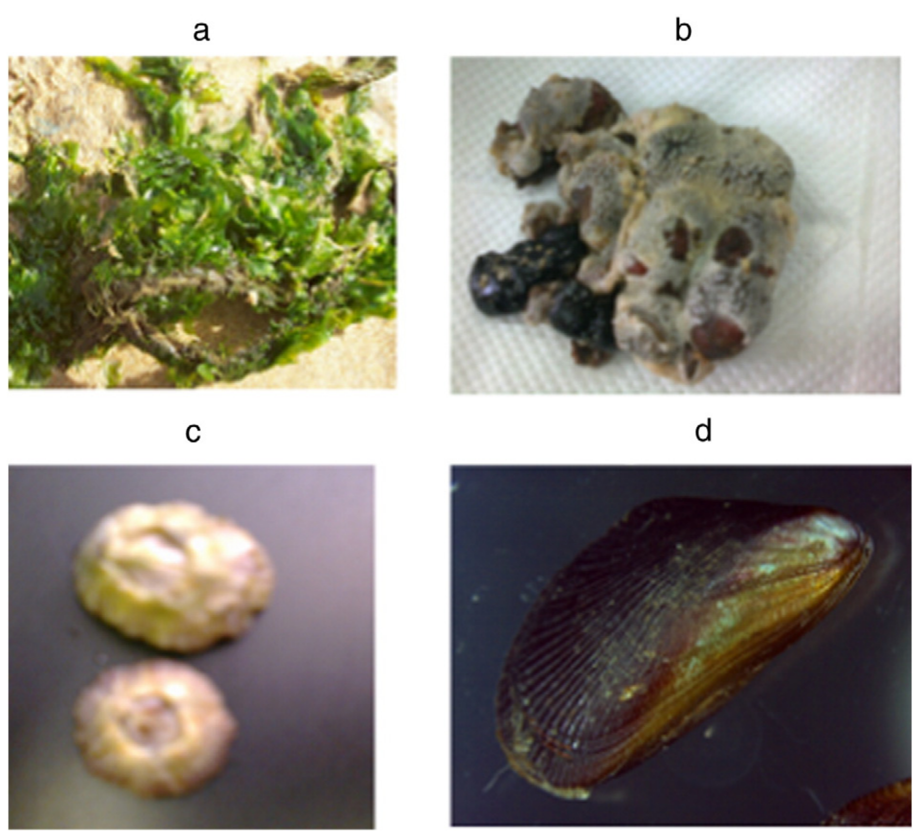

Fig. 2. Examples of fouling organisms commonly found on the hard substrata submerged in the marine waters. a: Macroalga; b: Ascidian; c: Barnacle; d: Bivalves.

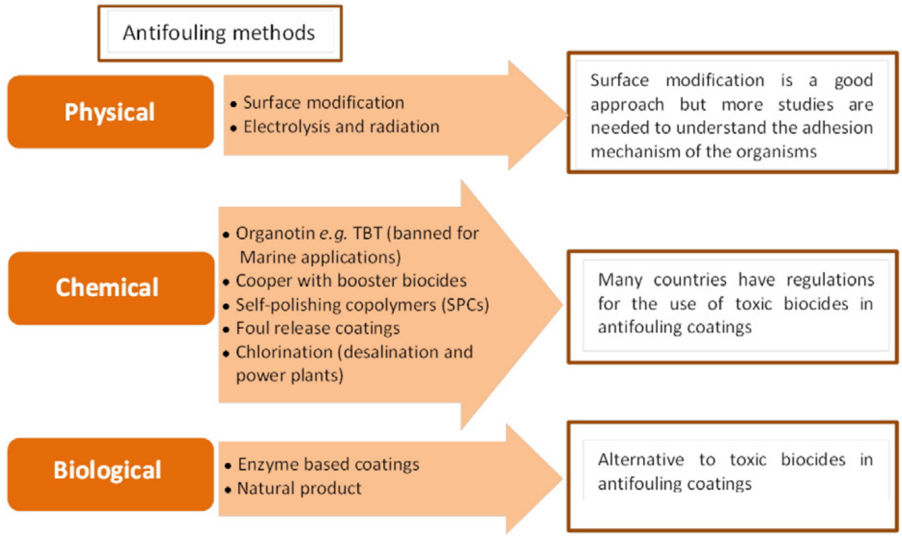

Fig. 3. Common antifouling adopted by various industries for biofouling management.

are keeping their surfaces free from fouling organisms [23,24] mainly through the production of secondary metabolites [1,25,26]. The secondary metabolites produced by many marine organisms that showed inhibitory activities against the biofouling organisms would be the ideal lead molecules for the development of natural product antifoulants that can be incorporated into paints [27,28]. The compounds belonging to terpenoids, steroids, carotenoids, phenolics, furanones, alkaloids, peptides and lactones extracted from the marine organisms showed antifouling activities [29]. Among the marine organisms, antifouling activities were largely reported from sponges and corals [24,30,31,32,33,34]. Sponges especially attracted the attention of the researchers due to their close relationship with wide variety of microbes and presence of large number of biologically active secondary metabolites [35]. Another important group attracted the attention of investigators is the ascidians from which good number of antifouling molecules were reported in the literature [36,37]. Antifouling activities were also reported from seaweeds, seagrasses, [38,39], bryozoans [40,41], mangroves and microorganisms [42,43,44,45].

Few antifouling coatings based on natural products from the marine organisms such as Sea Nine- 211, Netsafe and Pearlsafe have already been commercialized [46,47]. During the past five decades bioactive metabolites from the marine environment attracted the attention of researchers all over the world for the discovery of lead compounds in medicine and industry [48,49,50,51,52,53,54,55]. Due to the concern on exploitation of large amount of marine organisms for natural products discovery, marine microbes are considered as the viable source for searching bioactive molecules. Many novel bioactive metabolites with antifouling activities were reported from marine microbes in the literature [56,57,58,59,60].

3. Marine macroorganisms–microbe associations

In the marine environment, macroorganisms are generally colonized by an array of microbial communities from the surrounding waters [61], sometimes in high density up to 40–60% of weight reported for sponge, *e.g.* Hentchel et al. [62] or diversity (*i.e.*, many strains in an animal, *e.g.* Li et al. [63]). This association also referred as 'symbiosis' (which includes both ectosymbiosis and endosymbiosis) has been described from all animal and plant groups in the marine realm [64]. The symbionts commonly reported in the literature include microorganisms belonged to bacteria, archaea and unicellular eukaryotes [64]. Generally, the microorganisms attached to marine invertebrates and plants possess more physiological activities than free-living ones [65,66]. The association between invertebrates and microbes occur for many purposes. For example, these microbes may produce secondary metabolites to enhance their survival in the competitive conditions prevailing on the surface of the host's body [67]. The production of secondary metabolites by these microbes was evident from the studies made by Burkholder et al. [68] in which they reported a bioactive metabolite from the bacterium obtained from the surface of Caribbean seagrass Thalassia. Microbes are believed to produce different types of metabolites with pharmocodynamic properties, insecticidal and repellants activities [69,70]. These metabolites are mainly exploited for screening of lead molecules for drugs and other compounds with industrial applications [71,72,73].

The microbes associated with marine organisms and their secondary metabolites may enhance (inductive) or inhibit (non-inductive) the larval settlement of marine organisms. Those microbes which inhibit the larval settlement could be used as a potential source for the exploration of antifouling compounds. Also, bacteria associated with the surface of marine invertebrates are reported to contain a higher proportion of antibacterial and antifouling activities than those occur as planktonic forms [74,75]. This hypothesis was confirmed by the studies made by Long and Azam [76] in which they reported that a major proportion of microbes attached with surfaces produce inhibitory compounds than free-living forms. Several studies indicate that the metabolite believed to be produced by the host organism for the defense purpose is actually originated from the microbes [77,78,79]. To confirm this hypothesis, many investigations were carried out to isolate the bacteria associated with sponges and number of novel metabolites have been reported [80,81]. For example, the cytotoxic macrolide swinholide 1, extracted from the sponge *Theonella swinhoei*, was found to be synthesized by one of the unicellular bacterial symbionts inhabiting the endosome of this sponge species [82]. Hence, microbial associations with higher organisms serve as a sustainable resource for novel biologically active secondary metabolites. This prompted more studies focusing on the metabolites produced by the microorganisms associated with marine macroorganisms.

4. Antifouling activities of microbes associated with marine invertebrates and ascidians

In this review, antifouling activities of bacteria and fungi associated with marine macroorganisms are highlighted with examples (Table 1 and Table 2). Among the marine organisms, microbes associated with sponges and corals topped the list for antifoulant screening assays (Fig. 4). To mention few, Kon-ya et al. [83] isolated upiquinone-8 from a sponge-associated bacterial strain *Alteromonas* sp. which possess

Table 1
Some bacterial strains isolated from the marine macroorganisms with reported antifouling activity/bioactivity.

Host organism	Bacterial strain	Activity	Reference
Sponge	*Alteromonas* sp.	Antifouling	[83]
Ascidian	*Acinetobacter* sp.	Antifouling	[84]
Macroalga	*Pseudoalteromonas ulvae* sp.	Antifouling	[101]
Nudibranchs	*Pseudomonas* sp.	Antifouling	[94]
Macroalga	*Vibrio* sp.	Antifouling	[104]
Sponge	*Pseudoalteromonas piscicida*	Antimicrobial	[138]
Macroalga	*Phaeobacter gallaeciensis*	Antifouling	[139]
Molluscan	*Pseudomonas fulva*	Antimicrobial	[140]
Coral	*Bacillus horikoshii*	Antibacterial/antibiofilm	[141]
Ascidian	*Pseudoalteromonas haloplanktis*	Antifouling	[118]
Soft coral	*Bacillus* sp.	Antibacterial	[142]
Seagrass	*Bacillus* sp.	Antifouling	[107]
Macroalga	*Pseudovibrio* sp.	Antibacterial	[143]
Sponge	*Bacillus licheniformis*	Antibacterial/antibiofilm	[144]
Macroalga	*Leucothrix mucor*	Antifouling	[145]
Macroalga	*Streptomyces praecox*	Antifouling	[108]
Sponge	*B. cereus*	Antifouling	[44]
Macroalga	*Streptomyces violaceoruber*	Antifouling	[110]
Sponge	*Bacillus* sp.	Antifouling	[90]
Sponge	*Bacillus* sp.	Antifouling	[89]
Macroalga	*Bacillus subtilis*	Antibacterial	[146]
Ascidian	*P. denitrificans*	Antifouling	[103]
Sponge	*Pseudomonas fluorescens*	Antimicrobial	[147]

inhibitory activities against barnacle larval settlement. Olguin-Uribe et al. [84] isolated an epibiotic bacterium, *Acinetobacter* sp. from the surface of the ascidian *Stomozoa murrayi*. This bacterium produces 6-bromindole-3-carbaldhyde that inhibited the settlement of cyprid of the barnacle *Balanus amphitrite* at a concentrations of 10 mg mL^{-1}. The ecological role of soft coral-associated bacterium *Arthrobacter* sp. against marine biofilm-forming bacteria was highlighted by Radjasa and Sabdono [85]. Another study by Dobretsov and Qian [86] assessed the antifouling effect of epibiotic bacteria isolated from the surface of the soft coral *Dendronephthya* sp. These researchers isolated 11 bacterial strains from the coral surface and found that 2 strains inhibited the settlement of the larva of tubeworm *Hydroides elegans*. Another study by Kanagasabhapathy et al. [87] examined the effects of four strains of Gram positive bacteria (PS2, PS9, PS11 and PS79) isolated from the sponge *Pseudoceratina pupurea* on the growth of bacteria isolated from

Table 2
Examples of fungal strains associated with different macroorganisms. These strains were reported to produce bioactive metabolites with antifouling and antimicrobial activities.

Host organism	Fungal strain	Activity	Reference
Sponge	*L. helminthicola*	Antifouling	[21]
Gorgonian	*Aspergillus* sp.	Antibacterial	[148]
Gorgonian	*C. lunatus*	Antifouling	[88]
Sponge	*Aspergillus insuetus*	Antifungal, cytotoxic	[149]
Sponge	*Aspergillus* sp.	Antibacterial, antifouling	[150]
Sponge	*Aspergillus* sp.	cytotoxic	[151]
Macroalga	*Drechslera* sp.	Antifouling, antibacterial	[152]
Gorgonian	*Penicillium* sp.	Antifouling, antibacterial	[22]
Coral	*Aspergillus*	Antifouling	[153]
Coral	*Alternaria*	Antifouling	[153]
Gorgonian	*Xylariaceae* sp.	Antifouling, enyme-inhibitory activity	[154]
Soft coral	*Aspergillus elegans*	Antifouling, antibacterial	[155]
Gorgonian	*Aspergillus terreus*	Antifouling, antiviral	[156]
Sea Anemone	*C. lunatus*	Antifouling, antifungal	[102]
Sponge	*Aspergillus sydowii*	Antimicrobial, antiviral	[157]
Gorgonian	*Aspergillus* sp.	Antimicrobial, antifouling	[158]
Gorgonian	*Talaromyces* sp.	Cytotoxic, antifouling	[16]
Gorgonian	*Scopulariopsis* sp.	Antifouling	[91]
Soft coral	*Aspergillus unguis*	Antifungal	[159]
Gorgonian	*P. pinophilum*	Antifungal, cytotoxic	[92]

the biofilms and standard strains of genera *Vibrio-Photobacterium*. Two antifouling compounds, 3-methyl-N-(2-phenylethyl) butanamide and cyclo(D-Pro-D-Phe) were isolated from a sponge-associated fungus *Letendraea helminthicola* [21]. Another fungal strain *Cochliobolus lunatus* associated with the gorgonian *Dichotella gemmacea* collected from the South China Sea showed antifouling activities [88]. The bacterium *Bacillus cereus* isolated from the surface of the sponge *Sigmodocia* sp. was capable of inhibiting the adhesion of biofilm bacteria and microalgae [44]. In a study carried out by Bao et al. [22] screened the antifouling activity of gorgonian derived fungus *Penicillium* sp. SCSGAF0023. The symbiotic bacteria associated with sponge *Aplysina gerardogreeni* showed antifouling activities against microfouling organisms such as bacteria and microalgae in laboratory assays [89]. The crude extracts of 52 bacterial strains associated with sponge species were tested for anti-adhesion activities against diatoms by Jin et al. [90] and suggested *Bacillus* sp. as potential source for antifouling compounds. Dihydroquinolin-2(1H)-one containing alkaloids from a fungal strain *Scopulariopsis* sp. associated with the gorgonian coral from the South China Sea showed strong antifouling activities against the larvae of barnacle *Amphibalanus amphitrite* [91]. The compounds produced by a gorgonian derived fungus *Penicillium pinophilum* showed inhibitory activities against the barnacle larvae at non-toxic concentrations [92].

The microbes associated with other macroorganisms were also subjected to extensive studies for antifouling activities. For example, bacterial communities associated with barnacle *B. amphitrite* (= *A. amphitrite*) was found to be active against the settlement of barnacle larvae [93]. The extract of bacterial strain NudMB50-11 isolated from the surface of the nudibranch, *Archidoris pseudoargus* was found to be active against fouling bacteria [4]. Three antibacterial compounds, pyolipic acid, phenazine-1-carboxylic acid and 2-alkylquinol-4-ones extracted from a *Pseudomonas* sp. isolated from the nudibranchs showed strong antifouling activities in both laboratory and field assays [94,95]. Extracellular polymeric substances produced by *Exiguobacterium* sp. associated with the polychaete *Platynereis dumerilii* showed inhibitory activities against the biofilm bacteria [96]. Another study by Shankar et al. [97] evaluated the antibiofilm activities of bacteria associated with polychaetes. The *Acinetobacter* sp. associated with the ascidian *S. murrayi* produces an antifouling metabolite 6-bromindole-3-carbaldhyde that inhibits the settlement of cyprids of the barnacle *B. amphitrite* [84]. *Pseudoalteromonas tunicata*, a bacterial strain isolated from the surface of ascidian *Ciona intestinalis* showed inhibitory activities against larval forms of barnacle, polychaete, ascidian and spores of macroalgae [98,99,100,101]. The resorcyclic acid lactones isolated from a sea anemone-associated fungus *C. lunatus* exhibited antifouling activities against the barnacle larvae in laboratory assays [102]. Eight bioactive compounds that belonged to di(1H-indol-3-yl) methane family were isolated from the ascidian associated *Pseudovibrio denitrificans* and all the compounds showed moderate to strong antifouling activities against larval forms of barnacle *B. amphitrite* and bryozoan *Bugula neritina* [103].

5. Antifouling activities of microbes associated with seaweeds and seagrasses 5

Microbes associated with seaweeds and seagrasses were also screened extensively for antifouling activity since they constitute an important source for bioactive substances. Among the seaweed epibiotic bacteria, the genus Pseudoalteromonas was highlighted as an important group with antifouling, antimicrobial and cytotoxic activities. For example, *Pseudoalteromonas ulvae* sp. nov., a bacterium with antifouling activities was isolated from the surface of the alga *Ulva lactuca* by Egan et al. [101]. The bacterial strains *Pseudoalteromonas* sp. and *Vibrio alginolyticus* isolated from an alga produce either non-soluble or waterborne metabolites that inhibit larval settlement [104]. Besides, Pseudoalteromonas and unidentified bacterial strains

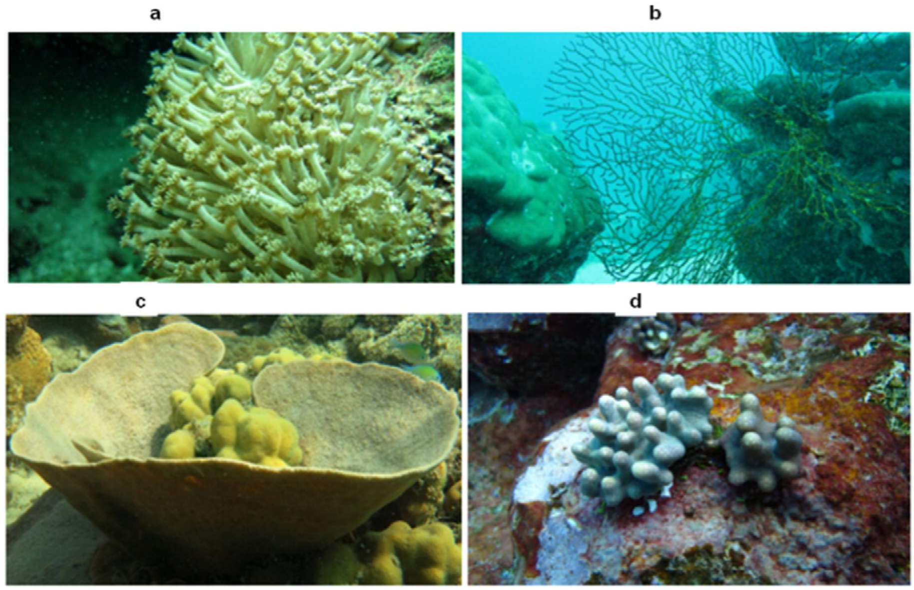

Fig. 4. Examples of marine invertebrate groups commonly reported in the literature for studying microbial symbionts. a: Coral; b: Gorgonian; c: Sponge; d: Soft coral. (Underwater images from the Red Sea).

were also reported to possess antifouling activities. A study by Dobretsov and Qian [105] reported that bacterial strains from the surface of the green alga *Ulva reticulata* showed inhibitive activities against micro- and macrofouling organisms. Active compounds from the cells and culture supernatant of the bacterial strain, FS-55 isolated from the surface of seaweed, *Fucus serratus*, were extracted using solid phase extraction, combined with acrylic based paint resin and showed good antifouling activity against the fouling bacteria [4]. A study carried out by Ma et al. [106] showed the inhibition of common fouling organisms in mariculture by epiphytic bacteria associated with the surface of seaweeds and invertebrates off the Dalian coast in China. The bacterial symbionts of seagrasses *Thalassia hemprichii* and *Enhalus acoroides* were screened for antifouling activities against biofilm-forming bacteria and identified members of the genus Bacillus and Virgibacillus as active symbionts [107]. The actinomycetes associated with seaweeds and sediments along the coast of Korea were evaluated for their antifouling activity by Cho et al. [108] and reported diketopiperazines as active metabolites. An unidentified epibiotic bacterium from the surface of the seaweed *Sargassum wightii* showed antifouling activity in laboratory and field assays [109]. Two furanone derivatives produced by the bacterium *Streptomyces violaceoruber* isolated from the surface of the brown seaweed *Undaria pinnatifida* showed antifouling activities against macroalgae and mussel larvae [110].

6. *Pseudoalteromonas* associated with marine organisms: A potential genus for antifouling research

Most of the antifouling screening studies on the microbes associated with marine organisms mainly focused on a particular species for detailed study based upon the activities. In general, *Alteromonas*, *Pseudoalteromonas*, *Vibrio* and *Bacillus* were dominant bacterial groups frequently found associated with marine macroorganisms [70,86]. Among these, *Pseudoalteromonas*, a genus reclassified by Gauthier et al. [111] is widely isolated from animal and plant surfaces and reported to produce many bioactive molecules [60,70,100,101,112]. The dominance of this genus on marine living surfaces may be due to the bacteriolytic and algicidal activities [100] which provide effective way for competition with other colonizing organisms [113]. They can also survive under poor nutritional conditions because of the biochemical pathways and production of secondary metabolites which include bioactive compounds and enzymes [114,115].

Pseudoalteromonas received more attention in recent years for natural product research due to the widespread distribution and easy cultivability under laboratory conditions [116]. Previous studies showed that the bioactive molecules present in this genus possess antifouling activities against micro and macrofouling organisms [117,118]. The antifouling activities are mainly related to the presence of yellow and purple pigments in *Pseudoalteromonas* [56] and Franks et al. [119] have identified the yellow pigments as a new member belonging to tambjamine compounds. In addition, many members of this genus are reported to produce extracellular enzymes, toxins and extracellular polymeric substances [100,120,121,122]. The compounds produced by *Pseudoalteromonas* will definitely serve as lead for the development of novel antifoulants. Due to the ecological and biotechnological significance of *Pseudoalteromonas*, more than 50 genomes of this genus have been sequenced [123]. Though, *Pseudoalteromonas* bacteria were isolated from many organisms, given the nature of vast diversity in the marine realm opportunities still exist for concerted research program for searching bioactive molecules with potential antifouling activities from this genus.

7. Advantages of microbes as a source of bioactive metabolites

Majority of the antifouling compounds isolated from the marine organisms are from invertebrates of tropical or subtropical seas where species diversity and resource competition are reported to higher than other ecosystems [50]. Bioactive compounds are synthesized in small quantities by the organisms and occur as a complex mixture [124] and due to that the extraction and purification are labor-intensive and a time-consuming process [124,125]. For the extraction of a bioactive compound from a marine organism, large number of animals or algae would have to be collected from the sea. The collection of large amount of marine organisms particularly sponges; corals and rare species will be a cause of concern from the biodiversity conservation point of view [21]. Contrary to this, if the microbe is considered as a source for the bioactive compound, then the product supply will be ensured by culturing the microorganisms or isolating the genes responsible for the biosynthesis of the particular metabolite [126,127,128,129].

Although the microbes are suggested as an alternative source for marine organisms for antifouling compound discovery, microbial symbionts have complex molecular structures that are hard to synthesize chemically [21]. The isolation of microbes from the macroorganisms is a bottleneck especially in sponges where the microbe lives inside the tissues. Notwithstanding above issues, the advantages are more when microorganisms associated with marine organisms are used as a source for the exploitation of antifouling compounds. The microbes can be cultured in the laboratory using appropriate culture media and conditions, though there are some limitations to culture some strains using traditional methods. Jensen et al. [130] confirmed higher recovery of cultivable bacteria from marine algal surfaces using culture-dependent methods. The fermentation process allows us to extract good quantity of metabolites from the microbes for bioassays [131]. The microbial strains will grow in laboratory under optimum temperature, pH, and nutrient conditions. Most of the previous studies suggested that microorganisms will grow successfully under conditions that mimic the physical and chemical characters of the natural environment. For example, Okazaki et al. [132] reported that a marine isolate from the shallow sea mud produce antibiotics only when supplemented with powdered Laminaria in the growth medium. In addition, there are possibilities that bacterial strains of the same species can produce different bioactive compounds depending on culture conditions and thus increasing the prospective number of valuable compounds [4]. Some of the microorganisms which showed antifouling activities in laboratory assays are failed to exhibit the same in field assays. For the development of natural product based antifouling coatings, there is a need for the evaluation of antifouling potential of the compound through laboratory and field trails (Fig. 5).

The antifouling performance of the bioactive compounds isolated from the marine microbes can be tested in the laboratory against biofilm-forming bacteria, diatoms and barnacle larvae as target organisms. An ideal natural product antifouling compound will act different ways on the target organisms (Fig. 6). Generally, the compound should prevent the formation of biofilms, which is considered as a cue for the further settlement of invertebrate larvae in the marine environment. The extracts or compounds from the microbes isolated from the marine macroorganisms showed inhibitory activities against an array of biofilm-forming bacteria [44,45,97]. The main mechanism of antibiofilm activities of microbial strains associated with marine macroorganisms includes antibiotic activity and anti-adhesion property and affects the extracellular polymers production (EPS) which is essential for biofilm formation [44]. It is believed that the compounds produced by the microbes associated with marine macroorganisms may exhibit same mode of mechanism (anti-settlement) against larval forms and macroalgal spores though more studies required to confirm the antifouling mechanism.

8. Conclusions and future perspectives

Marine microorganisms are taxonomically diverse and unique, which makes them as potential source for discovery of novel bioactive molecules [133]. In the aquatic ecosystems, microbial communities possess strong affinity towards the living and non-living surfaces [134]. The microbial association with living surfaces in the marine environment provides ample opportunities for bioprospecting natural products. This review clearly confirms the antifouling activities expressed by microbes associated with living surfaces in the marine environment. However, most of the studies were conducted under laboratory conditions and failed to test the compounds in natural water for commercial applications. Hence two possible approaches are suggested for further research. First, as pointed out by Qian et al. [10,18], those metabolites which showed antifouling/antimicrobial activities should be investigated further through different antifouling assays using various target species. These assays may also include field trials by incorporating these metabolites into a suitable paint. Most of the previous investigators used pure compounds or crude extracts from microbes for preparing the antifouling paints [15,94,109]. This approach is rather good than incorporation of surface-associated bacterial strains in suitable paints. Second, more bioprospecting efforts are required to recover novel antifouling molecules from the marine macroorganism–microbe association. Culture dependent methods were previously used to identify the bacterial communities and the advent of molecular methods provides many tools for studying the microbes associated with surfaces [131,135]. Hence, applying the genomic tools along with bioassay guided antifouling assays will yield valid information and novel metabolites from the microbial consortia associated with marine macroorganisms.

The industries certainly request a potent antifouling system with long durability (at least 5 years), cost effective, easy for application and non-toxic to marine ecosystem [136]. However, most of the new antifouling systems failed to meet the above characters. Natural products can be successfully used for antifouling applications by incorporating in a suitable paint. However, preparation of an

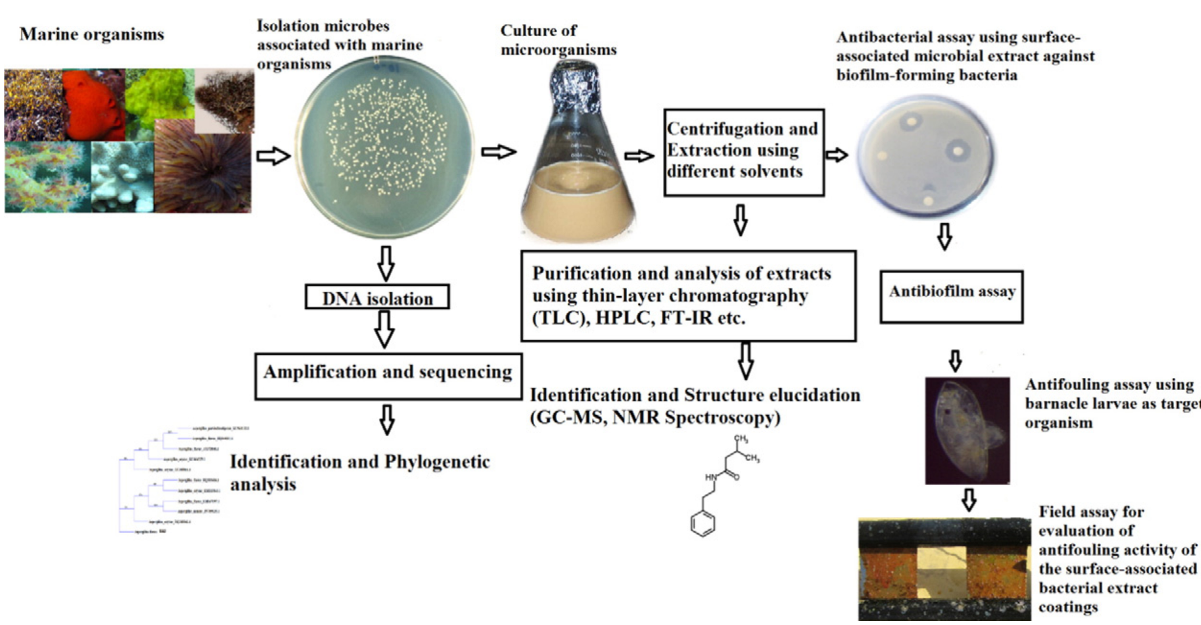

Fig. 5. Schematic diagram showing the steps involved in isolation and identification of natural product antifouling compounds from the microbes associated with marine macroorganisms.

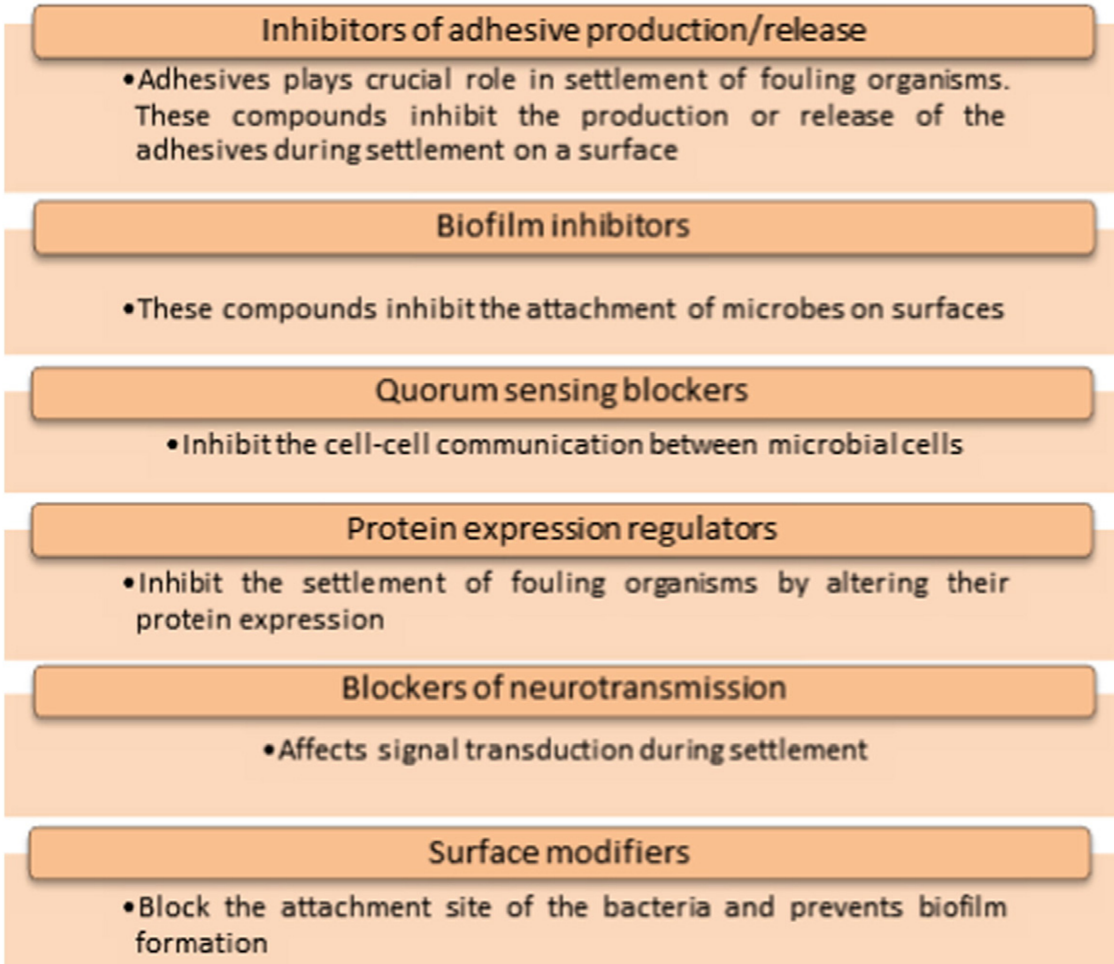

Fig. 6. General mode of action of antifouling compounds on fouling organisms (contents adapted from Qian et al. [160]).

antifouling coat using microbial products is a major challenge as these compounds will breakdown rapidly in the environment [137]. Finding a best way to increase the durability of the compound when applied as antifouling coating may provide more opportunities for natural product based antifouling systems. Developing a natural product antifouling coatings based on microbes associated with marine macroorganisms definitely takes much time and efforts. The toxicity of compounds produced by these microbes on non-target organisms in the marine ecosystem also needs to be analyzed before commercial applications [19]. In conclusion, the microbes associated with marine macroorganisms are an untapped source for natural product antifouling compounds and many more novel compounds could be identified through interdisciplinary approach.

Conflict of interest statement

The authors declare that there are no conflict of interest.

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