**Marine Actinomycetes: Species Diversity and Potential Bioactive Compounds**

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**Abstract**

Marine organisms have evolved diverse structural, physiological and metabolic characteristics that allow them to survive under extreme conditions. Marine microorganisms, in particular, actinomycetes, are one of the promising sources of bioactive compounds. Actinomycetes are Gram Positive filamentous bacteria that are extensively studied for the production of diverse secondary metabolites. The studies on marine actinomycetes and their bioactive compounds intensified with the advancement in technologies that enabled their culture-independent isolation and characterization. The diversity of actinomycetes in the marine environment with an emphasis on those associated with marine organisms and their bioactive compounds is focused on in this chapter.

**Keywords**: Actinomycetes, Marine Environment, Diversity, Bioactive compounds

**Introduction**

The marine ecosystem entails a rich variety of organisms, both macro and micro with specific and unique morphological and metabolic characteristics that make them capable of surviving under extreme pressure, salinity, and temperature (Abdelmohsen et al., 2014). These diverse microbial communities of marine habitats and the ecology of marine ecosystems remain largely unexplored. Actinomycetes make up a promising group of marine microbes. Novel antimicrobial drugs have been produced by actinomycetes, including the most important classes of tetracyclines, aminoglycosides, macrolides, and glycopeptides. Marine actinomycetes provide a fresh perspective on microbial natural product research with their novel secondary metabolites discovered from unique taxa and isolated rare populations. Actinomycete diversity and the effects of marine adaptations on secondary metabolite production need to be determined in order to better understand the potential of marine actinomycetes.

Actinomycetes are Gram-positive filamentous bacteria with a high G+C content [Jensen et al., 2005]. Approximately 70% of antibiotics used in the human treatment are produced by actinomycetes (Bérdy, 2005) making them the most powerful natural source of antibiotics. In the past, actinomycete natural products were obtained by culturing them in media that were different from their natural environments. Since the 1980s, the search for natural products from actinomycetes has declined rapidly due to the re-discovery of compounds (Van Middlesworth and Cannell, 1998). Subsequently, the efforts to isolate novel compounds from actinomycetes witnessed a massive shutdown, parallel to which there was the rise in antibiotic-resistant pathogenic microbes. Since the advent of omics and high throughput technologies and with thousands of actinomycete genome sequences readily available, it has become evident that actinomycetes can produce NPs that have never been observed before [Behie et al., 2017]. This has elicited huge interest in exploring them for the discovery of novel products using innovative strategies. The chapter provides an overview of the Actinomycete diversity in the marine environment and the potent bioactive compounds produced by them.

**Actinomycete Diversity in the Marine Environment**

There are many unique features of marine environments that distinguish them from other aquatic environments. Extreme environmental conditions like salinity, high temperature, pressure, and pH variations induce bioactive compound production in marine microorganisms in comparison to their terrestrial counterparts (Sarkar and Suthindhiran, 2022). Marine actinomycetes are diverse and inhabit sediment, seawater, and aquatic organisms. The majority of the actinomycetes isolated have been from the sponges, corals, ascidians etc. as well as from the brown algae. There are also reports of isolation of potent actinomycetes from other marine sources like sediments (mangroves, estuaries, coastal areas, lagoons, deep sea lakes) and from marine vertebrates.

Sediments: Marine actinomycetes predominantly Streptomyces sp. were isolated from sediments by several researchers. Ellaiah et al. (1996 and 2004) isolated Streptomyces sps. from marine sediments of Machilipatnam and Kakinada coast in Andra Pradesh, India. About 94 strains of Actinomycetes predominantly Streptomyces sps. were isolated from the marine sediments of a shrimp farm by You et al. (2005). Jose and Jha (2017) in their study isolated a total of 148 Actinobacteria from intertidal marine sediments of Diu Island (India) in Arabian Sea and based on 16S rRNA gene sequence, determined to belong to Glycomycete, Micromonospora, Nocardia, Nocardiopsis, Pseudonocardia, Streptomyceta, and Thermomonospora sp.. A total of 73 actinobacterial strains were isolated from marine soil of East coast regions of Andhra Pradesh, India; 8 of them were characterized and were found to belong to Dietzia sp., Kocuria sp., Nocardiopsis sp. and Streptomyces sp. Gozari et al. (2019) isolated 168 actinomycete colonies from 14 sediment samples of the northern part of the Oman sea. The majority (66%) of the isolates belonged to Streptomycetaceae followed by Micromonosporaceae (14%), Nocardiaceae (6%) and Pseudonocardiaceae (4%). The deep-sea sediment isolates of Actinomycete in the previous studies were not well- characterized (Goodfellow and Williams, 1983). Native marine actinomycetes showed to exist in the oceans from culture-independent studies (Ward and Bora, 2006), which include Dietzia sp., Rhodococcus sp. (Heald et al., 2001), Streptomyces sp. (Moran et al. 1995), Salinispora sp. (Mincer et al., 2005, Jensen et al., 2005, Maldonado et al., 2005) and Marinispora sp. (Jensen et al., 2005, Kwon et al., 2006) and *Aeromicrobium marinum* (Bruns et al. 2003).

Invertebrates: Bioactive compounds have been derived from marine invertebrates, such as sponges and corals, but their small biomass makes them unreliable sources (Jagannathan et al., 2021). The Marine sponges belong to the phylum Porifera and are among the primitive multicellular animals (Love et al., 2009) on Earth which inhabit diverse microbes, and their symbiotic relationships with bacteria are among the most complex (Taylor et al., 2007; Sun et al., 2015). Studies suggest the microorganisms within these invertebrates are the true sources of these bioactive compounds (El Samak et al., 2018). Rare actinomycete genera such as Actinokinetospora, Amycolatopsis, Nonomuracea, Saccharomonospora, Saccharopolyspora, Pseudonocardia, Pseudonocardia, Actinomadura, Knoellia and Verrucosispora have been isolated from marine sponges which could be targeted for novel lead compounds (Abdelmohsen et al., 2014). Several studies evidenced the isolation of new marine actinomycete genera from sponges. Pimentel-Elardo et al. (2008) isolated an obligate marine marine actinomycete *Streptomyces axinellae* sp. nov. from the sponge Axinella polypoides collected from Banyuls-surmer, France. The knowledge of actinobacterial diversity in coral reef systems is scant. Mahmoud and Kalendar, (2016) studied the richness and diversity of Actinomycete present in three types of coral viz., *Coscinaraea columna*, *Platygyra daedalea* and *Porites harrisoni* surviving in the coral reef system north of the Arabian Gulf. The actinobacterial genera isolated belong to the common Streptomyces as well as Micrococcus, Brevibacterium, Renibacterium, Nocardia, Microbacterium, Dietzia, Cellulomonas, Ornithinimicrobium, Micromonospora, Rhodococcus, Agrococcus, Kineococcus, Dermacoccus, Devriesea, Kocuria, Marmoricola, Brachybacterium and Arthrobacter. Several researchers have also isolated rare actinomycetes which are the non-streptomyces actinomycete from the marine environment with the ability to produce novel compounds (Ezeobiora et al., 2022). Table 1 shows some of the rare actinomycetes isolated from marine sponges and corals.

Table 1. Rare actinomycetes isolated from marine sponges & corals

|  |  |  |  |
| --- | --- | --- | --- |
| Host species | Identified actinomycete genera | Location of sample collection | Reference |
| **Sponge-associated actinomycete** | | | |
| *Xestospongia* sp. | *Nocardia xestospongiae* | Andaman sea | Thawai et al., 2017 |
| *Speciospongia vagabunda* | *Actinokinespora spheciospongiae* | Red sea | Kampfar et al., 2014 |
| *Amphimedon viridis* | *Williamsia spongiae* | Praia Guaecá (São Paulo, Brazil) | Afonso et al., 2017 |
| *Glodia corticostylifera* | *Marmoricola aquaticus* | São Paulo, Brasil | De Memezes, et al. 2015 |
| Unidentified marine sponge | *Micromonospora spongicola* | Gulf of Thailand | Supong et al., 2013a |
| Xestospongia sp. | *Verrucosispora andamanensis* | Phuket Province of Thailand | Supong et al., 2013b |
| **Coral-associated actinomycete** | | | |
| *Galaxea fascicularis* | *Prauserella corallicola* | - | Wu et al., 2014 |
| *Nocardiopsis coralliicola* | *Gorgonian coral, Menella praelonga* | Weizhou Island, Guangxi province, China | Li et al., 2012 |

**Marine Actinomycetes producing Bioactive Compounds**

The advancement in technologies provided us with different ways and methods to determine microbial diversity and determine the biosynthesis ability of potent marine microorganisms (Chen et al., 2021) which are unculturable. The actinomycete-derived bioactive compounds of marine origin are mainly isolated from marine sponges. The actinomycete genera belonging to Micrococcineae are reported to be the predominant sponge symbionts but with limited potential for secondary metabolism. In contrast, those belonging to Streptomycetaceae, Micromonosporaceae, and Pseudonocardiaceae which are less abundant in sponges show more potential for secondary metabolite production and have prospects to produce novel drug / bioactive leads (Chen et al., 2021). The symbiotic actinomycete in the marine environment are potent sources of novel natural products (El Samak et al., 2018).

Table 2. Natural products / Bioactive compounds (Alkaloids, Polyketides, Peptides and Steroids from Actinomycete associated with Marine organisms (Adapted from Chen et al., 2021)

|  |  |  |  |
| --- | --- | --- | --- |
| Actinomycete sp. | Bioactive compound | Bioactivity | Reference |
| **Alkaloids** | | | |
| Micromonospora sp. L-31-CLCO-002 (associated with marine sponge *Clathrina coriacea*) | 4’-N-methyl-5’-hydroxystaurosporine,  5’-hydroxystaurosporine, staurosporine | Cytotoxicity | Abdelmohsen et al., 2014a; Hernandez et al., 2000 |
| Saccharopolyspora sp. nov., (associatedwith marine sponge *Mycale plumose*) | Metacycloprodigiosin, Undecylprodigiosin | Cytotoxicity | Liu et al., 2005 |
| Micromonospora sp. (associatedwith marine sponge *Acanthostrongylophora sp.)* | manzamine A,  8-hydroxy manzamine | Antibacterial and Antiviral | Abdelmohsen et al., 2014a |
| Salinispora sp. strain M403 (associatedwith marine sponge *Pseudoceratina clavate*) | Rifamycins B and SV | Antibacterial | Abdelmohsen et al., 2014a; Kim et al., 2006 |
| Streptomyces sp. strain Ni-80 (associated with unidentified Sponge) | Urauchimycins A and B | Antifungal | Abdelmohsen et ala., 2014; Imamura et al., 1993 |
| Streptomyces sp. strain HB202 (associated with marine sponge *Halichondria panicea*) | Streptophenazines A-H | Antibacterial | Mitova et al., 2008 |
| Salinispora sp.FS-0034 (associated with marine sponge *Theonella* sp.) | Rifamycin W | Antibacterial | Singh et al., 2014 |
| Streptomyces sp. strain RV15 (associated with marine sponge *Dysidea tupha*) | Naphthacene glycoside SF2446 A2 | Antibacterial | Reimer et al., 2015 |
| Strain MCCB267 (associatedwith marine sponge *Mycale* sp.) | Ikarugamycin (IK), clifednamide A (CF), 30-oxo-28-N-methylikarugamycin and 28-N-methylikarugamycin (MI) | Cytotoxicity | Dhaneesha et al., 2019 |
| Streptomyces sp. OUCMDZ-1703 (associated with soft coral) | Watasemycin A, pulicatin G, aerugine | Antibacterial | Peng et al., 2013 |
| Streptomyces sp. (associated with *Lophelia pertusa*) | Lobophorin K | Cytotoxicity | Brana et al., 2017 |
| Salinispora pacifica LL-371366 (derived from marine ascidian *Polysyncraton lithostrotum*) | Lomaiviticins A and B | Cytotoxicity | Chen et al., 2018; Janso et al., 2014; He et al., 2001 |
| **Polyketides** | | | |
| Micromonospora sp. L-25-ES25-008 (associated with Marine sponge) | IB-96212 (26-membered spiroketal macrolide) | Cytotoxicity | Abdelmohsen et al., 2014a; Canedo et al., 2000 |
| Saccharopolyspora taberi PM070747 (associated with Marine sponge) | Angucyclinone PM070747 | Cytotoxicity | Perez et al., 2009 |
| Streptomyces sp. Sp080513GE-26 (associated with Marine sponge) | Tetracenoquinocin | Cytotoxicity | Abdelmohsen et al., 2014a; Motohashi et al., 2010 |
| Nocardiopsis strain HB383 (associated with Marine sponge *Halichondria panacea*) | γ-pyrones nocapyrones A-D | Antibacterial | Abdelmohsen et al., 2014a; Pimentel-Elardo et al., 2011 |
| Streptomyces sp. BCC45596 (associated with Marine sponge *Xestospongia sp.*) | Urdamycinone E, Uramycinone G and dehydroxyaquayamycin | Antibacterial,  Antiparasitic | Wang et al., 2020; Supong et al., 2012 |
| Actinokineospora sp. EG49 (associated with Marine sponge *Spheciospongia vagabunda*) | Actinosporin C and D | Antioxidant | Abdelmohsen et al., 2014b; Grkovic et al., 2014 |
| Micrococcus sp. EG45 (associated with Red Sea sponge) | Microluside A | Antibacterial | Vicente et al., 2015 |
| Streptomyces sp. PG-19 (associated with Cortez gorgonian octocoral Pacifigorgia sp.) | Octalactins A and B | Cytotoxicity | Tapiolas et al., 1991 |
| Streptomyces sp. SCSIO 41399 (Coral associated) | Araciamycin K | Cytotoxicity | Cong et al., 2019 |
| *Streptomyces variabilis* (associated with Scleractinia coral *Acropora formosa*) | 1-hydroxy-1-norresistomycin (HNM) | Cytotoxicity | Ramalingam et al., 2019 |
| *Streptomyces sp.* #N1-78-1 (associated with sea squirt *Ecteinascidia turbinata*) | Bisanthraquinones 1 and 2 | Antibacterial | Chen et al., 2018; Socha et al., 2006 |
| *Pseudonocardia sp.* HS7 (associated with sea cucumber *Holothuria moebii)* | Curvularin macrolides (5) | Cytotoxicity | Cao et al., 2019 |
| *Streptomyces sp.* 112CH148 (associated with starfish *Acanthaster planci)* | 3,4,6-trisubstituted α-pyrone derivatives violapyrones H and I | Cytotoxicity | Shin et al., 2014 |
| *Micromonospora* (associated with marine mammals*)* | Glycosylated polyketide phocoenamicin | Antibacterial | Ochoa et al., 2018 |
| **Peptides** | | | |
| Streptomyces sp. DA18 (associated with marine sponge *Craniella australiensis*) | Diketopiperazines (DKPs) | Antifouling | Gao et al., 2010 |
| Streptomyces sp. strains 22 and 23 (associated with marine sponge *Aplysina aerophoba* and *Axinella polypoides* ) | Cyclic depsipeptide Valinomycin | Antiparasitic | Abdelmohsen et al., 2014a; Pimentel-Elardo et al., 2011 |
| *Kocuria palustris* (associated with marine sponge) | Kocurin | Antibacterial | Palomo et al., 2013; Martin et al., 2013 |
| Streptomyces sp. SBT348 (associated with marine sponge) | Petrocidin A (cyclic dipeptide) | Cytotoxicity | Kitani et al., 2017 |
| Micromonospora sp. L-13ACM2-092 (associated with soft coral) | Thiocoraline | Cytotoxicity  Antibacterial | Boger et al., 2000; Qi et al., 2020 |
| **Steroids** | | | |
| Actinomadura sp. SBMs009 (associated with marine sponge *Suberites japonicus*) | 3-keto sterols bendigoles D-F | Antiinflammatory | Abdelmohsen et al., 2014a; Simmons et al., 2011 |
| *Streptomyces seoulensis* IFB-A01 | Streptolactone | Antiviral | Jiao et al., 2013 |
| *Streptomyces seoulensis* sp. RM66 (associated with marine sponge) | Manadoperoxide H and acanthosterol sulfate F | Antiprotozoal | Alkhalifah, 2021 |

As is evident from Table 2 that several actinomycetes associated with marine organisms are characterized and have pronounced bioactive compound production potential. Molecules with apparent activities have entered clinical trials. Further investigations of marine actinomycetes could uncover new compounds not known to date from these versatile microbes.

**Conclusion**

Given the vast diversity of the marine environment, it is increasingly obvious that the oceans contain numerous unique chemical compounds. Novel metabolites with pharmaceutical and industrial applications are generated by actinomycetes. Actinomycetes inhabiting extreme environments like the ocean have rich metabolic diversity, making them ideal candidates as sources of novel bioactive compounds. In light of the rise of antibiotic resistance and the need for alternatives, it is essential to expand research on actinomycetes and explore their potential. As highlighted in this chapter, there have been several breakthroughs in bioactive leads from marine actinomycetes in the past decade which are to be harnessed to find potential applications.

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