RSC Advances

REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Adv.*, 2022, **12**, 34531

Natural products as antivibrio agents: insight into the chemistry and biological activity

Noer Kasanah, *[a] Maria Ulfah [b] and David C. Rowley[c]

Vibriosis causes serious problems and economic loss in aquaculture and human health. Investigating natural products as antivibrio agents has gained more attention to combat vibriosis. The present review highlights the chemical diversity of antivibrio isolated from bacteria, fungi, plants, and marine organisms. Based on the study covering the literature from 1985–2021, the chemical diversity ranges from alkaloids, terpenoids, polyketides, sterols, and peptides. The mechanisms of action are included inhibiting growth, interfering with biofilm formation, and disrupting of quorum sensing. Relevant summaries focusing on the source organisms and the associated bioactivity of different chemical classes are also provided. Further research on *in vivo* studies, toxicity, and clinical is required for the application in aquaculture and human health.

Received 13th August 2022
Accepted 15th November 2022

DOI: 10.1039/d2ra05076e

rsc.li/rsc-advances

1. Introduction

The genus *Vibrio* is Gram-negative, curved-rod shape bacteria, halophilic, fermentative, motile by polar flagella, catalase, and oxidase-positive. The genus inhabits aquatic environment, freshwater, water column, sediment, and is associated with marine organisms.[1,2] *Vibrio* spp. play roles as nutrient cyclers in aquatic ecosystems, take up organic material, produce poly-unsaturated fatty acids to the aquatic food web, and degrade chitin.[3] These groups of bacteria are responsible for several serious infections and opportunistic pathogens to aquatic animals and humans.[1,4,5]

Studies about the effects of increasing sea surface temperature on the biology and ecology of *Vibrio* showed that there are correlations between the escalation of the emergence of *Vibrio* infections and global warming. Climate change induces global warming and as a result, the rising sea surface temperature corresponds to the number and distribution of *Vibrio* as reported in many places worldwide. Salinity less than 25 ppt contributes to *Vibrio* prevalence and infection in the marine system.[5–8]

The term vibriosis is used to refer to infections by the member family of Vibrionaceae both in aquatic animals and humans.[9] Vibriosis is one of the primary problems in aquaculture that causes severe economic losses and large-scale mortality of shrimp, fish, and shellfish.[10] Comprehensive reviews are available focusing on vibriosis in fish,[11–13] shrimps,[14] crustaceans,[15–17] and mollusks.[18]

More than a hundred *Vibrio* species have been identified and caused infections in humans. About 14 species of *Vibrio* reported as causative agents of human vibriosis cause foodborne and non-foodborne *Vibrio* infections such as *V. cholerae*, *V. parahaemolyticus*, *V. alginolyticus*, and *V. vulnificus*.[9,19] *Vibrio* spp. infect humans worldwide and is responsible for gastroenteritis, septicemia, and invasive skin and soft tissue infection (SSTI).[9,20] Non-foodborne *Vibrio* infections, caused by *V. vulnificus*, *V. alginolyticus*, and *V. parahaemolyticus* are fatal and often leads to the amputation or death of immunocompromised patients suffering from liver disease, alcohol abuse, or diabetes.[20–22]

A single or combinational antibiotic is the treatment for curative against vibriosis both in aquatic animals and humans.[20] Most *Vibrio* spp. are susceptible to most antibiotics for animals or humans. Overuse and unregulated antibiotic used in aquaculture are contributing to growing problems and concerns in antimicrobial resistance that impacts human health. Antimicrobial resistance may reduce the effectiveness of treatment options for fish and human health management.[23,24] Multiple-antibiotic resistance of *V. vulnificus* and *V. parahaemolyticus* were reported in countries such as the United States, Italy, Brazil, Philippines, Malaysia, Indonesia, Thailand, China, India, Iran, South Africa, and Australia.[24–30]

Antibiotic resistance and the restricted choices of available antivibrio agents are the reasons for searching natural products as new antivibrio agents. The increase in the emergence of antibiotic-resistant bacterial pathogens, including *Vibrio* spp. is a major public health concern. Therefore, it has intensified the interest in research on the search for effective alternatives to cope with the issue of antibiotic-resistant bacteria. Attempts have been done on screening, isolation, and structure determination of antivibrio compounds from natural products. This review intends to deliver the exploration of natural products for new antivibrio compounds.

[a]*Department of Fisheries, Faculty of Agriculture, Universitas Gadjah Mada, Indonesia. E-mail: noer.kasanah@ugm.ac.id*

[b]*Integrated Lab. Agrocomplex, Faculty of Agriculture, Universitas Gadjah Mada, Indonesia*

[c]*Department of Biomedical and Pharmaceutical Sciences, College of Pharmacy, The University of Rhode Island, USA*

2. Targets for antivibrio

Antibiotic resistance is becoming an important issue in the world of medicine. Newly developed antibiotics also starting to lose their effectiveness against some bacterial strains. As a result, it is critical to look for novel antimicrobial agents that are both effective against resistant microbes and long-lasting.

Quorum sensing (QS) is a small diffusible signaling molecule that trigger the expression of multiple genes that govern a wide range of activities including bioluminescence, virulence control, sporulation, host colonization, biofilm development, defense against competition, and environmental adaptability. *Vibrio fischeri*, *V. harveyi*, *V. cholerae*, *V. anguillarum*, and *V. vulnificus* use QS to regulate their pathogenicity.[31] Biofilm is a complex structure of microbiome having different bacterial colonies or single type of cells in a group; adhere to the surface that are embedded in a membrane structure of the extracellular polymeric substances (EPS) composed of eDNA, proteins and polysaccharides. The matrix complex are attached to the biotic or abiotic surface, showed high resistance to antibiotics.[32,33] Biofilms formation is the key factor for accelerating *Vibrio* spp. to grow and survive by providing access to nutrients, protecting from the host immune system, defending from the predator, and antimicrobial compounds. Studies showed that biofilm is important for survival, virulence and stress resistance of *Vibrio* sp.[34,35] The formation and maintenance of biofilms, as well as their resistance to antimicrobials and the host's innate immune system, are controlled by QS-regulated gene expression.[35–37]

In the aquaculture system, QS regulates virulence factors and the formation of biofilm. Thus, disruption of QS is a potential strategy for preventing disease in aquaculture systems. Quorum sensing inhibitors (QSIs) or quorum quenchers inhibit both the expression of virulence-associated genes and attenuate the virulence of aquaculture pathogens.[32] Quorum sensing plays a role in the formation of biofilms. Thus, fighting *Vibrio* spp. by interrupting quorum sensing and biofilms formation are the right strategies to combat vibriosis.[38,39] Inhibiting growth, interrupting quorum sensing, and interfering biofilms formation are targets for antagonistic effects in searching for antivibrio.

3. Antivibrio from bacteria

3.1. Actinobacteria

Actinobacteria are important assets for microbial natural products with therapeutic properties for medicinal, agricultural, veterinary, and aquaculture applications including chloramphenicol, tetracycline, erythromycin, rifamycin, rapamycin, vancomycin, bleomycin, and avermectin. Actinobacteria are known to produce 70% of the antibiotics used today.[40,41]

Screening have been carried out to obtain isolates that produce antivibrio compounds. Actinobacteria mainly *Streptomyces* spp. from different sources were tested for the antagonistic effect against *Vibrio* spp.[42–47] A comprehensive review showed a list of 128 strains of *Streptomyces* isolated from terrestrial and marine environments that are active against *Vibrio* spp.[48] Most of the studies have focused on the preliminary screening bioactivity of crude extract fermentation. To date, only a limited number of structure elucidations and identified the bioactive compounds that displayed potent antibacterial activity against *Vibrio* spp. Herein, we collected data on antivibrio compounds isolated from Actinobacteria presented in Fig. 1 and Table 1.

Brevibacterium casei MSI04 associated with a marine sponge *Dendrilla nigra* produces poly-hydroxy butyrate with the activity as antiadhesive. The inhibition activity was tested again on pathogen *Vibrio* spp. from shrimp aquaculture. The compound inhibited *V. vulnificus* and *V. fischeri* (96%), *V. parahaemolyticus* and *V. alginolyticus* (92%), and *V. harveyi* (88%).[49]

Actinobacteria produce wide type of antibiotics such as nanaomycins, munumbicins and guadinomine active against *Vibrio* spp. Nanaomycins are quinone antibiotics produced by *Streptomyces rosa* var *notoensis* OS-3966. Nanaomycin A (**1**) showed bioactivity against *V. parahaemolyticus* K-1 and *V. alginolyticus* 138–2 at MIC 3.1 μg mL^{-1} and 6.3 μg mL^{-1}, respectively. Nanaomycin D (**2**) has the greater activity against *V. parahaemolyticus* K-1 and *V. alginolyticus* 138–2 at MIC less than 0.05 μg mL^{-1}. The mechanism of action is inhibiting biosynthesis of protein, DNA, RNA, and cell-wall peptidoglycan.[50] Munumbicins are antibiotic peptides with broad spectrum activity against Gram-positive and negative bacteria. The peptides were isolated from endophytic *Streptomyces* NRRL 3052. Munumbicins A–D were tested against *V. fischeri* PIC 345 at a concentration of 10 μg. Munumbicin A was inactive, while munumbicins B (**3**), C, and D showed zone inhibition of 16, 9, and 12 cm, respectively.[51] Guadinomine B (**4**) is an antibiotic peptide produced by *Streptomyces* sp. K01-0509. The compound works as an antivirulence at IC_{50} 14 nM with a novel mechanism of action as an inhibitor of the type III secretion system (TTSS) of Gram-negative bacteria including *Vibrio* sp.[52,53]

Streptomyces atrovirens PK288-21 associated with seaweed *Undaria pinnatifida* produces two compounds 2-hydroxy-5-(3-methylbut-2-enyl) benzal-dehyde (**5**) and 2-hepta-1,5-dienyl-3,6-dihydroxy-5-(3-methylbut-2-enyl) benzaldehyde (**6**) were isolated from. Compound (**5**) inhibited *V. anguillarum* and *V. harveyi* at MIC 65 and 20 μg mL^{-1}, respectively. While compound (**6**) was active against *V. anguillarum* and *V. harveyi* at MIC 65 and 32 μg mL^{-1}, respectively.[54]

High throughput screening of crude extract of marine Actinobacteria was examined targeting peptide deformylase (PDF) of *V. anguillarum* that catalyzes the removal of *N*-formyl group from *N*-terminal methionine following translation in prokaryotes. Extraction of fermentation broth of *Streptomyces* sp. NHF 165 yielded Actionin (**7**) that inhibited peptide deformylase (PDF) of *V. anguillarum* at IC_{50} was 2.85 μM.[55]

Streptomyces leeuweenhoekii strain C34 isolated from the Chilean hyper-arid Atacama Desert soil produces a new type of antibiotic ansamycin which is active as antivibrio. Using the OSMAC approach led to isolating new 22-membered macro lactone-type polyketides called Chaxalactin A-C (**8–10**). Chaxalactins A (**8**), B (**9**), and C (**10**) inhibited *V. parahaemolyticus* at MIC 12.5; 20; and 12.5 μg mL^{-1}, respectively.[56,57] *Streptomyces* sp. SCSIO 01689 produces antivibrio compounds pyranosesquiterpene (**11**) and cyclic peptides Cyclo(D)-Pro-(D)-Ile

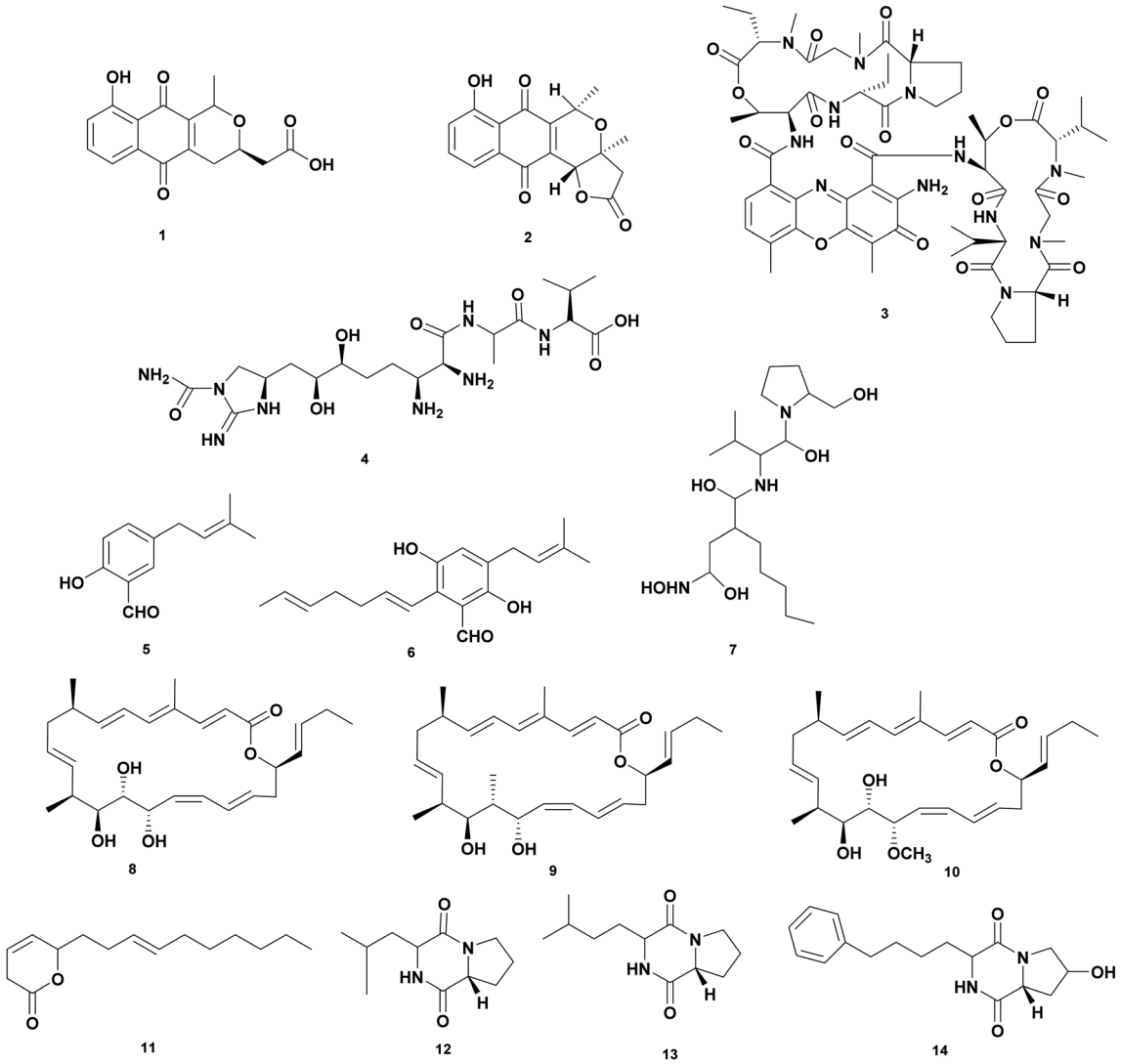

Fig. 1 Antivibrio compounds isolated from actinobacteria.

(**12**), Cyclo(D)-Pro-(D)-Leu (**13**), and Cyclo(D)-trans-4-OH-Pro-(D)-Phe (**14**). The compound **11** inhibited *V. anguillarum* at MIC at > 100 μg mL^{-1} while the cyclic peptides showed potency at concentrations of 0.05, 0.04, and 0.07 μg mL^{-1} for **12**, **13**, and **14**, respectively.[48]

3.2. Pseudoalteromonas

The genus *Pseudoalteromonas* is Gram-negative bacteria, heterotrophic, aerobic, and belongs to the γ-Proteobacteria class. This genus attracts attention due to its wide array of metabolites and ecological role in the ocean. The metabolites of *Pseudoalteromonas* have bioactivity including antimicrobial agents.[58,59] Antivibrio compounds isolated from *Pseudoalteromonas* spp. are presented in Fig. 2 and Table 2.

Pseudoalteromonas A1-J11 from the coastal Kagoshima Bay, Japan produced bioactive quilinolinol derivatives 2-*n*-pentyl-4-quinolinol (**15**). Disk diffusion assay of the compounds was conducted against *V. harveyi* ATCC 14126, *V. harveyi* ATCC 35084, *V. alginolyticus* ATCC 17749, *Vibrio* sp. 9M-P5-1, *V. fischeri* VF-74, *V. parahaemolyticus* IFO 12711. Based on the bioassay compound **15** was active against *V. harveyi* ATCC 14126, *V. harveyi* ATCC 35084, and *V. fischeri* VF-74 at a concentration of 10 μg.[60]

Crude extract of *Pseudomonas haloplanktis* INH from scallop hatchery was tested against *V. ordalii* ATCC 33509, *V. algiynolyticus* ATCC 17749, *V. anguillarum* IFO 13266, and *V. anguillarum* (VAR). The inhibition of *V. ordalii* ATCC 33509 was observed at a concentration of 1 mg mL^{-1}. Antibacterial compounds from the ethyl acetate extract were identified as isovaleric acid (**16**) and 2-methyl butyric acid (**17**).[61]

Pseudoalteromonas strain J010 associated with the surface of the crustose coralline alga *Neogoniolithon fosliei*, produced bioactive compounds antivibrio tetrabromopyrrole (**18**), 4′-((3,4,5-tribromo-1*H*-pyrrol-2-yl)methyl)phenol (**19**), and koromicins G–I (**20–22**) and K (**23**). The compounds were tested at a concentration of 200 μg mL^{-1} using disk diffusion assay and showed antagonistic effects to *Vibrio campbellii*, *V.*

Table 1 Bioactivity of antivibrio compounds isolated from Actinobacteria

No.	Compounds	Sources	Antivibrio activities	Mechanism of action	Ref.
1	Nanaomycin A (**1**)	*Streptomyces rosa var. notoensis* OS-3966	*V. alginolyticus* 138-2, MIC 6.3 μg mL^{-1}, *V. parahaemolyticus* K-1, MIC 3.1 μg mL^{-1}	Inhibition of inhibiting biosyntheses of protein, DNA, RNA, and cell-wall peptidoglycan	50
2	Nanaomycin D (**2**)	*Streptomyces rosa var. notoensis* OS-3966	*V. alginolyticus* 138-2, MIC < 0.05 μg mL^{-1}, *V. parahaemolyticus* K-1, MIC < 0.05 μg mL^{-1}	Affect respiratory chain-linked flavin dehydrogenases of a *Vibrio alginolyticus*	50
3	Munumbicin B (**3**)	*Streptomyces* NRRL 3052	*V. harveyi* PIC 345, dose 10 μg	Inhibition of the growth	51
4	Guadinomine B (**4**)	*Streptomyces* sp. K01-0509	*Vibrio* sp. IC_{50} 14 nM	Inhibition of type III secretion system (TTSS) in *Vibrio* spp.	52
5	2-Hydroxy-5-(3-methylbut-2-enyl) benzaldehyde (**5**)	*Streptomyces atrovirens* PK288-21	*V. anguillarum*, MIC 65 μg mL^{-1}, *V. harveyi*, MIC 20 μg mL^{-1}	Inhibition of the growth	54
6	2-Hepta-1,5-dienyl-3,6-dihydroxy-5-(3-methylbut-2-enyl) benzaldehyde (**6**)	*Streptomyces atrovirens* PK288-21	*V. anguillarum*, MIC 65 μg mL^{-1}, *V. harveyi*, MIC 32 μg mL^{-1}	Inhibition of the growth	54
7	Actionin (**7**)	*Streptomyces* sp. NHF 165	*V. anguillarum*, IC_{50} 2.85 μM	Inhibition of peptide deformylase (PDF) of *V. anguillarum*	55
8	Chaxalactin A (**8**)	*S. leeuweenhoekii strain* C38	*V. parahaemolyticus*, MIC 12.5 μg mL^{-1}	Inhibition of the growth	56
9	Chaxalactin B (**9**)	*S. leeuweenhoekii strain* C38	*V. parahaemolyticus*, MIC 12.5 μg mL^{-1}	Inhibition of the growth	56
10	Chaxalactin C (**10**)	*S. leeuweenhoekii strain* C38	*V. parahaemolyticus*, MIC 20 μg mL^{-1}	Inhibition of the growth	56
11	Pyranosesquiterpene (**11**)	*Streptomyces* sp. SCSIO 01689	*V. anguillarum*, MIC > 100 μg mL^{-1}	Inhibition of the growth	45
12	Cyclo(D)-Pro-(D)-Ile (**12**)	*Streptomyces* sp. SCSIO 01689	*V. anguillarum*, MIC 0.05 μg mL^{-1}	Inhibition of the growth	45
13	Cyclo(D)-Pro-(D)-Leu (**13**)	*Streptomyces* sp. SCSIO 01689	*V. anguillarum*, MIC 0.04 μg mL^{-1}	Inhibition of the growth	45
14	Cyclo(D)-trans-4-OH-Pro-(D)-Phe (**14**)	*Streptomyces* sp. SCSIO 01689	*V. anguillarum*, MIC 0.07 μg mL^{-1}	Inhibition of the growth	45

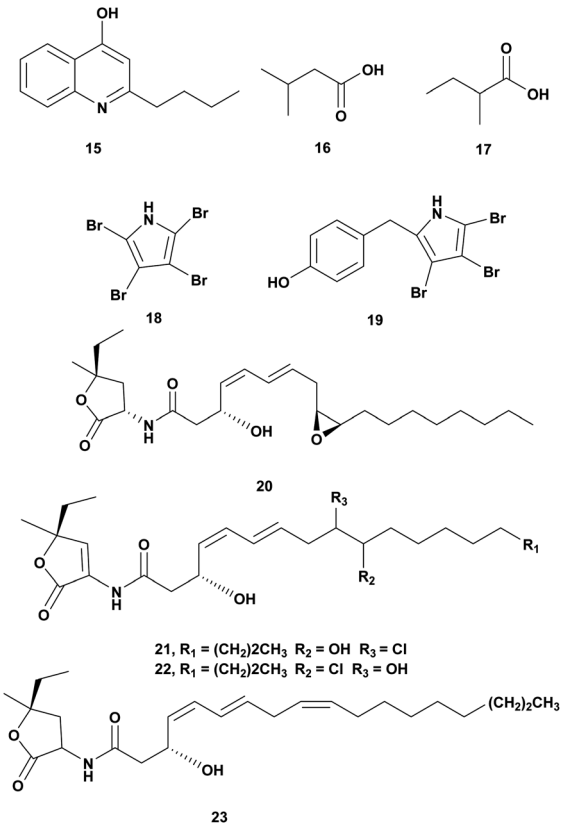

Fig. 2 Antivibrio compounds isolated from *Pseudoalteromonas* spp.

coralliilyticus, *V. harveyi*, and *V. vulnificus*. The korormicins may play a role in disrupting quorum sensing.[62]

3.3. *Pseudomonas* spp.

Pseudomonas aeruginosa is Gram-negative bacteria, widespread in the terrestrial and marine environment. It has been reported that *Pseudomonas aeruginosa* exhibited antagonistic activity to aquaculture and agriculture pathogens. Some antivibrio compounds have been identified from *P. aeruginosa* as seen in Fig. 3 and Table 3.

Pseudomonas MCCB 102 and 103A produces phenazine antibiotic, *N*-methyl-1-hydroxyphenazine (**24**). The compound

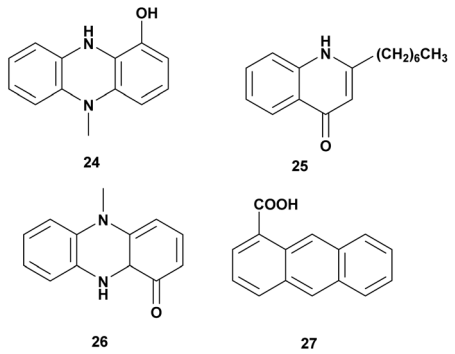

Fig. 3 Antivibrio compounds isolated from *Pseudomonas*.

has bacteriostatic activity against *V. harveyi* at the dose of 0.5 mg L^{-1}. The toxicity in *Penaeus monodon* haemocyte at IC_{50} was 1.4 ± 0.31 mg L^{-1}.[63] Investigation of bioactivities and toxicities of ethyl acetate extract of *Pseudomonas aeruginosa* sp. W3 led to the isolation of 2-heptyl-4-quinolone (HHQ) (**25**) that was active against 18 strains of shrimp pathogenic of *V. harveyi.* The compound was active at MIC value 225–450 μg mL^{-1}.[64]

Antagonistic activity of *Pseudomonas aeruginosa* was tested against *V. parahaemolyticus*, *V. vulnificus*, *V. alginolyticus*, *V. fluvialis*, *V. mediteranii*, *V. nereis*, and *V. harveyi*. Isolation of extract fermentation led to identify pyocyanin (**26**) as the bioactive compound responsible for the antagonistic effect at a concentration of more than 30 mg L^{-1}.[65] *Pseudomonas aeruginosa* PA31X produces phenazine-1-carboxylic acid (**27**) that is active against *V. anguillarum* C312 at 3 μg mL^{-1}.[66]

3.4. Miscellaneous bacteria

A Gram-positive marine bacterium *Halobacillus salinus* produced two phenetylamide metabolites: *N*-(2′-phenylethyl)-isobutyramide (**28**) and 3-methyl-*N*-(2′-phenylethyl)-butyramid (**29**). The compounds are anti-quorum sensing and bioluminescence of *V. harveyi* at a concentration below 200 μg mL^{-1}.[67]

Oleic acid (**30**) isolated from *Vibrio* sp. from North Chile inhibited the growth of *V. parahaemolyticus*. Long-chain fatty acids such as oleic, linoleic, and linolenic have antibacterial activity through inhibition of fatty acid synthesis (Table 4).[68]

Table 2 Bioactivity of antivibrio compounds from *Pseudoalteromonas*

No.	Compounds	Sources	Antivibrio activities	Mechanism of action	Ref.
1	2-*n*-Pentyl-4-quinolinol (**15**)	*Pseudoalteromonas* A1-J11	*V. harveyi* ATCC 14126, *V. harveyi* ATCC 35084, *V. fischeri* VF-74, *V. harveyi*, Dose 10 μg per disk	Inhibition of the growth	60
2	• Isovaleric acid (**16**), • 2-methyl butyric acid (**17**)	*Pseudoalteromonas haloplanktis* INH	*V ordalii* ATCC 33509, *V. alginolyticus* ATCC 17749, *V. anguillarum* IFO 13266, dose 1 mg mL^{-1}	Inhibition of the growth	61
3	• Tetrabromopyrrole (**18**), • 4′-((3,4,5-tribromo-1*H*-pyrrol-2-yl) methyl) phenol (19), • korormicin G-I (**20–22**), • korormicin K (**23**)	*Pseudoalteromonas* J010	*V. campbelii*, *V. vulnificus*, *V. coralliilyticus*, *V. harveyi*, Dose 200 μg mL^{-1}	• Inhibition of the growth, • disrupting of quorum sensing	62

Table 3 Bioactivity of antivibrio compounds from *Pseudomonas* spp

No	Compounds	Sources	Antivibrio activities	Mechanism of action	Ref.
1	*N*-Methyl-1-hydroxyphenazine (**24**)	*Pseudomonas* MCCB 102 and 103	V. *harveyi*, dose 0.5 mg L^{-1}	Bacteriostatic	63
2	2-Heptyl-4-quinolone (**25**)	*Pseudomonas aeruginosa* sp. W3	*V. harveyi*, MIC: 225–450 μg mL^{-1}	Inhibition of the growth	64
3	Pyocyanin (**26**)	*Pseudomonas aeruginosa*	*V. parahaemolyticus*, *V. vulnificus*, *V. alginolyticus*, *V. fluvialis*, *V. mediteranii*, *V. nereis*, *V. harveyi*, Dose 30 mg L^{-1}	Inhibition of the growth	65
4	Phenazine-1-carboxylic acid (**27**)	*Pseudomonas aeruginosa* PA31X	*V. anguillarum* C312, dose 3 μg mL^{-1}	Inhibition of the growth	66

Table 4 Bioactivity of antivibrio compounds from Miscellaneous bacteria

No	Compounds	Sources	Antivibrio Activities	Mechanism of Action	Ref.
1	• *N*-(2′-Phenyl ethyl)-iso butyramide (**28**), • 3-methyl-*N*-(2′-phenyl ethyl)-butyramid (**29**)	*Halobacillus salinus*	*V. harveyi*, dose 500 μg per disk	Quorum sensing inhibitor	67
2	Oleic Acid (**30**)	*Vibrio* sp.	*V. parahaemolyticus.*	Inhibition of fatty acid biosynthesis	68
3	Amicoumacin A (**31**)	*Bacillus pumilus* H2	*V. natriegens*, *V. vulnificus*, *V. alginolyticus*, *V. harveyi*, *V. azareus*, *V. campbelli*, *V. fischeri*, MIC 0.5–64 μg mL^{-1}		69

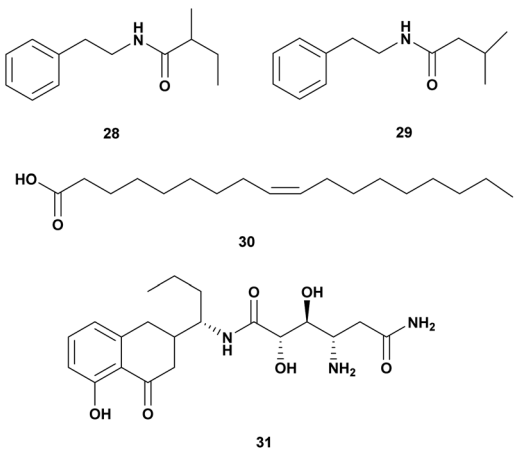

Fig. 4 Antivibrio compounds isolated from miscellaneous bacteria.

Bacillus pumilus H2 produces an antibacterial compound amicoumacin A (**31**) (Fig. 4) inhibited broad range species of *Vibro V. natriegens*, *V. vulnificus*, *V. alginolyticus*, *V. harveyi*, *V. azareus*, *V. campbelli*, *V. fischeri*.[69]

4. Antivibrio from marine fungi

Since the discovery of penicillin from *Penicillium chrysogenum* in the twentieth century, the fungus is an important source of natural products for drug discovery. Marine fungi have been explored for their bioactive secondary metabolites and potential for anti-microbial agents.[70–72] To date, 38% of 22.000 bioactive microbial metabolites are from fungi.[73] Among those metabolites, there are only a few antivibrio agents derived from marine fungi as presented in Fig. 5 and Table 5.

The genera of *Penicillium* contributes diverse of antivibrio compounds. Extraction of culture *Penicillium* sp. AS-79 associated with sea anemone *Haliplanella luciae* yielded indole diterpenoids that are active against *V. parahaemolyticus* and *V. alginolyticus*. The various compounds: 6-hydroxylpaspalinine (**32**), paspalitrem C (**33**), emindole SB (**34**), 3-deoxo-4*b*-deoxypaxilline (**35**), and 10,23-dihydro-24,25-dehydroaflavinine (**36**) exhibited activity against the aquatic pathogen *V. parahaemolyticus.* In addition, compounds **33**, **34**, **36** showed inhibition activity against *V. alginolyticus*.[74] Chemical investigation of ethyl acetate extract of culture *Penicillium janthinellum* yielded two indole diterpenoid penijanthine C (**37**) and D (**38**), two new steroids penijanthoid A (**39**) and B (**40**) along with two known analogs PC-M6 and 7-hydoxy-13-dehydroxypaxilline. The compounds **37–40** were active against *V. anguillarum*, *V. parahaemolyticus,* and *V. alginolyticus.* Indole diterpenoid is a new class of antivibrio agents.[75]

The genera of *Aspergillus* produce flourishing classes of antivibrio compounds. Deep investigation of marine-derived fungus *Aspergillus* sp. ZA-01 led to the isolation of new antivibrio compounds prenylxanthone derivate aspergixanthones I–K (**41–43**) along with known compounds (**44–47**). The compounds were tested against *V. parahaemolyticus*, *V. anguillarum*, and *V. alginolyticus.*[76] Marine fungi *Aspergillus terreus* EN-539 associated red algae *Laurencia okamurai*, produced new prenylated phenol derivative terreprenphenol A (**48**) along with 4-hydroxy-3-prenybenzoic acid (**49**), and 4-hydroxy-3-(3-methyl-but-2-enyl)-benzaldehyde (**50**). Evaluation of antivibrio activity against *V. harveyi*, *V. parahemolyticus*, and *V. vulnificus* showed inhibitory activity at MIC values ranging from 4 to 64 μg mL^{-1}.[77] The deep-sea sediment-derived fungus *Aspergillus versicolor* SD-330 yielded one new aromatic bisabolene-type sesquiterpenoid (**51**) along with four known analogs, aspergoterpenin C (**52**), (7S,11S)-(þ)-12-hydroxysydonic acid (**53**), (S)-(þ)-11-dehydrosydonic acid (**54**), and engyodontiumone I (**55**). All compounds exhibited inhibitory activities against *V.*

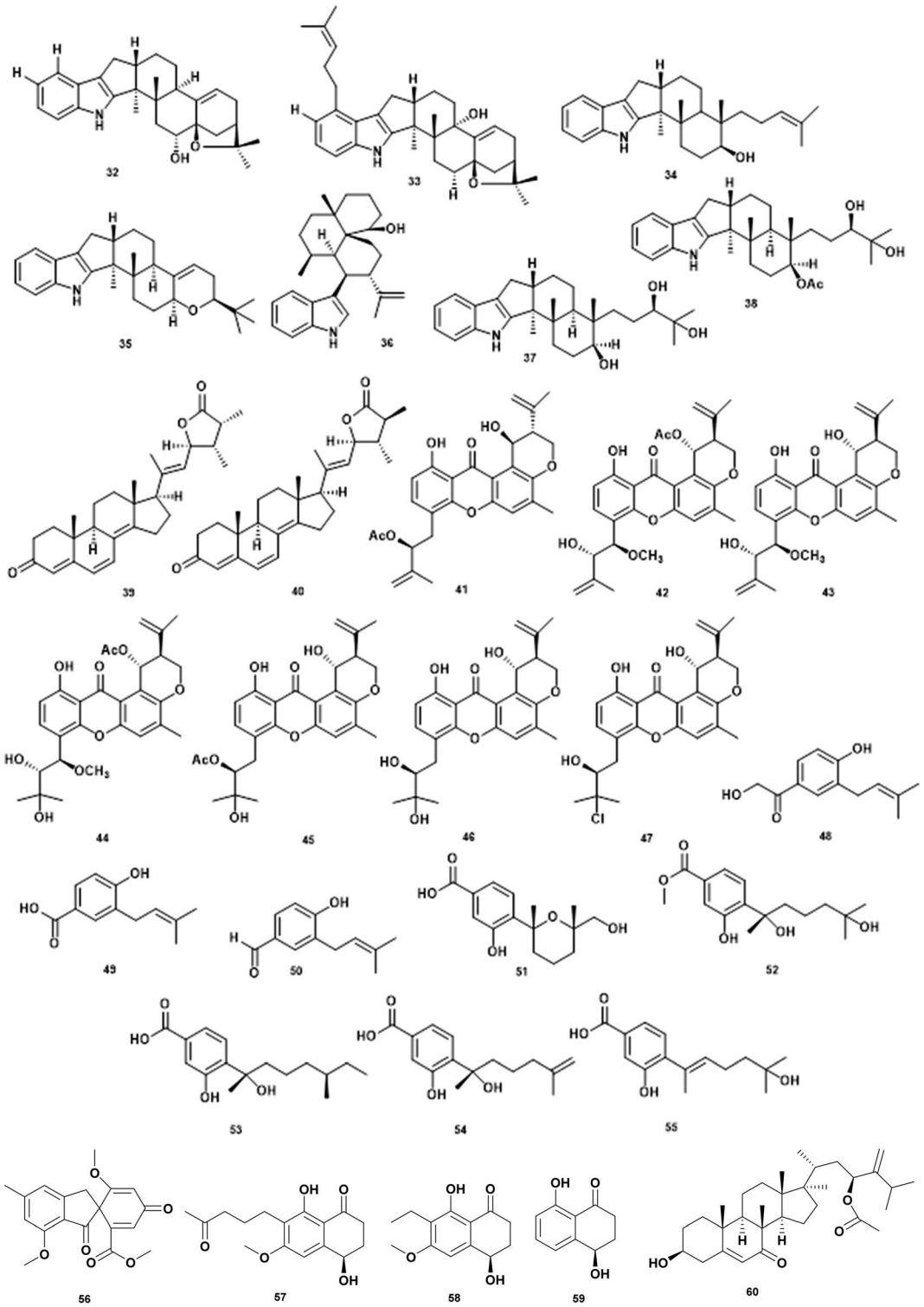

Fig. 5 Antivibrio compounds isolated from fungi.

anguillarum, *V. harveyi*, and *V. parahaemolyticus* with the MIC values ranging from 4 to >32 μg mL^{-1}.[78] Bioassay-guided isolation has identified the bioactive compound trypacidin (**56**) from a marine symbiotic fungi *Aspergillus fumigatus* HX-1. *In vitro* bacteriostatic assay confirms the MIC value at 31.25 μg mL^{-1}.[79] The MIC of each compound is presented in Table 5.

Marine fungi associated with crab, *Paraconiothyrium* sp., produced a new polyketide, paraconthone A (**57**) together with botryosphaerone (**58**) and *O*-methylaspmenone (**59**). The compounds showed moderate inhibitory effects against *V. anguillarum* and *V. parahaemolyticus* at 30 μg mL^{-1}.[80]

Table 5 Bioactivity of antivibrio compounds isolated from marine fungi

No.	Compounds	Sources	Antivibrio activities	Mechanism of action	Ref.
1	6-Hydroxylpaspaline (**32**)	*Penicillium* sp. AS-79	*V. parahaemolyticus* MIC 64.0 μg mL^{-1}	Inhibition of the growth	74
2	Paspalitrem C (**33**)	*Penicillium* sp. AS-79	*V. parahaemolyticus* MIC 8.0 μg mL^{-1}, *V. alginolyticus* MIC 4 μg mL^{-1}	Inhibition of the growth	74
3	Emindole SB (**34**)	*Penicillium* sp. AS-79	*V. parahaemolyticus* MIC 2.0 μg mL^{-1}, *V. alginolyticus* MIC 1 μg mL^{-1}	Inhibition of the growth	74
4	3-Deoxo-4*b*-deoxypaxilline (**35**)	*Penicillium* sp. AS-79	*V. parahaemolyticus* MIC 16.0 μg mL^{-1}	Inhibition of the growth	74
5	10,23 Dihydro-24,25-dehydroaflavinine (**36**)	*Penicillium* sp. AS-79	*V. parahaemolyticus* MIC 0.5 μg mL^{-1}, *V. alginolyticus* MIC 0.5 μg mL^{-1}	Inhibition of the growth	74
6	Penijanthine C (**37**)	*Penicillium janthinellum*	*V. anguillarum* MIC 3.1 μM, *V. parahaemolyticus* MIC 6.3 μM, *V. alginolyticus* MIC 3.1 μM	Inhibition of the growth	75
7	Penijanthine D (**38**)	*Penicillium janthinellum*	*V. anguillarum* MIC 12.5 μM, *V. parahaemolyticus* MIC 12.5 μM, *V. alginolyticus* MIC 12.5 μM	Inhibition of the growth	75
8	Penijanthoid A (**39**)	*Penicillium janthinellum*	*Vibrio* spp. MICs 25.0–50.0 μM	Inhibition of the growth	75
9	Penijanthoid B (**40**)	*Penicillium janthinellum*	*Vibrio* spp. MICs 25.0–50.0 μM	Inhibition of the growth	75
10	Aspergixanthone I (**41**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 1.56 μM, *V. anguillarum* MIC 1.56 μM, *V. alginolyticum* MIC 3.12 μM	Inhibition of the growth	76
11	Aspergixanthone J (**42**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 6.25 μM, *V. anguillarum* MIC 25 μM, *V. alginolyticum* MIC 25 μM	Inhibition of the growth	76
12	Aspergixanthone K (**43**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 3.12 μM, *V. anguillarum* MIC 25 μM, *V. alginolyticum* MIC 12.5 μM	Inhibition of the growth	76
13	Aspergixanthone A (**44**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 25 μM, *V. anguillarum* MIC 25 μM, *V. alginolyticum* MIC 25 μM	Inhibition of the growth	76
14	15-Acetyl tajixanthone hydrate (**45**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 12.5 μM, *V. anguillarum* MIC 25 μM, *V. alginolyticum* MIC 12.5 μM	Inhibition of the growth	76
15	Tajixanthone hydrate (**46**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 6.25 μM, *V. anguillarum* MIC 6.25 μM, *V. alginolyticum* MIC 12.5 μM	Inhibition of the growth	76
16	16-Chlorotajixanthon (**47**)	*Aspergillus* sp. ZA-01	*V. parahaemolyticus* MIC 25 μM, *V. anguillarum* MIC 6.25 μM, *V. alginolyticum* MIC 25 μM	Inhibition of the growth	76
17	Terreprenphenol A (**48**)	*Aspergillus terreus* EN-539	*V. harveyi* MIC 4 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}, *V. vulnificus* MIC 32 μg mL^{-1}	Inhibition of the growth	77
18	4-Hydroxy-3-prenybenzoic acid (**49**)	*Aspergillus terreus* EN-539	*V. harveyi* MIC 32 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}	Inhibition of the growth	77
19	4-Hydroxy-3-(3-methyl-but-2-enyl)-benzaldehyde (**50**)	*Aspergillus terreus* EN-539	*V. harveyi* MIC 8 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}, *V. vulnificus* MIC 64 μg mL^{-1}	Inhibition of the growth	77
20	Bisabolene sesquiterpenoid (**51**)	*Aspergillus versicolor* SD-330	*V. harveyi* MIC 4 μg mL^{-1}, *V. parahemolyticus* MIC 16 μg mL^{-1}	Inhibition of the growth	78

Table 5 (*Contd.*)

No.	Compounds	Sources	Antivibrio activities	Mechanism of action	Ref.
21	Aspergoterpenin C (**52**)	*Aspergillus versicolor* SD-330	*V. harveyi* MIC 8 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}	Inhibition of the growth	78
22	(7*S*,11*S*)-(þ)-12-Hydroxysydonic acid (**53**)	*Aspergillus versicolor* SD-330	*V. anguillarum* MIC 32 μg mL^{-1}, *V. harveyi* MIC 16 μg mL^{-1}, *V. parahemolyticus* MIC 32 μg mL^{-1}	Inhibition of the growth	78
23	(*S*)-(þ)-11-Dehydrosydonic acid (**54**)	*Aspergillus versicolor* SD-330	*V. anguillarum* MIC 32 μg mL^{-1}, *V. harveyi* MIC 32 μg mL^{-1}	Inhibition of the growth	78
24	Engyodontiumone I (**55**)	*Aspergillus versicolor* SD-330	*V. harveyi* MIC 4 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}	Inhibition of the growth	78
25	Trypacidin (**56**)	*Aspergillus fumigatus* HX-1	*V. harveyi* MIC 31.25 μg mL^{-1}	Inhibition of the growth	79
26	Paraconthone A (**57**)	*Paraconiothyrium* sp.	*V. anguillarum* & *V. parahemolyticus*, MIC 30 μg mL^{-1}	Inhibition of the growth	80
27	Botryosphaerone (**58**)	*Paraconiothyrium* sp.	*V. anguillarum* & *V. parahemolyticus*, MIC 30 μg mL^{-1}	Inhibition of the growth	80
28	*O*-Methylaspmenone (**59**)	*Paraconiothyrium* sp.	*V. anguillarum* & *V. parahemolyticus*, MIC 30 μg mL^{-1}	Inhibition of the growth	80
29	Acremocholone (**60**)	*Acremonium* sp. NBUF150	*V. scophthalmi* MIC 8 μg mL^{-1}, *V. shiloni* MIC 8 μg mL^{-1}, *V. brasiliensis* MIC 8 μg mL^{-1}	Inhibition of the growth	81

A new steroid acremocholone (**60**) was produced by sponge-associated fungi *Acremonium* sp. NBUF150. Acremocholone exhibited antivibrio activity against *V. scophthalmi*, *V. shilonii* and *V. brasiliensis* at MIC of 8 μg mL^{-1} .[81]

5. Antivibrio from sponges

Sponges are the oldest metazoan and have been investigated extensively for bioactive metabolites. Three new alkaloids isonaamide D, di-isonaamide A, and leucettamine D, and two known compounds isonaamine A and isonaanidine from a sponge *Leucetta chagosensis* Dendy, 1863 from French Polynesia. The compounds were screened for quorum sensing (QS) inhibitor of *V. harveyi*. The result showed that Isonaamidine A (**61**) inhibited the QS pathway at IC_{50} 1 μg mL^{-1}. None of the compounds affected bacterial growth at 50 μg mL^{-1}.[82]

In the searching for antimicrobial agents against *V. vulnificus* twelve pure marine compounds from a variety of sponges were screened for inhibition effect. Psammaplin A (**62**), a bromotyrosine derivative from the sponge *Poecillastra* sp., *Jaspis* sp., and *Psammaplin aplysilla* inhibited *V. vulnificus in vitro* and *in vivo* assay at 5–50 μg (Table 6).[83]

Alkaloid aaptamin and derivates from sponge *Aaptos aaptos* were tested against *Vibrio* spp. and *V. harveyi.* Aaptamine (**63**), 9-demethylaaptamine (**64**), 4-*N*-methylaaptamine (**65**), 9-methoxyaaptamine (**66**) were active at concentration 1 mg mL^{-1} (Fig. 6).[84]

6. Antivibrio from coral

Four new steroids, dendronecholones A–D (**67–70**), and two known analogues, 12β,16β,20-trihydroxycholesta-1,4-dien-3-one 16-acetate (**71**) and nanjiol A (**72**) were identified from soft coral *Dendronephthya* collected in waters off Zhejiang Province, China. Antivibrio assay was conducted against *V. parahaemolyticus*, *V. scophthalmi*, and *V. harveyi*. The MIC range from 8–>32 μg mL^{-1} is presented in Table 7.[85]

7. Antivibrio from seaweeds

Seaweeds are well known as rich sources of primary and secondary metabolites with diverse applications for food, feed, agriculture, pharmaceutical, and cosmetics.[86,87] Numerous substances were isolated from seaweed such as halogenated compounds,[88,89] polyether,[90] phenolic compounds,[91] and polyunsaturated fatty acid.[92] Antimicrobial activity testing of seaweed extracts support the possibility of using seaweeds as a source of antimicrobial agents or as a health-promoting feed for aquaculture.[93] Bioactive compounds from seaweed can be applied in aquaculture health and disease management to control bacterial infection.[94–96] Seaweeds are rich in fatty acid and the mechanism of action of fatty acid as an antibacterial agent through inhibition of the electron transport chain and normal oxidative phosphorylation in bacterial cell membranes.[97] Polysaccharides from seaweed have been examined for the purpose as prebiotic or immunostimulant in

Table 6 Bioactivity of antivibrio compounds isolated from sponge

No.	Compounds	Sources	Antivibrio activities	Mechanism of action	Ref.
1	Isonaamidin A (**61**)	*Leucetta chagosensis*	*V. harveyi*, quorum sensing, dose 1 μg mL^{-1}	Altering of quorum sensing	82
2	Psammaplin A (**62**)	*Poecillastra* sp., *Jaspis* sp., *Psammaplinaplysill*a	*V. vulnificus* dose 5–50 μg	Inhibition of the growth	83
3	Aaptamine (**63**), 9-demethyl aaptamine (**64**), 4-*N*-methyl aaptamine (**65**), 9-methoxy aaptamine (**66**)	*Aaptos aaptos*	*V. harveyi* dose 1 mg mL^{-1}	Inhibition of the growth	84

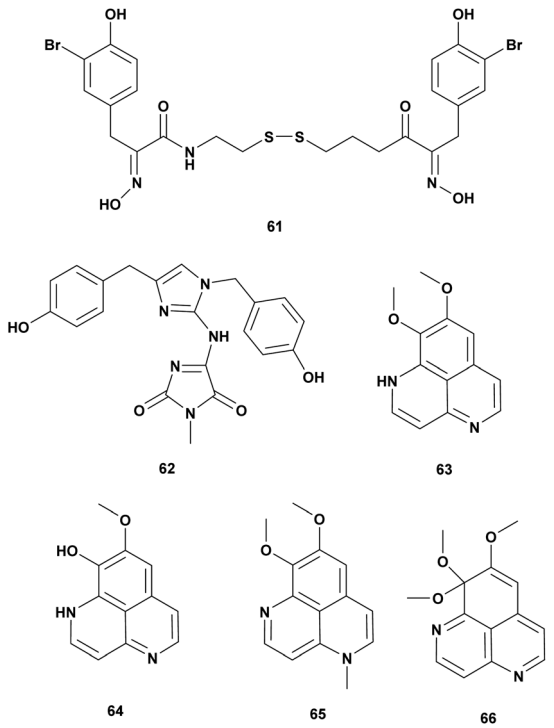

Fig. 6 Antivibrio compounds isolated from sponge.

aquaculture[98] while red seaweed (Rhodophyta) are good source of antibacterial agents (Table 8).[99]

Water-soluble fractions of red algae *Palmaria paltata* and *Grateloupia turuturu* were examined for the activity against *V. harveyi*. The NMR data suggested that the active water fraction of *Palmaria paltata* contains floridoside (**73**) (Fig. 7).[16] Further structure elucidation should be done to identify principal compounds responsible for an antivibrio agent.[16]

Red algae *Delisea pulchra* produced halogenated furanones called fimbrolide (Fig. 8).[101] Brominated furanones from marine algae inhibited biofilm formation and quorum sensing (QS) Gram-negative without affecting their growth. The structure is similar to bacterial acyl homoserine lactones (AHL).[100] Some marine algae produced halogenated furanones as AHL antagonists as a response to the negative impact of bacterial colonization. Fimbrolide 1 (**74**) and Fimbrolide 2 (**75**) were tested for inhibiting bioluminescence in *V. harveyi* and *V. campbellii* with the target on LuxS, PhaB, and uncharacterized IMPD protein.[101]

Extracts of Indonesian red seaweeds have been screened for bioactivity against fish pathogens including *Vibrio* spp. Extract of *Gracilaria arcuata* was active against *Vibrio* sp. at a concentration of 2.5 μg μL^{-1}. The active fraction contained hexadecanoic acid and sterol compounds such as Ergost-5-en-3-ol

Table 7 Bioactivity of antivibrio compounds isolated from coral

No.	Compounds	Sources	Antivibrio Activities	Mechanism of action	Ref.
1	Dendronecholone A (**67**)	*Dendronephthya*	*V. scophthalmi* MIC 32 μg mL^{-1}, *V. parahemolyticus* MIC >32 μg mL^{-1}, *V. harveyi* MIC 32 μg mL^{-1}	Inhibition of the growth	85
2	Dendronecholone B (**68**)	*Dendronephthya*	*V. scophthalmi* MIC 8 μg mL^{-1}, *V. parahemolyticus* MIC >32 μg mL^{-1}, *V. harveyi* MIC 8 μg mL^{-1}	Inhibition of the growth	85
3	Dendronecholone C (**69**)	*Dendronephthya*	*V. scophthalmi* MIC 32 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}, *V. harveyi* MIC >32 μg mL^{-1}	Inhibition of the growth	85
4	Dendronecholone D (**70**)	*Dendronephthya*	*V. scophthalmi* MIC 16 μg mL^{-1}, *V. parahemolyticus* MIC >32 μg mL^{-1}, *V. harveyi* MIC >32 μg mL^{-1}	Inhibition of the growth	85
5	12β,16β,20-Trihydroxycholesta-1,4-dien-3-one 16-acetate (**71**)	*Dendronephthya*	*V. scophthalmi* MIC 8 μg mL^{-1}, *V. parahemolyticus* MIC >32 μg mL^{-1}, *V. harveyi* MIC >32 μg mL^{-1}	Inhibition of the growth	85
6	Nanjiol A (**72**)	*Dendronephthya*	*V. scophthalmi* MIC 8 μg mL^{-1}, *V. parahemolyticus* MIC 8 μg mL^{-1}, *V. harveyi* MIC 8 μg mL^{-1}	Inhibition of the growth	85

Table 8 Bioactivity of antivibrio compounds isolated from seaweed

No.	Compounds	Sources	Antivibrio Activities	Mechanism of action	Ref.
1	Floridosid (**73**)	*Palmaria palmata*	*V. harveyi*	Inhibition of the growth	16
2	Fimbrolide A and B (**74–75**)	*Delisea pulchra*	*V. harveyi*, *V. campbelli*	Altering of quorum sensing	101
3	Hexadecanoic acid, Ergost-5-en-3-ol (**76**), Stigmast-5-en-3.β.-ol (**77**)	*Gracilaria arcuata*	*Vibrio* spp. MIC 1.25 μg mL^{-1}	Inhibition of the growth	102
4	Cholest-8-en-3-ol (**78**), 9-hexadecenoic acid (**79**) hexadecanoic acid (**80**), 13-octadecenoic acid (**81**), 10-octadecenoic acid (**82**) eicosanoic acid (**83**)	*Gracilaria edulis*	*V. fluvialis* MIC 2.5 μg mL^{-1}	Inhibition of the growth	103
5	*N*-Benzyl cinnamamide (**84**), α-resorcylic acid (**85**)	*Gracilaria fischeri*	*V. harveyi* 1114 MIC 11.27 mg mL^{-1}, *V. harveyi* 1114 MIC 1.66 mg mL^{-1}	Altering of quorum sensing	105

(**76**), Stigmast-5-en-3β-ol (**77**). The MIC of the active fraction was 1.25 μg μL^{-1}.[102] Extract of Indonesian seaweed *Gracilaria edulis* showed inhibition against *V. fluvialis* and *V. compbelii*. Further analysis showed that the active fraction contained sterol cholest-8-en-3-ol (**78**) and long-chain fatty acids such as pentadecanoic acid (**79**), hexadecanoic acid (**80**), 13-octadecenoic acid (**81**), 10-octadecenoic acid (**82**), eicosanoic acid (**83**). The active

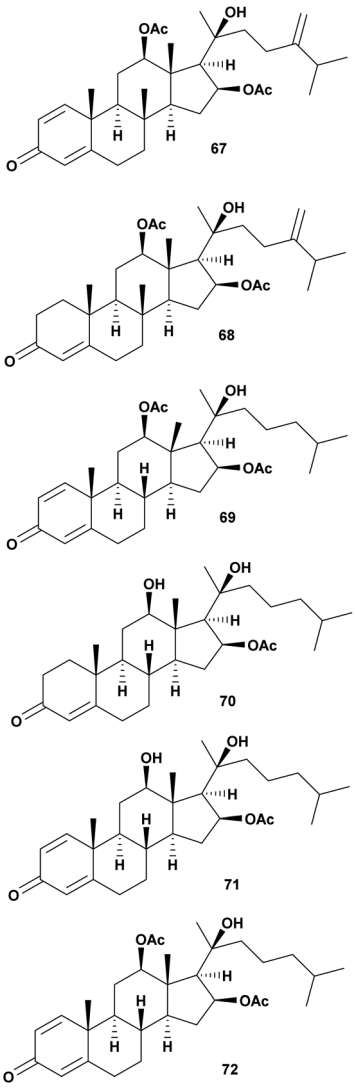

Fig. 7 Antivibrio compounds isolated from coral.

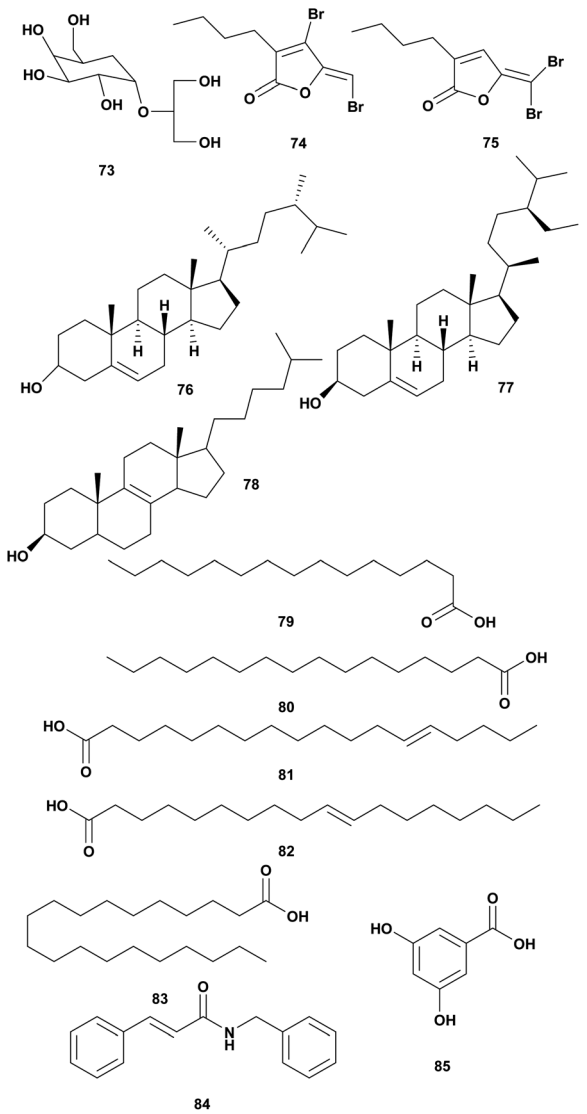

Fig. 8 Antivibrio compounds isolated from seaweed.

Table 9 Bioactivity of antivibrio from plants

No.	Compounds	Sources	Antivibrio Activities	Mechanism of action	Ref.
1	Capsaicin (**86**)	*Capsicum annum*	*V. chloreae*	Inhibition of toxin	112
2	Curcumin (**87**)	*Curcuma longa*	*V. harveyi* reduce bioluminescence 88%	Interfere the production of QS-dependent virulence factors in *Vibrio* spp., inhibition of bacterial adhesion and RTX toxin binding	113
3	Piperidine (**88**)	*Piper bettle*	*Vibrio* spp., MIC_{90} 2–6 mg mL^{-1}	Inhibition of the growth	114
4	Chlogenic acid (**89**)	*Piper bettle*	*Vibrio* spp. MIC_{90} 5–16 mg mL^{-1}	Inhibition of the growth	114
5	Eugenyl acetate (**90**)	*Piper bettle*	*Vibrio* spp. MIC_{90} 5–20 mg mL^{-1}	Inhibition of the growth	114
6	Punicalagin (**91**)	*Punica granatum* Linn	*V. anguillarum* MIC 25 mg mL^{-1}	Inhibition of the growth	115

fraction showed inhibition against *V. fluvialis* at MIC 2.5 μg mL^{-1}.[103]

Ethanolic extract of *Gracilaria fischeri* exhibited anti-quorum sensing activity in *V. harveyi* and *V. parahaemolyticus* at concentrations of 5, 10, and 100 μg mL^{-1}. The extract also reduced the luminescence of *V. harveyi*.[104] Further investigation showed *G. fisheri* contains *N*-benzyl cinnamamide (**84**) and α-resorcylic acid (**85**) and which are responsible for antivibrio activity.[105]

8. Antivibrio from plants

Plants are well known as a source of bioactive compounds and are used in traditional medicine. Various plant extracts containing phenolic, alkaloid, flavonoid, and polysaccharide have been tested and used in aquaculture as an immunostimulant, antioxidant, prebiotic, antibacterial, and antifungal.[106,107] Plant extracts have been screened as sources for antivibrio agents.[108,109] Phytochemicals can be used to interfere with bacterial quorum sensing to counteract the biofilm resistance. Medicinal plants are rich resources for screening bioactive QS.[110] Antivibrio compounds identified from plants are shown in Table 9.

The essential oil from aromatic plants *Mentha longifolia*, *M. pulegium*, *Eugenia caryophyllata*, *Thymus vulgaris,* and *Rosmarinus officinalis* were tested against *V. alginolyticus*, *V. parahaemolyticus*, *V. vulnificus,* and *V. fluvialis* strains. Results showed variable activity and essential oils of *T. vulgaris* yielded the highest zone of growth inhibition against *V. parahaemolyticus*.[111]

One of the approaches in the screening of natural products as antivibrio is targeting the production of virulence factors such as capsaicin and curcumin. Extract methanol of *Capsicum annum* containing capsaicin was reported to inhibit CT (cholera toxin) production in *V. cholerae.* The transcriptions of *ctxA*, *tcpA*, and *toxT* genes were repressed by capsaicin (**86**). On the contrary, capsaicin significantly enhanced the transcription of the *hns* gene, the product of which is known to regulate negatively the transcription of *ctx*AB, *tcp*A, and *tox*T genes. These results suggest that capsaicin might act as a potent repressor for CT production possibly by enhancing the transcription of *hns*.[112] Curcumin (**87**) from *Curcuma longa* reduced 88% of bioluminescence of *V. harveyi* and inhibited components of biofilms and virulence factor in *V. parahaemolyticus*, *V. vulnificus*, *V. harveyi*.[113]

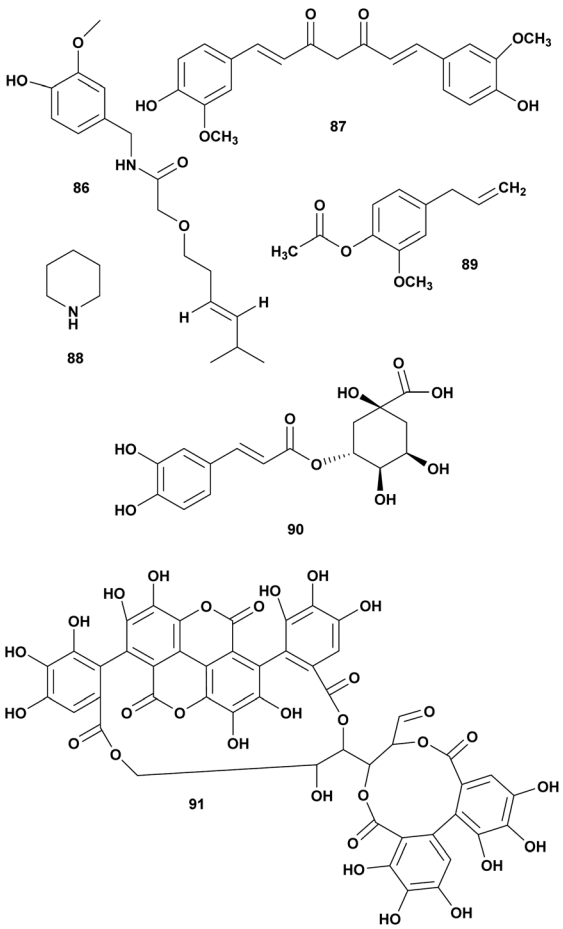

Fig. 9 Antivibrio compounds isolated from plants.

Three compounds piperidine (**88**), chlorogenic acid (**89**), and eugenyl acetate (**90**) isolated from *Piper bettle* were reported as bactericidal against several pathogenic *Vibrio* spp. The MIC range 0.6 to 16 mg mL^{-1}. Piperidine has the strongest inhibition effect on *Vibrio* spp. compare to chlorogenic acid and eugenyl acetate (Fig. 9).[114]

Punicalagin (**91**) from pomegranate (*Punica granatum* Linn.) was reported against *V. anguillarum* at MIC 25 μg mL^{-1}.[115]

9. Conclusions and perspective

Climate change and global warming will impact increasing cases of vibriosis in the future. *Vibrio* spp. cause serious problems in aquaculture with consequent huge economic losses. Moreover, vibriosis threatens human health through seafood contamination and contact with seawater during wound events. To date, an effective vaccine to prevent vibriosis has not been available yet. Efforts have been done to prevent vibriosis in aquaculture with probiotics, prebiotics, and immunostimulants. The rising incidence of *Vibrio* resistance to antimicrobial agents and the limited option of antibiotics have driven the search for new antivibrio agents.

Different stages of work have been performed ranging from the preliminary screening to an in-depth characterization of antivibrio compounds. This review provides proof that natural products are promising as a source of antivibrio agents. Screening of natural products from different sources has been carried out to discover antivibrio agents. Fig. 10 summarizes the exploration of natural resources to discover antivibrio agents. Natural product compounds exhibit bioactivity against *Vibrio* spp. through mechanism of action inhibiting the growth, disrupting quorum sensing, and interfering with biofilm formation.

This review shows that natural products as antivibrio are produced by prokaryotes and eukaryotes living in terrestrial and marine environments (Fig. 11). Based on data on this review, marine fungi demonstrated prolific sources of antivibrio and contribute 36% of bioactive antivibrio. Actinobacteria and sponges are well-known as sources of bioactive compounds for decades, but their compounds account for only 16% and 7%, respectively for antivibrio. The type classes of natural antivibrio derived from natural product compounds are alkaloid, polyketide, peptide, sterol, terpene, organic acid, and fatty acid.

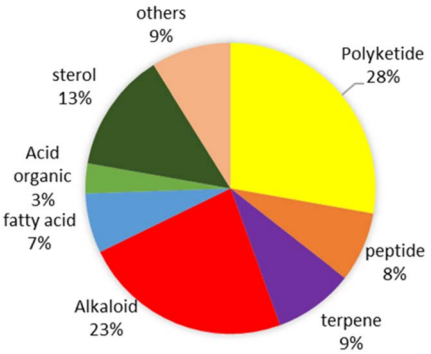

Fig. 11 The structure type of antivibrio compounds derived from natural resources.

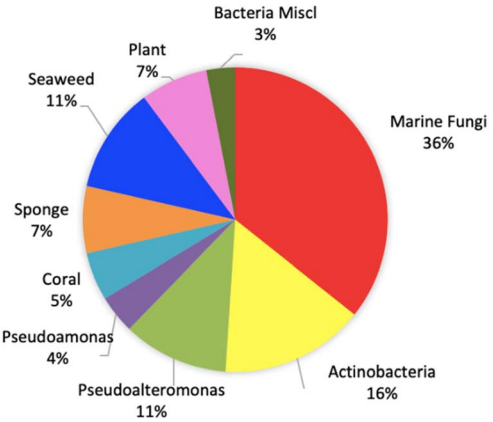

Fig. 12 The biological sources of natural products with antivibrio activity.

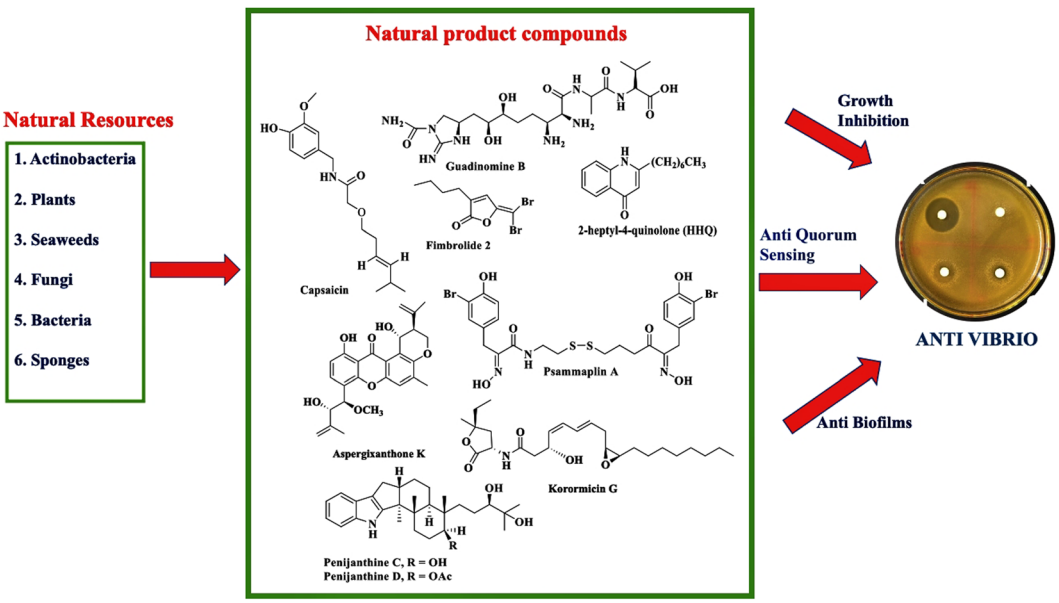

Fig. 10 Summary of the chemistry of natural products as antivibrio and their mechanism of actions.

Polyketide and alkaloid are the major class of antivibrio compounds and count about 28% and 23%, respectively presented in this review (Fig. 12). The alkaloids are produced by fungi and sponges, while polyketides were produced by mostly all organisms except coral. Antivibrio from coral and seaweed are mostly sterol.

This review summarizes that nature has provided a plethora of natural products with extraordinary chemistry and bioactivity against *Vibrio* spp. Further research and development of promising compounds are necessary for application in aquaculture and human health. Future efforts are necessary to evaluate the biological activities *in vivo*, toxicity, and mechanisms of action. Biofilms is the leading cause of multidrug resistance among microorganisms including *Vibrio* spp. Thus, study and examination of antivibrio compounds as inhibitor of biofilm formation is needed. The clinical study of antivibrio compounds has not been reported yet.

Author contribution

NK and MU wrote the manuscript, DCR helped supervise the project and reviewed the manuscript, MU contributed to collect data and references. NK received the funding and DCR provided lab access to do research on antivibrio.

Conflicts of interest

The authors report there are no competing interests to declare.

Acknowledgements

This work is a part of Research Antivibrio for Human Health and Aquaculture. N. K. would like to thank DIKTI-Fulbright Visiting Scholar Program 2019 (PS 00285337) for a scholarship to conduct part of the study in collaboration with David C. Rowley, Department of Pharmaceutical and Biomedical Sciences, College of Pharmacy, University of Rhode Island.

References

1 B. Austin, *Vet. Microbiol.*, 2010, **140**(3), 310–317, DOI: 10.1016/j.vetmic.2009.03.015.
2 C. N. Johnson, *Microb. Ecol.*, 2013, **65**(4), 826–851, DOI: 10.1007/s00248-012-0168-x.
3 F. L. Thompson, T. Iida and J. Swings, *Microbiol. Mol. Biol. Rev.*, 2004, **68**(3), 403–431, DOI: 10.1128/MMBR.68.3.403-431.2004.
4 A. Newton, M. Kendall, D. J. Vugia, O. L. Henao and B. E. Mahon, *Clin. Infect. Dis.*, 2012, **54**, 391–395, DOI: 10.1093/cid/cis243.
5 L. Vezzulli, R. R. Colwell and C. Pruzzo, *Microb. Ecol.*, 2013, **65**(4), 817–825, DOI: 10.1007/s00248-012-0163-2.
6 L. Vezzulli, I. Brettar, E. Pezzati, P. C. Reid, R. R. Colwell, M. G. Hofle and C. Pruzzo, *ISME J.*, 2012, **6**, 21–30, DOI: 10.1038/ismej.2011.89.
7 C. Baker-Austin, J. A. Trinanes, N. G. H. Taylor, R. Hartnell, A. Siitonen and J. Martinez-Urtaza, *Nat. Clim. Change*, 2013, **3**, 73–77, DOI: 10.1038/nclimate1628.
8 L. Vezzulli, E. Pezzati, I. Brettar, M. Hofle and C. Pruzzo, *Microbiol. Spectrum*, 2014, **3**, 1, DOI: 10.1128/microbiolspec.VE-0004-2014.
9 J. M. Janda, A. E. Newton and C. A. Bopp, *Clin. Lab. Med.*, 2015, **35**(2), 273–288, DOI: 10.1016/j.cll.2015.02.007.
10 M. Y. Ina-Salwany, N. Al-Saari, A. Mohamad, F.-A. Mursidi, A. Mohd-Aris, M. N. A. Amal, H. Kasai and M. Zamri-Saad, *J. Aquat. Anim. Health*, 2019, **31**, 3–22, DOI: 10.1002/aah.10045.
11 A. E. Toranzo, B. Magarinos and J. L. Romalde, *Aquaculture*, 2005, **246**, 37–61, DOI: 10.1016/j.aquaculture.2005.01.002.
12 I. Frans, C. W. Michiels, P. Bossier, K. A. Willems, B. Lievens and H. Rediers, *J. Fish Dis.*, 2011, **34**, 643–661, DOI: 10.1111/j.1365-2761.2011.01279.x.
13 N. Mohamad, M. N. A. Amala, I. S. Yasin, M. Z. Saad, N. S. Nasruddin, N. Al-Saarif, S. Minog and T. Sawab, *Aquaculture*, 2019, **512**, 734289, DOI: 10.1016/j.aquaculture.2019.734289.
14 U. Khimmakthong and P. Sukkarun, *Microb. Pathog.*, 2017, **113**, 107–112, DOI: 10.1016/j.micpath.2017.10.028.
15 B. Austin and X. H. Zhang, *Lett. Appl. Microbiol.*, 2006, **43**(2), 119–124, DOI: 10.1111/j.1472-765X.2006.01989.x.
16 N. Garcia-Bueno, P. Decottignies, V. Turpin, J. Dumay, C. Paillard, V. Stiger-Pouvreau, N. Kervarec, Y.-F. Pouchus, A. A. Marŕin-Atucha and J. Fleurence, *Aquat. Living Resour.*, 2014, **27**, 83–89, DOI: 10.1051/alr/2014009.
17 J. Dubert, J. L. Barja and J. L. Romalde, *Front. Microbiol.*, 2017, **8**, 762, DOI: 10.3389/fmicb.2017.00762.
18 R. Beaz-Hidalgo, S. Balboa, J. L. Romalde and M. J. Figueras, *Environ. Microbiol. Rep.*, 2010, **2**(1), 34–43, DOI: 10.1111/j.1758-2229.2010.00135.
19 C. Baker-Austin, J. D. Oliver, M. Alam, A. Ali, M. K. Waldor, F. Qadri and J. Martinez-Urtaza, *Nat. Rev. Dis. Prim.*, 2018, **4**, 8, DOI: 10.1038/s41572-018-0005-8.
20 R. Finkelstein and I. Oren, *Curr. Infect. Dis. Rep.*, 2011, **13**, 470–477, DOI: 10.1007/s11908-011-0199-3.
21 A. M. Dechet, A. Y. Patricia, N. Koram and J. Painter, *Clin. Infect. Dis.*, 2008, **46**, 970–976, DOI: 10.1086/529148.
22 S.-P. Heng, V. Letchumanan, C.-Y. Deng, N.-S. S. Mutalib, T. M. Khan, L.-H. Chuah, K.-G. Chan, B.-H. Goh, P. Pusparajah and L.-H. Lee, *Front. Microbiol.*, 2017, **8**, 997, DOI: 10.3389/fmicb.2017.00997.
23 S. M. Aly and A. Albutti, *J. Aquacult. Res. Dev.*, 2014, **5**, 4, DOI: 10.4172/2155-9546.1000247.
24 J. E. M. Watts, H. J. Schreier, L. Lanska and M. S. Hale, *Mar. Drugs*, 2017, **5**, 158, DOI: 10.3390/md15060158.
25 R. H. Rebouças, O. V. Sousa, A. S. Lima, F. R. Vasconcelos, P. B. Carvalho and R. H. S. F. Viera, *Environ. Res.*, 2011, **11**, 21–24, DOI: 10.1016/j.envres.2010.09.012.
26 C. Scarano, C. Spanu, G. Ziino, F. Pedonese, A. Dalmasso, V. Spanu, S. Virdis and E. P. De Santis, *New Microbiol.*, 2014, **37**(3), 329–337.

27 R. X. Wang, J. Y. Wang, Y. C. Sun, B. L. Yang and A. L. Wang, *Mar. Pollut. Bull.*, 2015, **101**(2), 701–706, DOI: 10.1016/j.marpolbul.2015.10.027.
28 Q. Yu, M. Niu, M. Yu, Y. Liu, D. Wang and X. Shi, *Food Control*, 2016, **60**, 263–268, DOI: 10.1016/j.foodcont.2015.08.005.
29 S. Elmahdi, L. V. DaSilva and S. Parveen, *Food Microbiol.*, 2016, **57**, 128–134, DOI: 10.1016/j.fm.2016.02.008.
30 C. H. Kang, Y. Shin, S. Jang, Y. Jung and J. S. So, *Environ. Sci. Pollut. Res.*, 2016, **23**(20), 21106–21112, DOI: 10.1007/s11356-016-7426-2.
31 D. L. Milton, *Int. J. Med. Microbiol.*, 2006, **296**(2), 61–71, DOI: 10.1016/j.ijmm.2006.01.044.
32 Y. Deng, Y. Liu, J. Li, X. Wang, S. He, X. Yan, Y. Shi, W. Zhang and L. Ding, *Eur. J. Med. Chem.*, 2022, **239**, 114513, DOI: 10.1016/j.ejmech.2022.114513.
33 J. Zhao, M. Chen, C. S. Quan and S. D. Fan, *J. Fish Dis.*, 2015, **38**(9), 771–786, DOI: 10.1111/jfd.12299.
34 F. H. Yildiz and K. L. Visick, *Trends Microbiol.*, 2009, **17**(3), 109–118, DOI: 10.1016/j.tim.2008.12.004.
35 L. A. Hawver, S. A. Jung and W. L. Ng, *FEMS Microbiol. Rev.*, 2016, **40**, 738–752, DOI: 10.1093/femsre/fuw014.
36 K. Papenfort and B. L. Bassler, *Nat. Rev. Microbiol.*, 2016, **14**(9), 576–588, DOI: 10.1038/nrmicro.2016.89.
37 B. Vu, M. Chen, R. J. Crawford and E. P. Ivanova, *Molecules*, 2009, **14**(7), 2535–2554, DOI: 10.3390/molecules14072535.
38 S. E. Rossiter, M. H. Fletcher and W. M. Wuest, *Chem. Rev.*, 2017, **117**, 12415–12474, DOI: 10.1021/acs.chemrev.7b00283.
39 J. F. M. Ong, H. C. Goh, S. C. Lim, L. M. Pang, J. S. F. Chin, K. S. Tan, Z.-X. Liang, L. Yang, E. Glukhov, W. H. Gerwick and L. T. Tan, *Mar. Drugs*, 2019, **17**, 72, DOI: 10.3390/md17010072.
40 O. Geniloud, *Nat. Prod. Rep.*, 2017, **34**, 1203–1232, DOI: 10.1039/c7np00026j.
41 S. W. Behie, B. Bonet, V. M. Zacharia, D. J. McClung and M. F. Traxler, *Front. Microbiol.*, 2017, **7**, 2149, DOI: 10.3389/fmicb.2016.02149.
42 J. L. You, L. X. Cao, G. F. Liu, S. N. Zhou, H. M. Tan and Y. C. Lin, *World J. Microbiol. Biotechnol.*, 2005, **21**(5), 679–682, DOI: 10.1007/s11274-004-3851-3.
43 J. L. You, X. L. Xue, L. X. Cao, X. Lu, J. Wang, L. Zhang and S. Zhou, *Appl. Microbiol. Biotechnol.*, 2007, **76**(5), 1137–1144, DOI: 10.1007/s00253-007-1074-x.
44 N. Augustine, S. Kerkar and S. Thomas, *Curr. Microbiol.*, 2012, **64**(4), 338–342, DOI: 10.1007/s00284-011-0073-4.
45 L. T.-H. Tan, K.-G. Chan, L.-H. Lee and B.-H. Goh, *Front. Microbiol.*, 2016, **7**, 79, DOI: 10.3389/fmicb.2016.00079.
46 M. Bodhaguru, S. Prakash, R. Ramasubburayan, N. K. Ahila, L. Mariselvam, G. Immanuel, A. Palavesa and E. Kannapiran, *Microb. Pathog.*, 2019, **134**, 103597, DOI: 10.1016/j.micpath.2019.103597.
47 G. Raissa, D. E. Waturangi and D. Wahjuningrum, *BMC Microbiol.*, 2020, **20**, 343, DOI: 10.1186/s12866-020-02022-z.
48 L. T.-H. Tan, L.-H. Lee and B.-H. Goh, *Prog. Microbes. Mol. Biol.*, 2019, **2**, 1.
49 G. S. Kiran, A. N. Lipton, S. Priyadharshini, K. Anitha, L. E. Suárez, M. V. Arasu, K. C. Choi, J. Selvin and N. A. Al-Dhabi, *Microb. Cell Fact.*, 2014, **13**, 114, DOI: 10.1186/s12934-014-0114-3.
50 M. Hayashi, T. Unemoto, S. Minami-Kakinuma, H. Tanaka and S. Omura, *J. Antibiot.*, 1982, **35**, 1078–1085, DOI: 10.7164/antibiotics.35.1078.
51 U. F. Castillo, G. A. Strobel, E. J. Ford, W. M. Hess, H. Porter, J. B. Jensen, H. Albert, R. Robinson, M. A. M. Condron, D. B. Teplow, D. Stevens and D. Yaver, *Microbiology*, 2002, **148**(9), 2675–2685, DOI: 10.1099/00221287-148-9-2675.
52 M. Iwatsuki, R. Uchida, H. Yoshijima, H. Ui, K. Shiomi, A. Matsumoto, Y. Takahashi, A. Abe, H. Tomoda and S. Omura, *J. Antibiot.*, 2008, **61**, 222–229, DOI: 10.1038/ja.2008.32.
53 T. C. Holmes, A. E. May, K. Zaleta-Rivera, J. G. Ruby, P. Skewes-Cox, M. A. Fischbach, J. L. DeRisi, M. Iwatsuki, S. Omura and C. Khosla, *J. Am. Chem. Soc.*, 2012, **134**(42), 17797–17806, DOI: 10.1021/ja308622d.
54 J. Y. Cho and M. S. Kim, *Fish. Sci.*, 2012, **78**(5), 1065–1073, DOI: 10.1007/s12562-012-0531-3.
55 N. Yang and C. Sun, *Front. Microbiol.*, 2016, **7**, 1467, DOI: 10.3389/fmicb.2016.01467.
56 M. E. Rateb, W. E. Houssen, W. T. A. Harrison, H. Deng, C. K. Okoro, J. A. Asenjo, B. A. Andrews, A. T. Bull, M. Goodfellow, R. Ebel and M. Jaspars, *J. Nat. Prod.*, 2011, **74**(9), 1965–1971, DOI: 10.1021/np200470u.
57 J. F. Castro, V. Razmilic, J. P. Gomez-Escribano, B. Andrews, J. Asenjo and M. Bibb, *Antonie van Leeuwenhoek*, 2018, **111**(8), 1433–1448, DOI: 10.1007/s10482-018-1034-8.
58 J. P. Bowman, *Mar. Drugs*, 2007, **5**, 220–241, DOI: 10.3390/md504220.
59 C. Offret, F. Desriac, P. L. Chevalier, J. Mounier, C. Jegou and Y. Fleury, *Mar. Drugs*, 2016, **14**, 129, DOI: 10.3390/md14070129.
60 C. S. Castillo, M. I. Wahid, T. Yoshikawa and T. Sakata, *Fish. Sci.*, 2008, **74**, 174–179, DOI: 10.1111/j.1444-2906.2007.01507.x.
61 G. Hayashida-Soiza, A. Uchida, N. Mori, Y. Kuwahara and Y. Ishida, *J. Appl. Microbiol.*, 2008, **105**(5), 1672–1677, DOI: 10.1111/j.1365-2672.2008.03878.x.
62 J. Tebben, C. Motti, D. Tapiolas, P. Thomas-Hall and T. Harder, *Mar. Drugs*, 2014, **12**, 2802–2815, DOI: 10.3390/md12052802.
63 R. Preeta, S. Jose, S. Prathapan and K. K. Vijayan, *Aquacult. Res.*, 2010, **41**(10), 1452–1461, DOI: 10.1111/j.1365-2109.2009.02436.x.
64 P. Rattanachuay, D. Kantachote, M. Tantirungkij, T. Nitoda and H. Kanzak, *World J. Microbiol. Biotechnol.*, 2011, **27**, 869–880, DOI: 10.1007/s11274-010-0529-x.
65 P. Priyaja, P. Jayesh, N. S. Correya, B. Sreelakshmi, N. S. Sudheer, R. Philip and I. S. B. Singh, *J. Coastal Life Med.*, 2014, **2**(1), 76–84, DOI: 10.12980/JCLM.2.2014J30.
66 L. Zhang, X. Tian, S. Kuang, G. Liu, C. Zhang and C. Sun, *Front. Microbiol.*, 2017, **8**, 289, DOI: 10.3389/fmicb.2017.00289.

67 M. E. Teasdale, J. Liu, J. Wallace, F. Akhlaghi and D. C. Rowley, *Appl. Environ. Microbiol.*, 2009, **75**(3), 567–572, DOI: 10.1128/AEM.00632-08.
68 Y. Leyton, J. Borquez, J. Darias, M. Cueto, A. R. Díaz-Marrer and C. Riquelme, *Mar. Drugs*, 2011, **9**(10), 2155–2163, DOI: 10.3390/md9102155.
69 X. Y. Gao, Y. Liu, L. L. Miao, E. W. Li, T. T. Hou and Z. P. Liu, *AMB Express*, 2017, **7**, 23, DOI: 10.1186/s13568-017-0323-3.
70 P. Bhadury, B. Mohammad and P. C. Wright, *J. Ind. Microbiol. Biotechnol.*, 2006, **33**(5), 325–337, DOI: 10.1007/s10295-005-0070-3.
71 J. F. Imhof, *Mar. Drugs*, 2016, **14**, 19, DOI: 10.3390/md14010019.
72 D. Tasdemir, *Fungal Biol. Biotechnol.*, 2017, **4**, 5, DOI: 10.1186/s40694-017-0034-1.
73 H. J. Shin, *Mar. Drugs*, 2020, **18**(5), 230, DOI: 10.3390/md18050230.
74 X.-Y. Hu, L.-M. Meng, X. Li, S.-Q. Yang, X.-M. Li and B.-G. Wang, *Mar. Drugs*, 2017, **15**, 137, DOI: 10.3390/md15050137.
75 X.-C. Guo, L.-L. Xu, R.-Y. Yang, M.-Y. Yang, L.-D. Hu, H.-J. Zhu and F. Cao, *Front. Chem.*, 2019, **7**, 80, DOI: 10.3389/fchem.2019.00080.
76 A. Zhu, X.-W. Zhang, M. Zhang, W. Li, Z.-Y. Ma and H.-J. Zhu, *Mar. Drugs*, 2018, **16**(9), 312, DOI: 10.3390/md16090312.
77 H. L. Li, X. M. Li, S. Q. Yang, L. H. Meng, X. Li and B. G. Wang, *Mar. Drugs*, 2019, **17**(11), 605, DOI: 10.3390/md17110605.
78 X. D. Li, X. Li, X. M. Li, X. L. Yin and B. G. Wang, *Nat. Prod. Res.*, 2021, **35**(22), 4265–4271, DOI: 10.1080/14786419.2019.1696792.
79 X. Xu, S. Guo, H. Chen, Z. Zhang, X. Li, W. Wang and L. Guo, *3 Biotech*, 2021, **11**(4), 1–7, DOI: 10.1007/s13205-021-02754-3.
80 X. Wei, Y. Ding and F. An, *Nat. Prod. Commun.*, 2021, **17**(3), 1–5, DOI: 10.1177/1934578X221075986.
81 Y.-P. Feng, H.-K. Wang, J.-L. Wu, P. Shao, W.-L. Zhou, Q.-L. Lai, H.-W. Lin, B. Naman, T.-T. Wang and S. He, *Chem. Biodiversity*, 2022, **19**(4), e202200028, DOI: 10.1002/cbdv.202200028.
82 T. Mai, F. Tintillier, A. Lucasson, C. Moriou, E. Bonno, S. Petek, K. Magre, A. A. Mourabit, D. Saulnier and C. Debitus, *Lett. Appl. Microbiol.*, 2015, **61**, 31–317, DOI: 10.1111/lam.12461.
83 B. C. Lee, A. Lee, J. H. Jung, S. H. Choi and T. S. Kim, *Mol. Med. Rep.*, 2016, **14**, 2691–2696, DOI: 10.3892/mmr.2016.5522.
84 H. Mohamad, R. Rosmiati, T. S. T. Muhammad, Y. Andriani, K. Bakar, N. Ismail, J. Saidin, J. Latip, N. Musa and A. Parenrengi, *Nat. Prod. Commun.*, 2017, **12**(8), 1227–1230, DOI: 10.1177/1934578X1701200819.
85 T. Wang, J. Zou, T. Li, P. Shao, W. Zhou, Q. Lai, Y. Feng, C. B. Naman, X. Yan and S. He, *Aquaculture*, 2022, **549**, 737727, DOI: 10.1016/j.aquaculture.2021.737727.
86 S. L. Holdt and S. Kraan, *J. Phycol.*, 2011, **23**, 543–597, DOI: 10.1007/s10811-010-9632-5.
87 A. Leandro, L. Pereira and A. M. M. Gonçalves, *Mar. Drugs*, 2019, **18**(1), 17, DOI: 10.3390/md18010017.
88 M. Kladi, C. Vagias and V. Roussis, *Phytochem. Rev.*, 2004, **3**, 337–366, DOI: 10.1007/s11101-004-4155-9.
89 M. T. Cabrita, C. Vale and A. P. Rauter, *Mar. Drugs*, 2010, **8**, 2301–2317, DOI: 10.3390/md8082301.
90 F. C. Pacheco, *Mar. Drugs*, 2010, **8**, 1178–1188, DOI: 10.3390/md8041178.
91 J. Cotas, A. Leandro, P. Monteiro, D. Pacheco, A. Figueirinha, A. M. M. Gonçalves, G. J. da Silva and J. Pereira, *Mar. Drugs*, 2020, **18**, 384, DOI: 10.3390/md18080384.
92 H. Pereira, L. Barreira, F. Figueiredo, L. Custódio, C. V. Duarte, C. Polo, E. Rešek, A. Engelen and J. Varela, *Mar. Drugs*, 2012, **10**, 1920–1935, DOI: 10.3390/md10091920.
93 S. Thanigaivel, N. Chadrasekaran, A. Mukherjee and J. Thomas, *Aquaculture*, 2015, **448**, 82–86, DOI: 10.1016/j.aquaculture.2015.05.039.
94 I. N. Vatsos and C. Rebours, *J. Appl. Phycol.*, 2015, **27**, 2017–2035, DOI: 10.1007/s10811-014-0506-0.
95 S. Thanigaivel, N. Chadrasekaran, A. Mukherjee and J. Thomas, *Aquaculture*, 2016, **464**, 529–536, DOI: 10.1016/j.aquaculture.2016.08.001.
96 V. Zammuto, M. G. Rizzo, A. Spanò, D. Spagnuolo, A. Di Martino, M. Morabito, A. Manghisi, G. Genovese, S. Guglielmino, G. Calabrese, F. Capparucci, C. Gervasi, M. S. Nicolo and C. Gugliandolo, *Algal Res.*, 2022, **63**, 102646, DOI: 10.1016/j.algal.2022.102646.
97 E. Shannon and N. Abu-Ghannam, *Mar. Drugs*, 2016, **14**, 81, DOI: 10.3390/md14040081.
98 K. Wongprasert, T. Rudtanatip and J. Praiboon, *Fish Shellfish Immunol.*, 2014, **36**, 52–60, DOI: 10.1016/j.fsi.2013.10.010.
99 N. Kasanah, T. Triyanto, D. S. Seto, W. Amelia and A. Isnansetyo, *Indones. J. Chem.*, 2015, **15**(2), 201–209, DOI: 10.22146/ijc.21215.
100 G. Brackman and T. Coenye, *Curr. Pharm. Des.*, 2015, **21**(1), 5–11, DOI: 10.2174/1381612820666140905114627.
101 W. Zhao, N. Lorenz, K. Jung and S. A. Sieber, *Angew. Chem., Int. Ed.*, 2016, **55**(3), 1187–1191, DOI: 10.1002/anie.201508052.
102 A. P. A. Wijnana, N. Kasanah and T. Triyanto, *Nat. Prod. J.*, 2018, **8**, 1–6, DOI: 10.2174/1573401313666170925161408.
103 N. Kasanah, W. Amelia, A. Mukminin, T. Triyanto and A. Isnansetyo, *Nat. Prod. Res.*, 2019, **33**(22), 3303–3307, DOI: 10.1080/14786419.2018.1471079.
104 K. Karnjana, C. Soowannayan and K. Wongprasert, *Fish Shellfish Immunol.*, 2019, **88**, 91–101, DOI: 10.1016/j.fsi.2019.01.058.
105 K. Karnjana, S. Nobsathian, C. Soowannayan, W. Zhao, Y. J. Tang and K. Wongprasert, *Mar. Drugs*, 2020, **18**(2), 80, DOI: 10.3390/md18020080.
106 M. Reverter, N. Bontemps, D. Lecchini, B. Banaigs and P. Sasal, *Aquaculture*, 2014, **433**, 50–61, DOI: 10.1016/j.aquaculture.2014.05.048.

107 P. Elumalai, A. Kurian, S. Lakshmi, C. Faggio, M. A. Esteban and E. Ringø, *Rev. Fish. Sci.*, 2021, **29**(1), 33–35, DOI: **10.1080/23308249.2020.1779651**.

108 E. Sanchez, S. Garcia and N. Heredia, *Appl. Environ. Microbiol.*, 2010, **76**, 6888–6894, DOI: **10.1128/AEM.03052-09**.

109 M. Aminzare, M. Hashemi, Z. Abbasi, Z. M. Mohseni and E. Amiri, *J. Appl. Pharm. Sci.*, 2018, **8**, 170–177, DOI: **10.7324/JAPS.2018.8126**.

110 A. Borges, A. C. Abreu, C. Dias, M. J. Saavedra, F. Borges and M. Simões, *Molecules*, 2016, **21**(7), 877, DOI: **10.3390/molecules21070877**.

111 M. Snoussi, H. Hajlaoui, E. Noumi, D. Usai, L. A. Sechi, S. Zanetti and A. Bakhrouf, *World J. Microbiol. Biotechnol.*, 2008, **24**(12), 3071–3076, DOI: **10.1007/s11274-008-9848-6**.

112 S. Chatterjee, M. Asakura, N. Chowdury, S. B. Neogi, N. Sugimoto, S. Haldar, S. P. Awasthi, A. Hinenoya, S. Aoki and S. Yamasaki, *FEMS Microbiol. Lett.*, 2010, **306**(1), 54–60, DOI: **10.1111/j.1574-6968.2010.01931.x**.

113 I. A. S. V. Packiavathy, P. Sasikumar, S. K. Pandian and A. V. Ravi, *Appl. Microbiol. Biotechnol.*, 2013, **97**, 10177–10187, DOI: **10.1007/s00253-013-4704-5**.

114 E. Acosta-Smith, N. Leon-Sicairos, S. Tiwari, H. Flores-Villasensor, A. Canizalez-Roman, R. Kumavath, P. Ghosh, V. Azevedo and D. Barh, *Pathogen*, 2019, **8**, 64, DOI: **10.3390/pathogens8020064**.

115 Z. Shan, N. Guan, Y. Yang, T. Jin, X. Xia and W. Liu, *Aquaculture*, 2021, **533**, 736109, DOI: **10.1016/j.aquaculture.2020.736109**.