GENOME MINING OF A MARINE-DERIVED STREPTOMYCES SP. PDH23 ISOLATED FROM SPONGE IN DA NANG SEA FOR SECONDARY METABOLITE GENE CLUSTERS

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SUMMARY

The streptomyces is one of the best characterized ubiquitous filamentous bacteria from the actinobacteriaclass. They are known to produce thousands of specialized metabolite biosynthesis gene clusters (SMBG). Their SMBG clusters have multiple activities ranging from antimicrobial, antitumor, antiviral and probiotic. Streptomyces strain and their isolates with interesting biological activities against gram-positive and gram-negative indicator strains was recently characterised. Currently, they are employed in more than half of all antibiotics used in human and veterinary medicine. With the increase in drug resistance bacteria, it is important to mine for new natural chemicals. In this study, screening via disk-diffusion agar method revealed that Streptomyces sp. PDH23 isolated from the Rhabdastrella globostellata marine sponge sample from Da Nang, Vietnam produce antimicrobial agents with a wide spectrum of activities. This species can produce highly active enzymes, which breakdown celluloses, amyloses and proteins. On top of that they are shown to restrict the grow of the gram positive Bacillus cereus ATCC14579 (BC), Staphylococcus aureus ATCC25923 (SA), the gram-negative Vibrio parahaemolyticus ATCC17802 (VP) and the Candida albicans ATCC10231 fungus (CA). They are antimethicillin-resistant S. aureus(MRSA) ATCC33591 andmethylcillin-resistant S. epidermidis (MRSE) ATCC35984. The taxonomy of PDH23 was characterized using 16S rRNA analysis. Whole genome sequencing of PDH23 showed 8594820 base pairs with GC content of 72.03%. Mining of secondary metabolites reveals gene clusters responsible for the biosynthesis of known and/or novel secondary metabolites, including different types of terpene, NRPS-like, PKS, PKS-like, hglE-KS, betalactone, melanin, t1pks, t2pks, t3pks, nrps, indole, siderophore, bacteriocin, ectoine, butyrolactone, phenazine.

Keywords: AntiSMASH, genome-mining, marine-actinomyces, sponge-associated, streptomyces.

INTRODUCTION

Marine sponges are filter feeders and may contain about 10^7-10^8 bacteria/ml. Other found species including bacteria, archaea, microalgae, and fungi(Taylor et al., 2007). Sponge-associated microorganisms would comprise around 50% of the sponge biomass, with many of them are significant for the communities (Koopmans et al., 2009; Brinkmann, 2017). In recent years, researchers have found that many of the biological compounds that were previously thought to belong to the sponges were in fact produced by the microorganisms with in the sponge. These findings help to guide the focus on sponge-associated microorganisms.
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Evidences suggest that sponges have the ability to select specific microorganisms, those are beneficial for their survival. The actinomycetes are generally not harmful and can produce a lot of biologically active metabolites and so a great symbiont for the sponge (Xiet al., 2012; Selvin et al., 2016).

The exploration of microorganisms capable of producing useful active compounds is of great interest. Nowadays, genome mining is a new strategy for the identification of natural products based on gene cluster sequences and biosynthetic pathways. The genome of streptomycetes allows us to explore their biosynthetic potential. Several useful compounds have been identified by studying the genome of streptomycetes (Yu et al., 2018). However, up to date, there are limited number of studies on the streptomycyes genomes. Using information about gene sequences involved in production of known useful compounds can help to detect and acquire new pathways with such activity. Our report shows that the Streptomyces sp. PDH23 from the sea sponge might be the source of several highly bioactive compounds.

Materials and Methods

Sampling of sponge

Sponge samples were collected by SCUBA diving at Da Nang, Viet Nam.

Isolation of pure strain

The sponge samples were washed three times with sterile autoclaved artificial seawater, dried in a drain in 5–10 mins. The sample was cut into small pieces and approximately 1 gram. Small pieces of sponge tissue was dissected and ground using sterile autoclaved artificial sea water. Serially diluted homogenate was spread on to isolation SCA medium containing (g/L): soluble starch 10.00, casein (vitamin free) 0.30, KNO3: 2.00, MgSO4.7H2O: 0.05, K2HPO4: 2.00, NaCl: 2.00, CaCO3: 0.02, FeSO4.7H2O: 0.01, agar: 18.00, sterile autoclaved artificial seawater: 1000 ml, pH (at 25°C) 7.0 ± 0.1. The medium was supplemented with nystatin 25µg/ml. After repeated streaking for obtaining pure culture, the clear colony of Streptomyces sp. PDH23 was collected and inoculated in 2 ml flask containing A1 medium containing (g/L): soluble starch 10.00, yeast extract: 4, peptone: 2, sterile autoclaved artificial seawater: 1000 ml pH (at 25°C) 7.0 ± 0.1) medium at 30 °C with 150rpm shaking for about 7 days. Strain was stored in A1 medium containing glycerol 20% (v/v) at 4 °C for short-term storage, at -20 °C for long-term storage.

Identification and phylogeny

Genomic DNA of Streptomyces sp. PDH23 was isolated using HiPurATM Streptomyces DNA Purification Kit following the manufacturer's instructions.

The DNA yield and quality were assessed using 1.0% (w/v) agarose gel electrophoresis. The primer pair 27F (5′-AGAGTTTGATCCTGGCTCAG-3′) and 1492R (5′-TACGGCTACCTTGTTACGACTT-3′) were used for PCR amplification of 16S rRNA. The PCR was performed in a final volume of 50 µL, which was composed of template DNA: 10 ng, 1.5 mM MgCl2, 0.2 mM of each dNTP, 200 pM of primer, and 2U of Taq DNA polymerase with the appropriate reaction buffer under the following conditions: initial denaturation at 94 °C for 4 min, followed by 32 cycles of 94 °C for 1 min, annealing at 56 °C for 50 sec, and 72 °C for 1 min 40 sec. The amplification products were separated by gel electrophoresis in 1% agarose gel. The PCR products were then sequenced using the Sanger sequencing platform. Mega 6.0 with bootstrap 1000 was used to demonstrate an evolutionary phylogenetic relationship.

Antibacterial and antifungal activity was determined by agar well diffusion method

Strains of bacterial VP; SA; BC and the yeast CA, MRSA, MRSE obtained from American Type Culture Collection (ATCC,
Manassas, VA), were used in this antimicrobial screening. The agar plate surface is inoculated by spreading a volume of the bacteria inoculum over the entire agar surface. Then, a hole with a diameter of 6 mm is punched aseptically with a sterile tip, and 50 µL of the Streptomyces sp. PDH23 fermentation broth (as antimicrobial agent) is introduced into the well. Then, agar plates are incubated under 37°C overnight. The antimicrobial agent diffuses into the agar medium and inhibits the growth of the microbial strain tested (Magaldi et al., 2004; Valgas et al., 2007; Saadoun, Muhana, 2008).

**Screening for enzyme activity**

The screening of the actinomycete strains for cellulase/amylase/protease production was studied by inoculating them on SCA (containing 2% substrate (cellulose/amylase/casein)) plates (Fossi et al., 2005) at 30 °C for 72 h. Following incubation, plates were flooded with Lugol’s iodine solution (1.5% KI, 1% I₂) for 5 mins. Subsequently, the staining solution was poured off and the plates were washed two times with suitable amount of distilled water. The organisms which secretes enzymes, produced zone of clearance or decolorization against the blue color background.

**Genome mining**

Whole genome sequencing was performed using the Illumina’s HiSeq 2000 Sequencing System. Adaptors and low quality reads were removed using bbduk bbtool. Clean reads were assembled de novo using SPAdes 3.11.1. Resulting scaffolds were subjected to MEGABLAST against the NCBI nucleotide database to identify for sequence contaminants, which were removed. The final genome was quality accessed using QUAST and annotation was done using RAST.

**Secondary metabolite mining**

The assembled scaffolds of the Streptomyces sp. were submitted to the antiSMASH server to search for potential secondary metabolite biosynthetic gene clusters. The core structures of secondary metabolite biosynthetic gene clusters were identified by antiSMASH and extracted for comparison with known gene clusters of other species using BLAST.

**RESULTS**

**Collected sample**

The sponge sample was collected by SCUBA diving at 14 m depth at location from central coastal region of Da Nang, Viet Nam. They were placed into sterile bottle with 30% glycerol on the ice for the transference to the laboratory. The Yellow pot sponge *Rhabdastrellaglobostella* was identified based on the morphological characteristics and 28S rRNA by Prof. Dr. Nguyen Thi Kim Cuc.

**Isolation and identification of actinomycetes strain**

Different concentration of crushed sponge were streak onto SCA agar plate. We have identified 5 strains based on their morphology. Figure below shows the diverse of these strains.

![Figure 1. Different strains collected from sponge (A: PDH20 strain; B: PDH21; C: PDH22; D: PDH23; E: PDH24).](image-url)
Figure 2. Activity on substrate plates: A. Casein plate. B. Cellulose plate and C. Starch plate.

Figure 3. Zone of inhibition test for antimicrobial activity of PDH23 strain on agar plates of SA; BC; VP and CA; MRSE; MRSA; (+): Positive control. (-): Negative control. (Mau): Sample PDH23. On MRSE and MRSE plates, (4): Sample. (5): Positive control.

Table 1. Antibacterial and antifungal activity of the strain PDH23 versus tested microorganisms.

| Substrates: Bacteria/ Fungi | Clear zone of antibacterial activity (mm) |
|----------------------------|------------------------------------------|
|                            | sample PDH23 | Positive control               |
| *Vibrio parahaemolyticus*  |             | Chloramphenicol (30 µg)        |
| (ATCC17802) VP             | 18           | 0                             |
| *Staphylococcus aureus*    |             | Chloramphenicol (30 µg)        |
| (ATCC25923) SA             | 18           | 22                            |
| *Bacillus cereus*          |             | Chloramphenicol (30 µg)        |
| (ATCC14579) BC             | 19           | 18                            |
| *Candida albicans*         |             | Nystatin (10 µg/ml)           |
| (ATCC1023) CA              | 18           | 14                            |
| Methicillin-resistant      |             | Azithromycin (80 µg/ml)       |
| *Staphylococcus aureus*    |             | 12,1                          |
| *Aureus*(MRSA) ATCC 33591  | 8,6          |                                |
| Methicillin-resistant      |             | Azithromycin (80 µg/ml)       |
| *Staphylococcus epidermidis*|             | 13,9                          |
| (MRSE) ATCC 35984          | 13,9         | 0                             |
These strains were tested to see their ability to produce enzymes for the degradation of specific substrates.

As a result (Figure 2) the PDH23 strain had capable of hydrolyzing starch, cellulose and casein with the clear zone diameter correspond to 29; 32; 31 mm respectively.

The antibacterial activity of PDH23 strain was tested on pathogenic microorganisms: Two intestinal microorganisms: B. cereus and S. aureus; one strain of microorganisms causing disease in aquatic products: V. parahaemolyticus; one strain of pathogenic fungi on genital tract: C. albicans and two strains of antibiotic resistant bacteria: MRSA and MRSE.

Morphology, identify and construct phylogenetic tree for PDH23

Visible appearance showed that the spores are dry, lumpy and have white colour. The filament spores appear to be brown. When cultured in SCA or A1 agar medium, PDH23 strain release colour and dye the surrounding red. The PDH23 strain was cultured in SCA medium for 10 days at 30°C. Under the SEM (JSM - 5410LV, Japan), the nodular of PDH23 are arranged in a series. The spores are prismatic with a diameter of about 0.5-1 µm with the distance between the nodular is about 1-1.5 µm.

Summary of assembled genome of Streptomyces sp. PDH23

The assembded of PDH23 strain genome was registered on NCBI with the accession code SUB5231575. The genome is assembled into 52 contigs with the total size of about 8.5 Mb. The longest contig is 804249 bp. The overall GC content is about 72%. The high GC content have previously been observed in Streptomycesotsuchiensis (NCBI accession ASM430357v1). Similarly to PDH23, this strain also has a 72% GC content, but the genome is smaller with only 6.15 Mb. As of writing this article this is the second completed assemble marine genome of Streptomyces (Terahara et al., 2019). This assembled genome is highest similarity was to Streptomycesesp. KPB2 (NZ_CP034353), which was isolated from kiwifruit, Streptomycesesp. CCM_MD2014 (NZ_CP009754.1) from top soil, Streptomycesesp. 2114.2 (NZ_LT629768.1) from plants. The genome similarity of these assemblies are shown below.
Figure 5. Relation of *Streptomyces* sp. PDH23 to the most 16S rRNA similar. *Xestospongia* sp 18s rRNA was used as outgroup. The tree topology is based on neighbor joining and built using MEGA6. Bootstrap analysis was performed with 1000 iterations. Only bootstrap values above 50% are displayed. The scale corresponding to the evolutionary distance calculated by using Kimura 2 values.

Table 2. General information of the assembled PDH23.

| Assembled | PDH23_scaffolds | Assembled | PDH23_scaffolds |
|-----------|-----------------|-----------|-----------------|
| # contigs (>= 0 bp) | 52 | # contigs (>= 0 bp) | 52 |
| # contigs (>= 1000 bp) | 52 | Total length (>= 50000 bp) | 8327403 |
| # contigs (>= 5000 bp) | 41 | Total length (>= 1000 bp) | 8594820 |
| # contigs (>= 10000 bp) | 40 | Longest Contig | 804249 |
| # contigs (>= 25000 bp) | 38 | Total length | 8594820 |
| # contigs (>= 50000 bp) | 33 | GC (%) | 72.03 |
| Total length (>= 0 bp) | 8594820 | N50 | 365348 |
| Total length (>= 1000 bp) | 8594820 | N75 | 183633 |
| Total length (>= 5000 bp) | 8571676 | L50 | 9 |
| Total length (>= 10000 bp) | 8566514 | L75 | 17 |
| Total length (>= 25000 bp) | 8529376 | # N's per 100 kbp | 2.33 |

There are 7674 genes transcribed with 7616 genes completing both the opening and ending codes (99.2%), 28 genes lacking the 3' ending (0.4%), 26 genes lacking the 5' heads and only 4 genes lack both. These genes were sent to Blast KOALA with default settings for overall analysis. Then, using the glossary on KEGG, we were able to find related genes and functional clusters.

**Genome assembly and annotation**

There largest number of genes are in signaling and cellular processing, follows by genetic information processing groups. The metabolism group has the largest number of genes with carbohydrate metabolism as the largest group. The unknown function genes, which does not include in any pathway is the third largest group. There are large interest in
the metabolism and the human diseases as they might contain interesting genes for further analysis.

Secondary metabolite using AntiSMASH

The secondary metabolism of microbe contains biosynthesis pathways such as antibiotics, chemotherapy, insecticides and novel or interesting chemicals. For the discovery of new compounds, these gene encoding clusters such as polyketide synthases (PKSs), lantibiotic synthases and non-ribosomal peptide synthetases (NRPSs) from the bacterial genomes are mined. The contigs of *Streptomyces* sp. PDH23 genome was the input for the antibiotics & Secondary Metabolite Analysis SHell (antiSMASH) server (version 5.0.0), which resulted in 26 predicted gene clusters. Multiple clusters were detected include: Siderophore, nrpsfragment-t1pks, bacteriocin-nrps-terpene, betalactone, nrps, bacteriocin, ectoine, melanin, terpene, type 2 pks, indole, type 3 pks, nrps-nrpsfragment-t1pks, phenazine, butyrolactone, otherks-t1pks-t2pks and otherks were predicted to be encoded in the genome. These results were compared with the MIBiG (Minimum Information about a Biosynthetic Gene cluster) to accurately predict certain metabolites and/or the most likely class (Table 3).

In comparison to the other genomes, the unknown and others are the two biggest clusters. In general the PDH23 has about the same number of NRPS, Terpene, RiPP and NRP + Polyketide as the other genomes. These numbers are underestimated as the whole genome is divided into multiple contigs, which some truncated. The biochemical results also show more chemicals detected than the number of predicted clusters.

Twelve clusters show more than 80% similarities to known gene clusters: Undecylprodigiosin, geosmin, streptothricin, coelichelin, ectoine, desferrioxamine B, melanin, albaflavenone, hopene, coelibactin, isorenieratene and hedamycin. The most common clusters are ectoine and sideophore desferrioxamine B, the anti-tumor herboxidine, coelichelin, the carotenoid light-harvesting pigment isorenieratene and the terpene hopene. In comparison to the marine *S. OTB305* (Assembly acc. ASM430597v1) only three gene clusters hopene, ectoine and herboxidiene are similar.

![Figure 6. The genome similarity of these assemblies with different *Streptomyces* strains. The darker the colour the more similarity they are against each other.](image-url)
There were three siderophore clusters predicted, with two predicted to be grincamycin (5%) and desferrioxamine B (83%). The desferrioxamine B is a member of iron-binding molecules called siderophores, which help the bacteria to take up iron from the environment. It
also has antioxidant potential and have been used in clinical for treatment of iron overload (Crichton, 2012; Raines et al., 2015). This is a highly conserved gene cluster in streptomyces genera. This gene cluster is 83% gene identical to AL645882.2 from S. coelicolor A3(2) and 100% identical to AP009493.1 from S. griseus subsp. griseus NBRC 13350. There are 5 main genes including the core siderophore biosynthesis enzyme (lucA_clucC), acetylene transferase, monoxygenase, pyridoxal-dependant dacarboxylase and siderophore-interacting protein.

Streptothricin is a broad spectrum antibiotic that is produced by streptomyces that affect both gram negative and positive bacteria as well as fungi. It inhibits protein synthesis by preventing the charged tRNAs to the A-site of the ribosome and blocking translocation of the peptidyl-tRNA to the P-site (Stankovic et al., 2014; Burchhardt, Semerena, 2017). The antibiotic was shown to have effects against escherichia coli, bacillus subtilis, staphylococcus aureus, bacillus cereus and pseudomonas aeruginosa (Ji et al., 2009).

Hedamycin is an antitumor polyketide antibiotic. It has anticancer activity, the gene cluster is 90%. It was found to be product of streptomyces griseoruber (Das, Khosla, 2009).

### Table 3. These results were compared with the MIBiG (Minimum Information about a Biosynthetic Gene cluster) to accurately predict certain metabolites and/or the most likely class.

| Cluster | Type | Size (bp) | Similar cluster | known id | MIBiG BGC-ID |
|---------|------|-----------|-----------------|----------|--------------|
| 1       | Siderophore | 11350 | - | - | - |
| 2       | T1pks-Nrpsfragment Bacteriocin-Nrps Terpene | 46911 | Undecylprodigiosin | 100% | BGC0001063 |
| 3       | Bacteriocin | 73908 | Geosmin | 100% | BGC0001181 |
| 4       | Betalactone | 27775 | Hormaomycin | 13% | BGC0000374 |
| 5       | Siderophore | 13239 | Grincamycin | 5% | BGC0000229 |
| 6       | Nrps | 61228 | Streptothricin | 87% | BGC0000432 |
| 7       | Bacteriocin | 10215 | Informatipeptin | 42% | BGC0000518 |
| 8       | Nrps | 51087 | Coelichelin | 100% | BGC0000325 |
| 9       | Ectoine | 10398 | Ectoine | 100% | BGC0000853 |
| 10      | Siderophore | 11775 | Desferrioxamine B | 83% | BGC0000940 |
| 11      | Melanin | 10593 | Melanin | 100% | BGC0000910 |
| 12      | Terpene | 21013 | Albaflavenone | 100% | BGC0000660 |
| 13      | T2pks | 72536 | Spore pigment | 66% | BGC0000271 |
| 14      | Terpene | 26732 | Hopene | 100% | BGC0000663 |
| 15      | Indole | 21127 | Ravidomycin | 5% | BGC0000263 |
| 16      | Terpene | 20425 | Carotenoid | 18% | BGC0000633 |
| 17      | T3pks | 41124 | Herboxidiene | 8% | BGC0001065 |
| 18      | T1pks-Nrpsfragment-Nrps | 66919 | - | - | - |
| 19      | Phenazine | 20425 | - | - | - |
| 20      | Nrps | 66476 | Coelibactin | 100% | BGC0000324 |
| 21      | Butyrolactone | 10749 | - | - | - |
Bioinformatics analysis shows that each strain of bacteria has the ability to synthesize 25-30 types of natural products, of which about 90% is still unknown. Even if only 20% of the 25-30 types of natural products produced by each strain are new structures, the number of new natural products we obtain will increase exponentially (Winter et al., 2011; Li et al., 2018). Marine actinomycetes are a potential source of novel compounds because their environments are completely different from those on land. Many researchers have isolated new antibiotics from the marine environment (Maskey et al., 2003; Sujatha et al., 2005). The actinomycetes produce many enzyme inhibitors, antibiotics and anti-cancer. Marine actinobacteria are good sources of enzyme inhibitors (Imada, 2005). According to (Peela et al., 2005) many types of marine actinomycetes were isolated from samples collected from the Andaman coast in the bay of Bengal and most of the isolates of the genus streptomycyes had antibacterial and antifungal activity. Streptomycetes have been shown to be capable of synthesizing antibacterial agents (Ramesh, Mathivanan, 2009), antifungal agents (Frapagdee et al., 2008; Ramesh, Mathivanan, 2009; Xu et al.,

|   | Terpene |   | Isorenieratene |   | 100% | BGC0000664 |
|---|---------|---|----------------|---|------|-------------|
| 22 |         | 25538 | Isorenieratene |   | 100% | BGC0000664 |
| 23 | Nbps    | 35083 | Carbapenem MM  |   | 6%   | BGC0000842 |
| 24 | T2pks-Otherks-T1pks | 82613 | Hedamycin 90%  |   |      | BGC0000233 |
| 25 | Otherks | 53479 | -              |   |      |             |
| 26 | Nbps    | 2819  | -              |   |      |             |

**Figure 9.** c00004_NODE_4_ - Region 1 – Siderophore Location: 202632 – 214407. The similarity in clustering of Desferrioxamine B in different species. Result generated from antisasmash.

**Figure 10.** Cluster similarity of nprps with Streptothricin and BD-12.

**Figure 11.** Cluster similarity with Hedamycin. Result generated from antiSMASH.

**DISCUSSION**

Marine actinomycetes are a potential source of novel compounds because their environments are completely different from those on land. Many researchers have isolated new antibiotics from the marine environment (Maskey et al., 2003; Sujatha et al., 2005). The actinomycetes produce many enzyme inhibitors, antibiotics and anti-cancer. Marine actinobacteria are good sources of enzyme inhibitors (Imada, 2005). According to (Peela et al., 2005) many types of marine actinomycetes were isolated from samples collected from the Andaman coast in the bay of Bengal and most of the isolates of the genus streptomycyes had antibacterial and antifungal activity. Streptomycetes have been shown to be capable of synthesizing antibacterial agents (Ramesh, Mathivanan, 2009), antifungal agents (Frapagdee et al., 2008; Ramesh, Mathivanan, 2009; Xu et al.,
In this study, we isolated, identified and studied Streptomyces sp. PDH23 (Registration number on genbank MN326756), which is a symbiotic association with the Rhhabdastrella globostella sponge specimen resided at the coastal areas of Da Nang, Vietnam. The PDH23 showed the high ability to produce enzymes and this strain exhibited quite strong inhibition some strains of pathogenic microorganisms. The entire genome sequence of the PDH23 strain was decoded with a total length of 8594820 bp with a GC content of 72.03%. The genome of the PDH23 has also been registered on NCBI with the code SUB5231575. Using software to exploit secondary metabolites shows that gene clusters are responsible for biosynthesis of known and/or new secondary metabolites, including various terpene types, such as NRPS, PKS, hglE-KS, betalactone, melanin, T1pks, T2pks, T3 Nprs, indole, siderophore, acteriocin, ectoine, butyrolactone, phenazine. These results show the potential for producing highly bioactive compounds of the PDH23 strain.

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KHAI THÁC DỮ LIỆU HỆ GEN CỦA CHỨNG STREPTOMYCES SP. PDH23 CÔNG SINH HẢI MIỀN PHÂN LẬP TẠI BIỂN DÀ NẴNG CHO CÁC CỤM GEN CÓ HOẠT TÍNH SINH HỌC

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TÓM TÀT

Trong nghiên cứu này, chúng xạ khuẩn Streptomyces sp. PDH23 được phân lập từ mẫu hai miền Rhabdastrella globostellata thu nhận từ vùng biển Đà Nẵng, Việt Nam thể hiện tiềm năng ứng dụng trong y sinh học cao. Chủng PDH23 cho khả năng sinh enzyme cellulase, amylase, protease và. Bên cạnh đó, chúng xạ khuẩn này biểu hiện ức chế sinh trưởng voi 2 chúng vi khuẩn Gram (+) BC(ATCC25923), và 1 chúng vi khuẩn Gram (-) VP(ATCC17802) và chúng nấm men CA (ATCC10231). Ngoài ra, chúng PDH23 còn cho kết quả khá tốt trong thử nghiệm hoạt tính kháng hai chúng vi khuẩn kháng thuốc gây bệnh đường ruột là MRSA (ATCC33591) và MRSE (ATCC335984). Trình tự bộ gen của chúng xạ khuẩn PDH23 đã được giải mã có tổng độ dài 8594820 bp với hàm lượng GC là 72.03%. Có 7674 gen được phân mài với 7616 gen hoàn thành cấu trúc mở đầu và mã kết thúc (99.2%), 28 gen thiếu đầu kết thúc 3' (0.4%), 26 gen thiếu đầu 5' và chỉ có 4 gen thiếu cả hai. Những gen này đã được gửi đến Blast KOALA với các cái đặt mặc định để phân tích tổng thể. Nghiên cứu đã sử dụng các phần mềm khai thác hợp chất chuyên hóa hữu thức cấp cho thấy các cụm gen chịu trách nhiệm sinh tổng hợp các chất chuyên hóa hữu thức cấp đã biết và/hoặc mới, bao gồm các loại terpene khác nhau, như NRPS, PKS, hglE-KS, betalactone, melanin, T1pks, T2pks, T3 Nrp, indole, siderophore, acteriocin, ectoine, butyrolactone, phenazine có tiềm năng tạo ra các hợp chất có hoạt tính sinh học cao của chúng xạ khuẩn PDH23.

Từ khóa: AntiSMASH, genome-mining, marine-actinomyces, sponge-associated, streptomyces.