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ORIGINAL RESEARCH

Hepatitis C Virus NS3 Protease and Helicase Inhibitors from Red Sea Sponge (*Amphimedon*) Species in Green Synthesized Silver Nanoparticles Assisted by in Silico Modeling and Metabolic Profiling

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Background: Hepatitis C virus (HCV) infection is a major cause of hepatic diseases all over the world. This necessitates the need to discover novel anti-HCV drugs to overcome emerging drug resistance and liver complications.

Purpose: Total extract and petroleum ether fraction of the marine sponge (*Amphimedon* spp.) were used for silver nanoparticle (SNP) synthesis to explore their HCV NS3 helicase- and protease-inhibitory potential.

Methods: Characterization of the prepared SNPs was carried out with ultraviolet-visible spectroscopy, transmission electron microscopy, and Fourier-transform infrared spectroscopy. The metabolomic profile of different *Amphimedon* fractions was assessed using liquid chromatography coupled with high-resolution mass spectrometry. Fourteen known compounds were isolated and their HCV helicase and protease activities assessed using in silico modeling of their interaction with both HCV protease and helicase enzymes to reveal their anti-HCV mechanism of action. In vitro anti-HCV activity against HCV NS3 helicase and protease was then conducted to validate the computation results and compared to that of the SNPs.

Results: Transmission electron–microscopy analysis of NPs prepared from *Amphimedon* total extract and petroleum ether revealed particle sizes of 8.22–14.30 nm and 8.22–9.97 nm, and absorption bands at λ_{max} of 450 and 415 nm, respectively. Metabolomic profiling revealed the richness of *Amphimedon* spp. with different phytochemical classes. Bioassay-guided isolation resulted in the isolation of 14 known compounds with anti-HCV activity, initially revealed by docking studies. In vitro anti–HCV NS3 helicase and protease assays of both isolated compounds and NPs further confirmed the computational results.

Conclusion: Our findings indicate that *Amphimedon*, total extract, petroleum ether fraction, and derived NPs are promising biosources for providing anti-HCV drug candidates, with nakinadine B and 3,4-dihydro-6-hydroxymanzamine A the most potent anti-HCV agents, possessing good oral bioavailability and penetration power.

Keywords: *Amphimedon*, nanoparticles, marine sponge, natural products, HCV helicase, protease, molecular docking, metabolomics

Introduction

Nanomaterials have a wide range of applications, though have many problems, accompanied by material sciences such as solar energy,[1] microelectronics[2] and antimicrobial activities.[3] Several methods have been reported for the preparation of silver nanoparticles (SNPs), including chemical-based methods,[4] which are not preferred, due to the toxicity

of the solvents used [5] and reducing or stabilizing agents, such as *N*,*N*-dimethylformamide,[6] that may lead to several biological and environmental hazards. Accordingly, green synthesis is preferred, because it utilizes the reducing power of natural extracts, a safer source for synthesized SNP reduction and stabilization.[7,8] Biosynthesized silver, gold, and platinum NPs have a wide range of pharmaceutical and medical applications, such as catalysis and as antiviral and antibacterial therapeutic agents,[9] in addition to the nonmedical applications, including the manufacturing of soap, cosmetic products, toothpaste, shampoo, and detergents.[10] SNP-based materials have specific dimensions, with particle sizes of 1–100 nm.[5] SNPs have been used in different fields, such as food packaging and water filtration, besides their multitherapeutic applications,[11] including antimicrobial activities.[12]

Hepatitis C virus (HCV) is an infectious liver disease that exists in many different genotypes. The HCV genome encodes three structural and six nonstructural proteins, of which NS3/4A protease and helicase are considered the most effective drug targets in current endeavors to design anti-HCV drug scaffolds. HCV infects about 170 million persons worldwide and thus acts as a viral pandemic,[19,20] and about 3% of the world's population is infected by it.[21] Several hepatic complications, such as steatosis, cirrhosis, and hepatocellular carcinoma, are induced by HCV infection.[22] One of the major health issues in Egypt is HCV, as it infects about 14.7% of the general population.[23]

The HCV genome consists of a single RNA-positive strand.[24] A polyprotein encoded by genomic RNA is translated by an internal ribosome, followed by cleavage through viral protease into ten mature viral proteins.[25] The remaining part is cleaved by viral protease, producing six nonstructural proteins, among which is NS3 protease.[26] The viral replication complex is formed due to these nonstructural proteins and their host factors.[24] Helicase exhibits an important role during RNA replication by unwinding the double RNA strand.[27] It has several other significant roles, such as assisting in viral replication through translation and protein processing.[27]

Available US Food and Drug Administration–approved drugs for HCV include nucleotide derivatives, eg, sofosbuvir, and nonnucleosides, eg, boceprevir, ledipasvir, telaprevir, and simeprevir.[28,29] These drugs inhibit the viral replication cycle that results in high rates of treatment in a shorter time.[29] Regardless of the available drugs offering improved viral response, some side effects have been reported during treatment with telaprevir and other protease inhibitors, such as skin rash, anemia, and gastrointestinal disorders.[30–32] These challenges encourage the search for new natural HCV inhibitors that can act against nonstructural proteins, such as NS3 polymerase and helicase, to inhibit virus replication.[33-35]

The marine ecosystem is still considered a promising reservoir of unexplored bioactive natural products. Marine metabolites have been considered a potential reservoir for antiviral compounds targeting HCV, and have provided inspiring scaffolds for combinatorial chemistry to design novel antiviral agents with enhanced therapeutic potential and minimal side effects.[38–41] Several marine sponges and their associated microbiota have been explored for anti-HCV activities.[24,42] Harzianoic acids A and B have been isolated from the sponge-associated *Trichoderma harzianum* fungus, and showed virus-inhibitory activity via reducing HCV RNA levels.[29] Discorhabdins A and C and dihydrodiscorhabdin C exhibit anti-HCV activity.[43] Manoalide exhibits inhibitory activity against NS3 helicase, leading to inhibition of virus RNA-helicase activity.[44] Members of the genus *Amphimedon* exhibit a wide range of biological activities, as it includes different classes of metabolites, in particular pyridine alkaloids[45] of manzamine[46] and purine types,[47] as well as macrocyclic lactones/lactams,[48] ceramides, cerebrosides,[49] and fatty acids.[50,51] In the literature, among 54 extracts from different marine organisms studied, ethyl acetate from *Amphimedon* spp. exhibited the highest anti-HCV activity,[24] as well as halitoxins, which are a group of toxic complexes with a 3-alkyl pyridinium structure isolated from the Red Sea sponge *Amphimedon chloros*, *Haliclona* sponges, and other marine sponges. It has been reported that 4.69 μg/mL of an organic extract of *Amphimedon* sponge containing halitoxins exhibited inhibitory activity (up to about 60%) against the West Nile Virus NS3 protease.[52] Despite continuous attempts made to discover new drug candidates[53], drugs with potential anti-HCV agents have remained underexplored.[13] However, the use of marine material in nanomedicine remains in the early stages of investigation and faces many challenges, due to difficulties in isolation and identification of the bioactive chemical entities.[14] As an example of marine organisms, the marine alga *Caulerpa racemosa* has been used to synthesize SNPs with antibacterial activity against *Proteus mirabilis*.[15] Moreover, marine sponge (*Haliclona exigua*) NPs exhibited activity against oral biofilm bacteria, including *Streptococcus salivarius* and *Streptococcus orulis*.[16] Nanotechnology studies have also extended to developing novel antiviral therapeutic agents that interfere with viral attachment and entry during infection.[17] NPs help in the treatment of HCV through their effect on HCV NS3.[18,36,37]

This inspired us to explore the anti-HCV potential of *Amphimedon* NPs, as this has never been explored before. The anti -HCV NS3 helicase and protease activity of total extract and petroleum ether *Amphimedon* fractions were first investigated, followed by liquid chromatography (LC)–high-resolution electrospray ionization (HRESI)–mass spectrometry (MS)–based metabolic profiling for dereplication purposes. A mechanistic insight for the identified antiviral compounds was provided by the in silico method using molecular docking studies. The in vitro inhibitory potential of the isolated compounds against HCV replication was then tested. Finally, physiochemical properties of the isolated compounds were assessed by Veber's oral bioavailability rule and Lipinski's rule of five.

Methods

Sponge Material

Amphimedon marine sponge was collected from Sharm El-Shaikh (Egypt). It was then air-dried and stored at −24°C until further analysis. Voucher specimens with registration numbers BMNH 2006.7.11.1 and SAA-66 were obtained from the Natural History Museum (London, UK) and the Pharmacognosy Department (Faculty of Pharmacy, Suez Canal University, Ismailia, Egypt), respectively.

Extraction and Isolation

Freeze-dried sponge material (6 g) was extracted with methanol–methylene chloride. The resulting crude extract was fractionated between water and petroleum ether, yielding petroleum ether fraction, followed by dichloromethane, ethyl acetate, and butanol. The remaining mother liquor was then deprived of its sugars and salts with an ion-exchange resin using acetone. The organic phase in each step was separately concentrated under a vacuum, yielding petroleum ether (1 g), dichloromethane (250 mg), ethyl acetate (250 mg), butanol (1 g), and acetone (2 g) fractions. The petroleum ether fraction was chromatographed on a silica-gel column (gradient elution of petroleum ether: EtOAc, then EtOAc), followed by methanol, which was then chromatographed on a Sephadex LH-20 (Merck, Bremen, Germany) using methanol:water as eluting solvent, and final purification on semipreparative HPLC with acetonitrile (MeCN) and water as mobile phase complemented by 0.05 percent trifluoroacetic acid with a gradient elution of 10% MeCN–H_2O to 100% MeCN over 30 minutes at a flow rate of 5 mL/min to yield compounds (1–14).

Synthesis of Silver SNPs

Total extract (0.002g) and petroleum ether fraction were individually dissolved in 1 mL DMSO. This was followed by the addition of 0.4 mL of each extract to 10 mL 1mM $AgNO_3$ at room temperature.

Characterization of Synthesized SNPs by Ultraviolet-Visible Spectrometry, Transmission Electron Microscopy, and Fourier-Transform Infrared Spectroscopy

SNP synthesis was detected by ultraviolet (UV)-visible spectrometry using a double-beam V630 (Jasco, Japan), Fourier-transform infrared (FTIR) using an FTIR-8400S, IR Prestige 21, and IR Affinity 1 (Shimadzu, Japan), and transmission electron microscopy (TEM) using a JEM-1010, (Jeol, USA).[11]

Metabolic Analysis

LCMS was carried out using a Synapt G2 HDMS quadrupole time-of-flight hybrid mass spectrometer (Waters, Milford, USA). The sample (2 µL) was injected into the BEH C_{18} column, adjusted to 40°C, and connected to the guard column. A gradient elution of mobile phase was used, starting from no solvent A and 0.1% formic acid in water to 100% acetonitrile as solvent B. MZmine 2.12 was employed for differential investigation of MS data, followed by converting the raw data into positive and negative files in mzML format with ProteoWizard.[13]

Anti–HCV Helicase and Protease Assay

Assay buffer (4 µL 25 mM MOPS pH 6.5, 1.25 mM $MgCl_2$, 0.1 mM DTT, 12.5 mM Tween 20, 6 µg/mL BSA) containing 5.56 nM NS3 substrate and 13.89 nM NS3 helicase fragments was distributed into wells of a 1,536 mL plate. The compounds tested (55 µL) were dissolved in DMSO. In each well, 110 mM thioflavin S or 0.8% of DMSO and 1 mL 5 mM ATP were added. Fluorescence intensity was measured after 1 hour of incubation at 25°C on a ViewLux (PerkinElmer). The ratio between RFU values obtained at t_0 (RFU_t_0) and t_{60} (RFU_t_{60}), named Ratio_RFU, was calculated: $Ratio\_RFU = RFU\_t_{60}/RFU\_t_0$. The percentage of inhibition was calculated. The activity score was classified according to the potency, ie, the most potent extract was that possessing the highest activity scores. Activity-score ranges for active and inactive extracts were 82–100 and 0–79, respectively.

Chemicals and Reagents

NS3 helicase fragments and assay buffer were supplied by Assay Provider, and 1,536-well plates (part 789,173) by Greiner. MOPS (part BP308-100), ATP (part BP413-25), and magnesium chloride (part BP214-500) were purchased from Fisher BioReagents. Thioflavin S (part T1892) was procured from Sigma-Aldrich, and a Cy5/quencher-labeled molecular beacon (custom-synthesized) was procured from Integrated DNA Technologies.

Assays of Activity of Isolated Compounds Against HCV

HCV cells were inoculated at 26×10^4 cells per well in a 48-well plate 24 hours before assays (Reblikon, Mainz, Germany) were conducted. Concentrations of 1–200 µM of each tested sample were prepared and a luciferase-assay system (Promega) utilized to measure luciferase activity. The resulting luminescence was measured with a luminescence plate reader (PerkinElmer) and this alternative to the level of the HCV replicon.[54]

Docking Studies

Docking simulations were performed using Molecular Operating Environment (MOE 2014.0901; Chemical Computing Group, Montreal, QC, Canada) on the compounds identified in *Amphimedon* spp., in addition to paritaprevir and ribavirin 5′-triphosphate (helicase inhibitor), for the sake of comparison to their inhibitory potential.[55] We drew two-dimensional structures of the known compounds with ChemSketch, then docked into the rigid binding pocket of HCV NS3–4A protease–helicase in complex with a macrocyclic protease inhibitor (PDB 4A92), HCV NS3/NS4A protease complexed with BI 201,335 (PDB 3P82), and HCV NS3 helicase with {6-(3,5-aminophenyl)-1-[4-(propane-2-yl)benzyl]-1*H*-indol-3-yl} acetic acid as a bound inhibitor (PDB4WXR). The 3-D crystal structure of these three enzymes was downloaded from Protein Data Bank.[55,56]

Results

Anti–HCV NS3 Helicase and Protease Activities

The total extract and the derived fractions of *Amphimedon* were tested for their HCV NS3 helicase and protease activities, and only the total extract, as well as the petroleum ether fraction, exhibited inhibitory potential against HCV NS3 helicase and protease (Table 1). This led us to use *Amphimedon* total extract and petroleum ether fraction in the formation of SNPs, which showed a better anti–HCV NS3 helicase and protease action (Table 2). The bioactive petroleum ether fraction was then subjected to further chromatographic separation with different chromatographic techniques to yield 14 known compounds (1–14, Figure 1), which were identified based on HRESI mass spectra in comparison to literature data.

Table 1 In vitro Anti–NS3 Helicase and Protease Activities of Total Extract and Fractions of *Amphimedon* sp.

	IC_{50}, µg/mL	
	NS3 helicase	**NS3 protease**
Petroleum ether	0.296063	3.875308
Total extract	2.066837	13.29783
Butanol	2.346521	35.29088
Ethyl acetate	2.782707	43.69913
DCM	11.09016	29.79358

Metabolomic Profiling of Total Extract and Petroleum Ether Fraction of *Amphimedon*

The crude extract of freeze-dried *Amphimedon* was subjected to dereplication of secondary metabolites using LC-HR-ESIMS (Table S1 and Figure 2). Twelve compounds belonging to different chemical classes were identified. This revealed the richness of this marine sponge.

Characterization of Synthesized SNPs of *Amphimedon* Total Extract and Petroleum Ether Fraction

Both the total extract and petroleum ether fraction of *Amphimedon*, possessing the highest activity, were used in green SNP synthesis. The total extract and petroleum

Table 2 In vitro Anti–NS3 Helicase and Protease Activities of the SNP Total Extract and Petroleum Ether Fraction of *Amphimedon* sp.

	IC_{50}, µg/mL	
	NS3 Helicase	**NS3 Protease**
Petroleum ether	0.11±0.62	2.38±0.57
Total extract	1.52 ±1.18	9.76±0.58
$AgNO_3$	77.72 ±4.57	52.67±0.33
Telaprevir (375 mg Tab)	—	4.77±0.26
Ribavirin	4.66±0.29	—

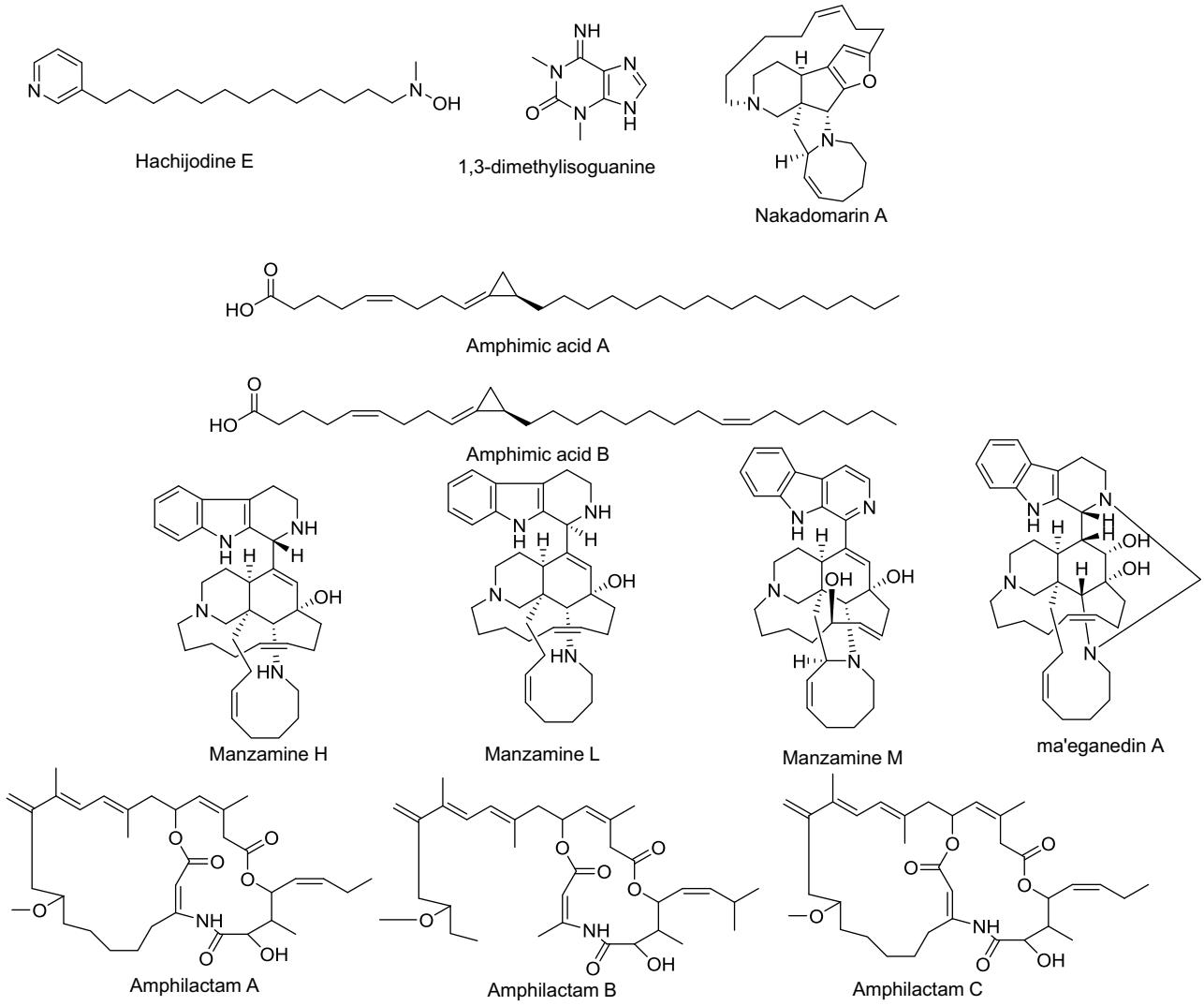

Figure 1 Compounds identified and dereplicated from high-resolution mass-spectra data sets of *Amphimedon* sp.

ether fraction of *Amphimedon* were treated with 1 mM $AgNO_3$, and caused the color to change to reddish brown, indicating SNP synthesis (Figure S1). NPs of total extract and petroleum ether fraction appeared spherical, with particle sizes of 8.22–14.30 nm and 8.22–9.97 nm, respectively, on TEM analysis (Figure 3).

UV-Visible Characterization of Synthesized SNPs of *Amphimedon* Total Extract and Petroleum Ether fraction

SNP formation was controlled by UV light at a wavelength of 200–600 nm. SNPs were formed by the addition of 0.4 mL *Amphimedon* total extract to 10 mL $AgNO_3$ (1 mM) and 0.6 mL petroleum ether extract of sponge extract in DMSO to of 10 mL silver (1 mM), then we used UV spectra to analyze the synthesized NPs. The total extract and petroleum ether fraction exhibited absorbance bands at 450 and 415 nm, respectively. This proved SNP synthesis (Figure 4).

FTIR Characterization of Synthesized SNPs

FTIR was used in characterization of functional groups' adherence to SNP surfaces. The FTIR spectrum showed peaks at 3,432.67, 3,419.17, 2,974.66, 2,930.31, 1,449.24, 876.488, and 872.631 cm^{-1} revealing the presence of different phytochemicals, ie, alkaloids, acids, and phenolic compounds. The peaks at 3,200–3,500 cm^{-1} confirmed the presence of O–H stretching of alcohols and phenolic compounds with strong hydrogen bonds, in addition to N–

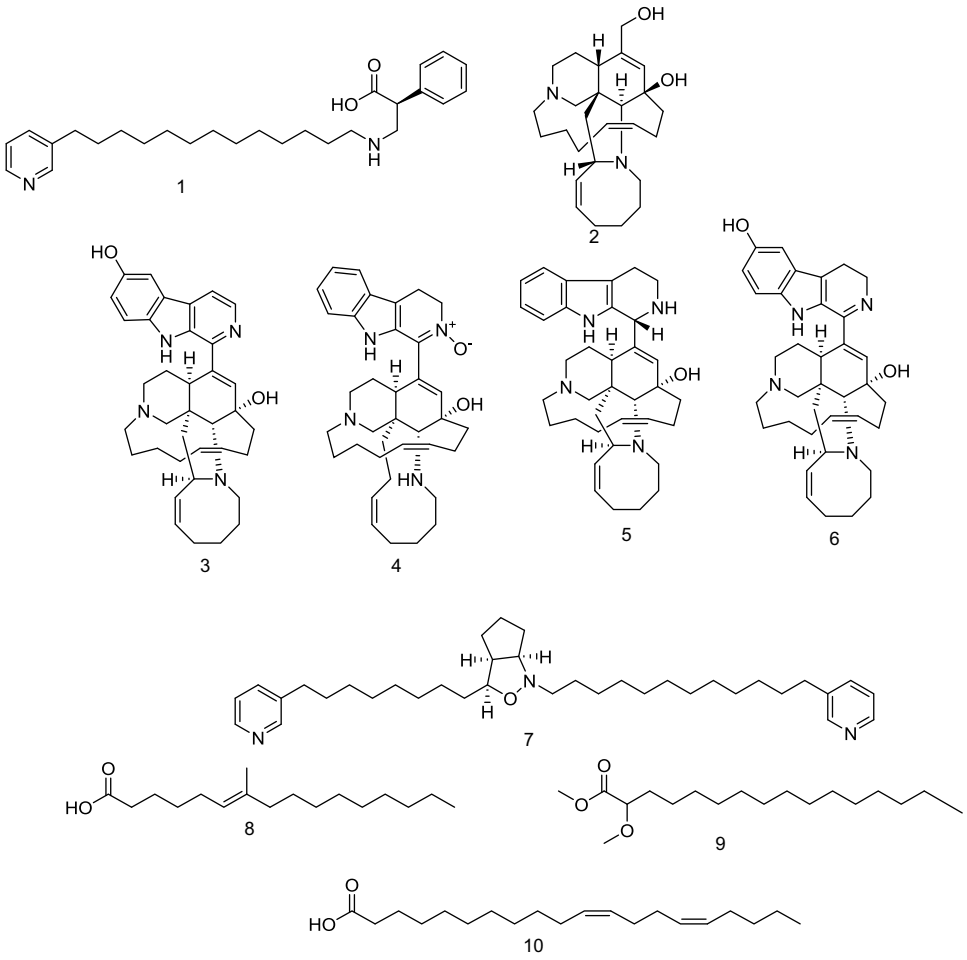

Figure 2 Structures of isolated compounds 1–14.

H group stretching. Peaks appearing at 2,800–3,000 cm^{-1} were characteristic of C–H and aldehydic C–H stretching. O–H stretching in carboxylic acid appeared at 2,700–3,350 cm^{-1}. C–C stretching in an aromatic ring showed characteristic peaks in the region of 1400–1500 cm^{-1}, which included C–H bending of alkanes at 1450–1470 cm^{-1}. However, C–H aromatics were detected at 675–900 cm^{-1} (Figure 5). These groups indicated the stability of the synthesized NPs.

Molecular Docking

The relative inhibitory potential of the tested compounds from *Amphimedon* was explored against HCV NS3 protease and helicase enzymes using an in silico approach via molecular docking. The docking study showed that most of the identified compounds were able to interact with the active sites of both HCV NS3 protease and helicase domains, but with differential binding affinity, expressed as docking S-scores (Table 3 and Figure 6). The potential binding interactivity between protease and helicase domains of HCV NS3 is shown in Figures S2 and S3. Pyrinodemin D (7) and nakinadine B (1) were potential anti-HCV drug candidates, owing to their noticeably strong inhibitory activity against NS3/4A protease–helicase enzyme. In vitro investigation for the tested compounds showed that the results matched those of the in silico study: pyrinodemin D showed the highest inhibitory activity against the HCV replicon, then nakinadine B, and finally 3,4-dihydro-6-hydroxymanzamine A, while the rest of the compounds displayed weak activity.

Lipinski Properties

The four Lipinski properties, in addition to two additional descriptors of topological polar surface area (tPSA) and numbers of rotation bonds of the 14 isolated compounds were analyzed (Table S2). Veber's oral bioavailability rule was estimated, and included two additional parameter ranges (tPSA ≤140 Å, number of rotatable bonds ≤10).

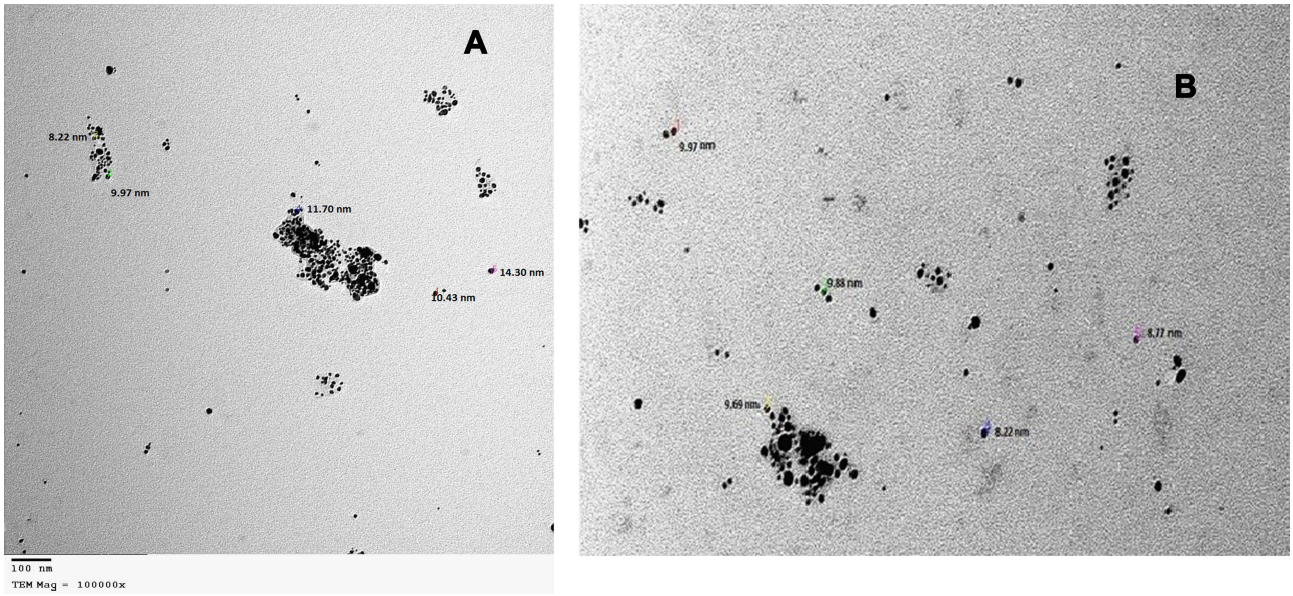

Figure 3 TEM for shape and size of produced SNPs of (**A**) total extract of *Amphimedon* sp. and (**B**) Petroleum ether fraction of *Amphimedon*.**Abbreviations**: TEM, transmission electron microscopy; SNPs, silver NPs

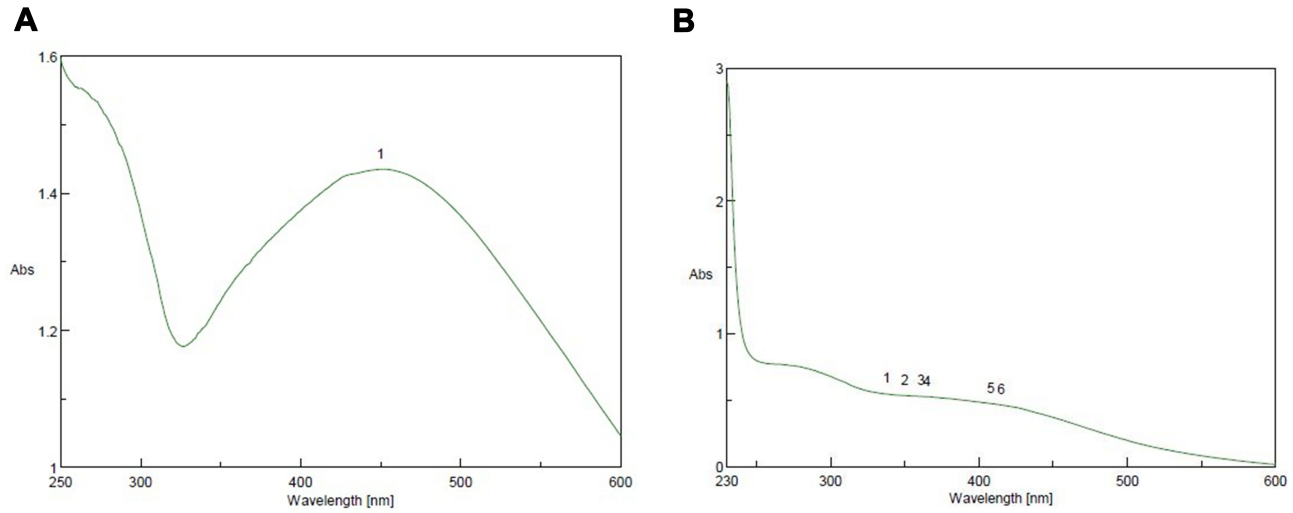

Figure 4 Ultraviolet-visible spectra analysis and color intensity of biosynthesized SNPs of (**A**) petroleum ether fraction of *Amphimedon* spp. and (**B**) total extract of *Amphimedon*.

The isolated compounds were tested for their oral bioavailability in humans, and about 71% (ten of 14) of the isolated metabolite followed Lipinski's rule of five with less than one violation, and the most active anti-HCV drugs perfectly obeyed the rule of five and the rule of PSA.

Discussion

Synthesis of SNPs was detected by the development of a reddish brown color at 37°C.[57] The actual mechanism of SNP reduction has previously been reported.[57] Both the spherical shape and size of 8.22–14.30 nm confirmed the formation of NPs, as measured by TEM. FTIR analysis revealed the presence of various phytochemical classes in the sponge with the ability to react with silver ions through their functional groups, leading to NP reduction. As previously reported, NPs may provide a successful tool in the treatment of HCV,[18] given their effect against HCV NS3. The green synthesized NPs of total extract and petroleum ether fraction exhibited activity against HCV NS3 helicase (IC_{50} 0.11±0.62 and 1.52±1.18) and protease (IC_{50} 2.38 ±0.57and 9.76±0.58), while silver nitrate NPs as controls exhibited activity against HCV NS3 helicase and protease

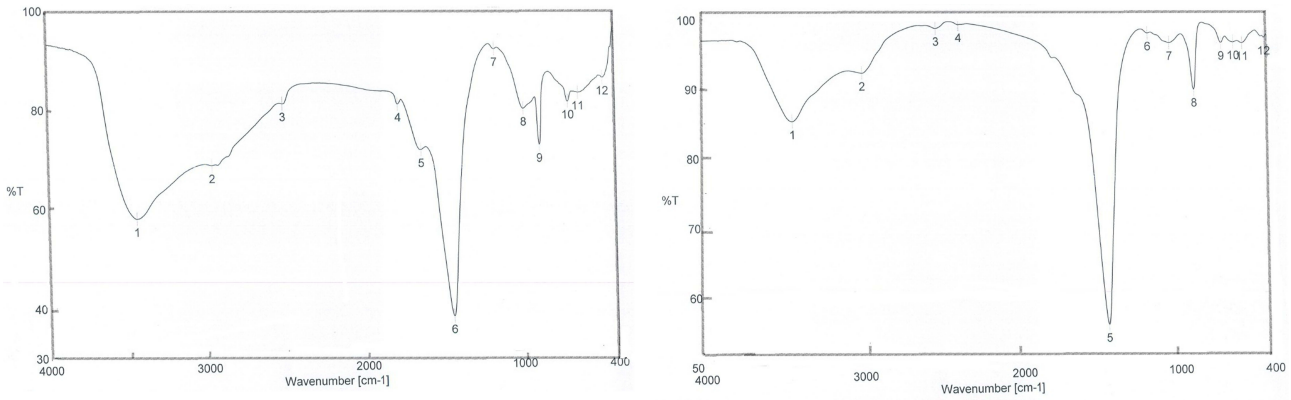

Figure 5 FTIR spectra after synthesis of nanoparticles of (**A**) petroleum ether fraction of *Amphimedon* sp. and (**B**) total extract of *Amphimedon*.

(IC_{50} 77.72±4.57 and 52.67±0.33), respectively. This showed the power of the total extract and petroleum ether fraction synthesized NPs of *Amphimedon*

HR-LCMS–based metabolite profiling of sponge extracts was conducted to identify putative constituents responsible for the activity. Dereplicated identified compounds shown in Figure 1 belonged to a diverse range of phytochemical classes, such as amphimic acids (A and B)[50] and alkaloids with various subclasses, eg, manzamine compounds, such as manzamine L,[58] H, and M, ma'eganedin A[59] and nakadomarin A,[60] in addition to purine alkaloid (1,3-dimethylisoguanine)[61] and pyridine alkaloids, ie, hachijodine E and[62] amphilactams A, B, and C.[48] Total extract and different fractions of *Amphimedon* were assayed in vitro against HCV NS3 helicase and protease, and the petroleum ether fraction was revealed to exhibit the most potent activity (Table 1). That is why we used this fraction in subsequent chromatographic separation with different techniques. Fourteen compounds (1–14), shown in Figure 2, were identified based on their HR-ESIMS and comparison with the literature: nakinadine B[63] (1), orcinol A[64] (2), 6-hydroxymanzamine A[65] (3), 3,4-dihydromanzamine A, J *N*-oxide[65] (4), manzamine D[58] (5), 3,4-dihydro-6-hydroxymanzamine A[66] (6), pyrinodemin D[45] (7), 7-methyl-6-hexadecenoic acid[67] (8), methyl 2-methoxyhexadecanoate[68] (9), 11,15-icosadienoic acid[67] (10), 20-hepacosenoic acid[69] (11), amphimedoside C[70] (12), keramaphidin B[71] (13), and amphimedine[72] (14).

Table 3 Docking Scores (kcal/Mol) of the 14 Tested Compounds, Paritaprevir, and Ribavirin 5′-Triphosphate Against Full-Length HCV NS3-4A Protease–Helicase (4A92), HCV NS3/NS4A Protease (3P82), and HCV NS3 Helicase (4WXR)

	S-Score		
	4A92	3P82	4WXR
Methyl 2-methoxyhexadecanoate	−5.07427	−4.75656	−5.51035
Icrinol A	−5.34033	−5.30877	−5.47285
6-hydroxymanzamine A	−5.49333	−5.37674	−6.26323
Pyrinodemin D	−6.98161	−5.14564	−7.64613
7-methyl-6-hexadecenoic acid	−5.09503	−4.49901	−5.4961
Amphimedine	−5.51757	−4.60604	−5.1061
Amphimedoside C	−5.84524	−5.22292	−5.84337
Keramaphidin B	—	—	—
20-hepacosenoic acid	−5.31298	−5.68273	−5.73547
3,4-dihydro-6-hydroxymanzamine A	−6.25434	−5.9257	−6.62751
3,4-dihydromanzamine A, J *N*-oxide	−6.26893	−4.72766	−5.56533
Nakinadine B	−6.4761	−6.17759	−6.80996
11,15-icosadienoic acid	−5.61213	−4.6286	−5.78322
Manzamine D	−5.62775	−5.10746	—
Paritaprevir		−5.95468	—
Ribavirin 5′-triphosphate			−5.94529

Docking studies showed that nakinadine B (1) possessed the lowest S-score(strongest binding affinity) and ranked top of the identified compounds, followed by 3,4-dihydro-6-hydroxymanzamine A (6) and 20-hepacosenoic acid (11). Nakinadine B (1) achieved hydrogen bonding with Thr40 of the protease domain, and 3,4-dihydro-6-hydroxymanzamine A (6) had an arene–hydrogen interaction with His528 and hydrogen bonding with Cys159. 20-Hepacosenoic acid (11) showed hydrogen bonding with Arg109. Pyrinodemin D (7), nakinadine B (1), 3,4-dihydro-6-hydroxymanzamine A (6), and 6-hydroxymanzamine A (3) were noted to possess the lowest docking scores in binding with HCV NS3 helicase enzyme among the studied compounds. Gly277 and Arg512 residues of the enzyme showed arene–H and H bonding with

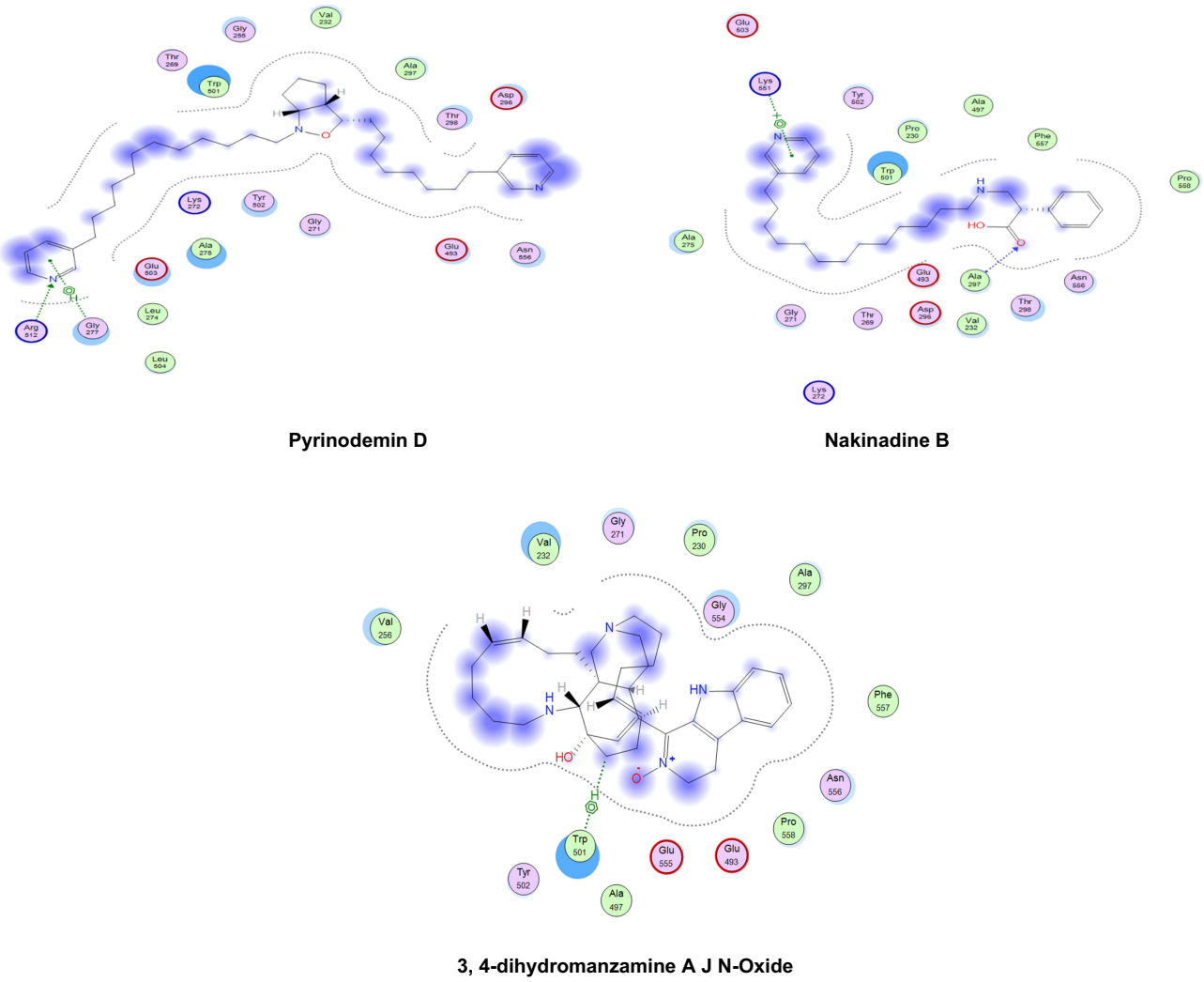

Figure 6 2-D interaction diagrams of docked compounds and ribavirin 5′-triphosphate (**M**) with the active sites of HCV NS3 helicase (4WXR). Green arrows represent side-chain acceptor/donor; blue arrows represent backbone acceptor/donor; blue shadows represent ligand exposure.

pyrinodemin D (7), respectively. However, the two enzyme residues Lys551 and Ala297 showed arene–cation and H-bonding with pyrinodemin D (**7**). 6-Hydroxymanzamine A (3) showed an arene–H bond with Trp501 and an H-bond with Glu493.

To explore the combined protease and helicase–inhibition activity of the studied compounds, they were further docked against HCV NS3–4A protease–helicase (Figure S4). Pyrinodemin D (7), nakinadine B (1), 3,4-dihydromanzamine A, J *N*-oxide (4), and 3,4-dihydro-6-hydroxymanzamine A (6) possessed the most active inhibitors on the basis of their docking scores. Pyrinodemin D (7) had the strongest binding affinity with the helicase enzyme through H-bonding with Gly137 and Arg 123, followed by nakinadine B (1), which showed two arene–H bonds with Gln41 and Cys159 and H-bonding with Ala157. However, 3,4-dihydromanzamine A, J *N*-oxide (4) showed H-bonding with His57 (Figure 6). His57 and Lys136 showed arene–H bonding with 3,4-dihydro-6-hydroxymanzamine A (6). It has been reported that the existence of the protease domain in full-length NS3 can modify substrate selectivity and improve the unwinding and binding of RNA.[73] Also, the helicase domain has been reported to enhance protease-domain activity when existing in full-length HCV NS3 protein,[74] as exemplified by polyuracil, which has been reported to stimulate protease activity of full-length NS3 but not the isolated protease domain.[75] Such activity was witnessed in our study with the compounds pyrinodemin D (7), and 3,4-dihydromanzamine A, J *N*-oxide (4), which had weak binding affinity with HCV NS3 protease enzymes, but were among the most active compounds inhibiting the full-length NS3–4A protease–helicase (Table 1). Additionally, it was concluded that protease improved helicase activity and

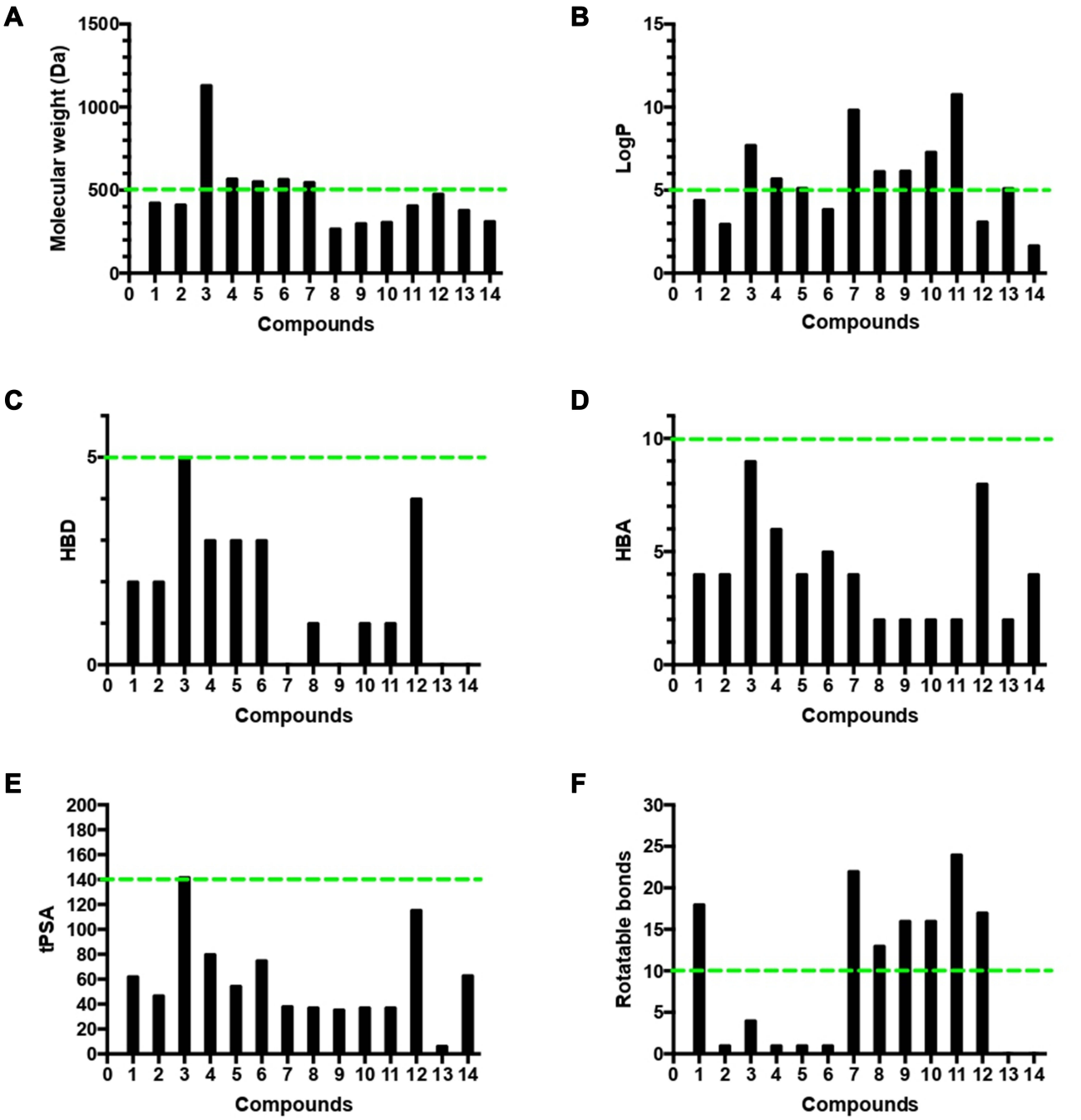

Figure 7 Analysis of physicochemical properties for the 14 isolated compounds by (**A**) molecular weight, (**B**) log P, (**C**) HBD, (**D**) HBA, (**E**) tPSA, and (**F**) number of rotatable bonds. The green line indicates the maximum desirable value for oral bioavailability defined by Lipinski's rule of five and Veber's oral bioavailability rule.

vice versa,[74] which might have contributed to the increased binding affinity of pyrinodemin D (7) with the full-length NS3–4A protease–helicase, despite exhibiting weak interactions with the isolated protease domain but strong inhibitory activity with the isolated helicase domain.

From this study, we can conclude that pyrinodemin D (7) and nakinadine B (1) can serve as potential anti-HCV drug candidates, owing to their observed strong inhibitory activity against the NS3–4A protease–helicase enzyme. The in silico results were substantiated by in vitro assays in which inhibitory activity against HCV replicons was recorded for pyrinodemin D, nakinadine B, and 3,4-dihydro-6-hydroxymanzamine A (IC 5.8, 15.6, and 17.2 μg/mL, respectively) the most active compounds. However, the rest of the compounds exhibited IC_{50} values >200 μg/mL.

Accordingly, our results highlighted pyrinodemin D, nakinadine B, and 3,4-dihydro-6-hydroxymanzamine A as the most promising anti-HCV drug leads. Since therapeutic agents must possess appropriate physicochemical properties for cell penetration and delivery to the target organ, we analyzed the four Lipinski properties and two additional descriptors — tPSA and numbers of rotation bonds for the 14 isolated compounds — to assess their oral bioavailability in humans (Table S2, Figure 7). We estimated Lipinski's rule of five, which defines four simple physicochemical parameter ranges (MW ≤500, logP ≤5, HBD ≤5, and HBA ≤10)[76] for orally active compounds and Veber's oral bioavailability rule, which includes two additional parameter ranges (tPSA ≤140 Å, number of rotatable bonds ≤10).[77] The results indicated that 71% (ten of 14) of the isolated compounds followed Lipinski's rule of five with less than one violation: MW ≤500 Da (nine of 14, Figure 7A), logP ≤5 (five of 14, Figure 7B), HBD ≤5 (14 of 14, Figure 7C), HBA ≤10 (14 of 14, Figure 7D), tPSA ≤140 Å (13 of 14) (Figure 7E), and number of rotation bonds ≤10 (five of 14) (Figure 7F). The active anti-HCV compound nakinadine B (1) was found to perfectly obey the rule of five and the rule of tPSA, and 3,4-dihydro-6-hydroxymanzamine A (6) violated only the MW rule with 566 Da, indicating their high potential to be promising anti-HCV drug candidates with good oral bioavailability and penetration power. However, the most active compound, pyrinodemin D (7), violated both the MW and logP rules, indicating its poor oral bioavailability.

Conclusion

This study presented a green synthesis of SNPs from total extract and petroleum ether fraction of *Amphimedon* with potent in vitro anti–HCV NS3 helicase and protease activity. A diverse phytochemical class of natural products was identified using LCMS-based metabolic investigation, followed by the identification of 14 known compounds via bioassay-guided isolation. Docking studies of the identified compounds postulated their mechanism of action, which was further evidenced by in vitro assays. Among the *Amphimedon* sponge phytochemicals, nakinadine B and 3,4-dihydro-6-hydroxymanzamine A were noted as promising anti-HCV drug candidates, warranting future clinical investigation.

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Disclosure

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