

Anti-Inflammatory Potential of Green Synthesized Silver Nanoparticles of the Soft Coral *Nephthea* Sp. Supported by Metabolomics Analysis and Docking Studies

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Omnia Hesham Abdelhafez¹
Taha Farouk Shehata Ali² 
John Refaat Fahim³
Samar Yehia Desoukey³
Safwat Ahmed⁴
Fathy A Behery^{5,6}
Mohamed Salah Kamel³
Tobias AM Gulder⁷
Usama Ramadan Abdelmohsen^{1,3}

¹Department of Pharmacognosy, Faculty of Pharmacy, Deraya University, New Minia 61111, Egypt; ²Department of Medicinal Chemistry, Faculty of Pharmacy, Minia University, Minia 61519, Egypt; ³Department of Pharmacognosy, Faculty of Pharmacy, Minia University, Minia 61519, Egypt; ⁴Department of Pharmacognosy, Faculty of Pharmacy, Suez Canal University, Ismailia 41522, Egypt; ⁵Department of Pharmacognosy, Faculty of Pharmacy, Mansoura University, Mansoura 35516, Egypt; ⁶Department of Pharmaceutical Sciences, College of Pharmacy, Riyadh Elm University, Riyadh 11681, Saudi Arabia; ⁷Chair of Technical Biochemistry, Department of Chemistry and Food Chemistry, Technical University of Dresden, Dresden 01069, Germany

Correspondence: Usama Ramadan Abdelmohsen
Department of Pharmacognosy, Faculty of Pharmacy, Minia University, Minia 61519, Egypt
Email Usama.ramadan@mu.edu.eg

Tobias AM Gulder
Chair of Technical Biochemistry,
Department of Chemistry and Food
Chemistry, Technical University of Dresden,
Bergstraße 66, Dresden 01069, Germany
Email tobias.gulder@chemie.tu-dresden.de

Background: Soft corals have been endorsed as a plentiful source of bioactive compounds with promising anti-inflammatory activities; therefore, exploring their potential as source of anti-inflammatory metabolites has stimulated a growing research interest.

Purpose: To investigate the anti-inflammatory potential of the soft coral, *Nephthea* sp., in its bulk and silver nanostructure. Metabolomics analysis of *Nephthea* sp., followed by molecular docking studies, was also conducted in order to explore and predict the secondary metabolites that might provide its inhibitory actions on inflammation.

Materials and Methods: The petroleum ether and ethyl acetate fractions were used to synthesize silver nanoparticles. The prepared silver nanoparticles were characterized through UV-vis spectrophotometric, transmission electron microscopy (TEM) and Fourier-transform infrared spectroscopy (FTIR) analyses. Testing for the anti-inflammatory activity was performed against COX-1 and COX-2. Furthermore, liquid chromatography–mass spectrometry (LC–MS) based metabolomics analysis and molecular docking were also applied.

Results: A variety of secondary metabolites were identified, among them, sesquiterpenes were found to prevail. The petroleum ether and acetone fractions of *Nephthea* sp. showed the highest COX-2 inhibitory activities, possibly attributable to their substantial contents of terpenoids. Additionally, the green synthesized silver nanoparticles of both the petroleum ether and ethyl acetate fractions of *Nephthea* sp. demonstrated higher anti-COX-2 properties.

Conclusion: The obtained results showed the effectiveness of non-targeted metabolomics technique in metabolic profiling of *Nephthea* sp., helping the search for new bioactive metabolites in future chemical studies on this soft coral. The interesting anti-inflammatory potential of the tested extracts and their nanoparticles could also be relevant to the development of new, effective anti-inflammatory agents.

Keywords: anti-inflammatory, metabolomics, molecular docking, nanoparticles, *Nephthea*, soft coral

Introduction

Inflammation is a pathological condition that represents a part of our immune system response to harmful stimuli, eg, irritants, injured cells, and pathogens.¹ Recently, a variety of appalling chronic diseases have been proven to be associated with inflammation, such as rheumatoid arthritis,² atherosclerosis,³ diabetes,⁴ Alzheimer's,⁵

inflammatory bowel disease,⁶ and cancer.⁷ Inflammatory processes usually involve several cell types encompassing neutrophils, basophils, eosinophils, and mononuclear cells (eg, monocytes and macrophages).^{8–10} Some pro- and anti-inflammatory mediators are also commonly produced during inflammation, including cytokines, chemokines, tumor necrosis factor- α , and inducible enzymes, such as cyclooxygenase-2 (COX-2) and inducible NO synthase (iNOS), which play some key regulatory roles.^{1,11} Therefore, different mechanisms and mediators implicated in painful and inflammatory states have been the focus of numerous recent studies.¹² Additionally, in spite of the available arsenal of anti-inflammatory agents, typically represented by glucocorticoids, non-steroidal anti-inflammatory drugs, and immunosuppressants, the therapy seems to be not effective enough and is also constrained by many undesired side effects,^{13–15} deepening the need for discovering other new anti-inflammatory drug candidates.

Natural products represent a long-standing and fruitful source of ubiquitous drug leads, offering both noteworthy structural diversity and varied biological potential.¹⁶ Oceans, which cover about 70% of our earth's surface, have attracted a special interest owing to their exceptionally important biodiversity.¹⁷ To date, marine organisms have provided wide-ranging natural compounds with promising antimicrobial, antiviral, antimalarial, antitumor, antioxidant, and anti-inflammatory properties.^{18,19} Among them, soft corals, a group of marine invertebrates found within the coral reefs of most oceans, are a biochemical storeroom of important secondary metabolites, eg, sesquiterpenes,²⁰ diterpenes,²¹ and sterols,²² which are endowed with antifouling, antiviral, antitumor, and anti-inflammatory activities.^{23,24} In this regard, some potent anti-inflammatory molecules have been described from soft corals, exemplified by isoparalemnone, which was obtained from the Formosan soft coral *Paralemnalia thyrsoidea*. This sesquiterpene was reported to significantly inhibit the expression of inflammatory iNOS protein by 70% at 10 $\mu\text{mol/L}$ in activated RAW 264.7 cells.²⁵ Likewise, the sesquiterpene erectathiol isolated from *Nephthea erecta* KUKENTHAL displayed substantial in vitro anti-inflammatory actions, as indicated by the remarkable reduction in the levels of both iNOS and COX-2 proteins by 58.0 ± 6.5 and $108.7 \pm 4.5\%$, respectively.²⁶

On the other hand, the application of modern interdisciplinary scientific approaches has increasingly contributed to recent drug discovery, including among others, metabolomics and nanoscience. Metabolomics is a valuable analytical tool used in the comprehensive, high throughput determination of

metabolites in a given metabolome.²⁷ It has recently gained growing importance in chemical profiling of various natural sources, such as medicinal plants,²⁸ marine organisms,²⁹ and bacteria.³⁰ This privileged technique allows the rapid identification (dereplication) and quantification of secondary metabolites in crude unfractionated extracts; avoiding laborious chromatographic work and reducing the time wasted in the re-isolation of known compounds.³¹ In the same context, nanoscience has been established as a new interdisciplinary field that is concerned with the understanding and controlling of matter within the size range of 1–100 nm.¹¹ Nanomaterials typically enjoy unique physicochemical properties, eg, very small size, large surface area to mass ratio, and high reactivity, giving them superior bioactivities to bulk materials of identical composition. Thus, they have found wide applications in medical sciences mostly to innovate new therapeutic and diagnostic remedies.³²

Recently, there is a great interest in utilizing noble metals for nanoparticle production in different industrial and pharmaceutical aspects.³³ Chemical methods used in preparation of nanoparticles have shown numerous limitations, such as the formation, monodispersity of the particles, and thermodynamic stability.³⁴ On the other hand, green synthesis is a preferred approach due to lower toxicity, increased feasibility and safety.³⁵ Silver nanoparticles have attracted much interest owing to their applications in industrial and therapeutic approaches.^{34,36,37} Silver nanoparticles exhibited potent antibacterial potential against: gram positive, gram-negative, methicillin-resistant strains and also anti-biofilm properties.^{38,39} Das et al have demonstrated that green synthesis of silver nanoparticles from *Ocimum gratissimum* L. leaf extract gave material that exhibited anti-bacterial potential against *Escherichia coli*. It was also found as an effective inhibitor of bio-film formation in both types of strains through destroying the bacterial cell membrane followed by ROS production.³⁸ Additionally, silver nanoparticles prepared by *Rosa canina* had highly effective anti-oxidant, antibacterial, antifungal, and DNA cleavage activities.⁴⁰ Silver nanoparticles also exhibited potent cytotoxic potential against a panel of cell lines^{41,42} together with interesting anti-inflammatory potential,⁴³ larvicidal activity⁴⁴ and wound healing properties.⁴⁵

Green synthesis of nanoparticles using marine organisms is underexplored. The marine sponge *Acanthella elongata* has been used for the synthesis of silver nanoparticles, which was clearly confirmed by UV-visible spectrum, TEM analysis, FT-IR and X-ray diffraction.⁴⁶ The red algae *Gelidium corneum* extract acted as a reducing agent in the synthesis of silver nano samples. The formed

nanoparticles showed potent anti-biofilm efficacy.⁴⁷ Additionally, the silver nanoparticles formed from the red algae *Spyridia filamentosa* exhibited potent antibacterial activity against *Staphylococcus* sp. and *Klebsiella* sp. and cytotoxic potential against MCF-7 cell lines.⁴⁸

Few studies have been conducted to evaluate the anti-inflammatory potential of green synthesized silver nanoparticles with their possible mechanism of action.⁴⁹ Although, the green synthesis of nanoparticles has attracted great attention in the last few decades, till now, no studies have been conducted to evaluate the anti-inflammatory activity of soft corals. Our study aims to investigate the in-vitro anti-inflammatory potential against COX-1 and COX-2 of the crude extract and its derived fractions, as well as, the green synthesized silver nanoparticles from *Nephthea* sp. petroleum ether and ethyl acetate fractions. Furthermore, we utilized an untargeted metabolomics approach to unveil the chemical profile of the total extract and different fractions of the soft coral; *Nephthea* sp. using liquid chromatography coupled with high-resolution electrospray ionisation mass spectrometry (LC–HR–ESI–MS), followed by docking analysis of all the dereplicated compounds to explore the chemical constituents that might contribute to the anti-inflammatory potential.

Materials and Methods

Soft Coral Material

The soft coral *Nephthea* sp. was collected by Prof. Safwat Ahmed, Professor of Pharmacognosy, Faculty of Pharmacy, Suez Canal University, Egypt, by scuba diving from the Egyptian coasts of the Red Sea at Sharm el-Sheikh at a depth of 10 m. It was then stored at –20°C until investigation. The animal biomass was identified by Dr. Tarek Temraz, Marine science Department, Faculty of Science, Suez Canal University, Ismailia, Egypt. A voucher specimen was deposited in the herbarium section of Pharmacognosy Department, Faculty of Pharmacy, Suez Canal University, Ismailia, Egypt under registration number SAA-26.

Chemicals and Reagents

Organic solvents used in this study, including n-butanol, ethyl acetate, acetone, dichloromethane, and petroleum ether (b.p. 60–80 °C) were of analytical grade and distilled prior to use. Dimethylsulfoxide (DMSO) was used in the preparation of silver nanoparticles. All these solvents were purchased from El-Nasr Company for Pharmaceuticals and Chemicals, Egypt. Solvents of HPLC grade such as acetonitrile and methanol were obtained from SDFCL sd fine-Chem

Limited, India. Both silver nitrate (AgNO₃; purity ≥ 99.5%) and the ion exchange resin were purchased from Sigma-Aldrich, Germany. Celecoxib and indomethacin were purchased from Sigma-Aldrich, Germany and used as standard anti-inflammatory drugs.

Extraction and Fractionation

The collected soft coral was freeze-dried, then extracted with methylene chloride – methanol (1:1) until exhaustion.⁵⁰ The concentrated organic extract (24.0 g) was suspended in distilled water and extracted successively with different organic solvents, including petroleum ether, ethyl acetate and n-butanol. The remaining mother liquor was deprived of its content of sugars and salts by an ion exchange resin using acetone. The organic phase in each step was separately concentrated under vacuum, yielding the petroleum ether fraction I (10.0 g), the ethyl acetate fraction II (3.0 g), the n-butanol fraction III (3.0 g), and the acetone fraction IV (200.0 mg). The total extract and its derived fractions were kept at 4°C for metabolomics and biological investigation.⁵¹

Synthesis of Silver Nanoparticles (SNPs)

The green silver nanoparticles were prepared by separately dissolving 0.005 g of each of the petroleum ether and ethyl acetate fractions in 1 mL DMSO. Then, 0.2 mL of each sample solution were added to 10 mL of 1 mM AgNO₃ and the reaction mixture was kept for 48 h at room temperature.⁵² Unfortunately, both the n-butanol and acetone fractions failed to be converted into nanoparticles, as clearly confirmed by monitoring the color change of the reaction mixtures during their preparation.

Characterization of the Synthesized SNPs by Transmission Electron Microscopy (TEM)

For TEM analysis, a drop of the silver nanoparticles' solution was added on a copper grid and coated with a carbon support film. After complete drying, the shape and size of SNPs were investigated utilizing a Transmission Electron Microscope (Jeol model JEM-1010, USA) at The Regional Center for Mycology and Biotechnology, Al-Azhar University, Cairo, Egypt.

Characterization of the Synthesized SNPs by UV-Visible Analysis

UV-visible analysis was performed to observe the development of SNPs. The analysis was achieved by using a

double beam V-630 spectrophotometer, Jasco, Japan at the Faculty of Pharmacy, Ain-Shams University, Cairo, Egypt at the wavelength range of 200–600 nm.

Characterization of the Synthesized SNPs by Fourier-Transform Infrared Spectroscopy (FTIR)

A FT-IR-8400S, IR Prestige-21, IR Affinity-1, Shimadzu, Japan, at the Faculty of Pharmacy, Cairo University, Cairo, Egypt, was employed for characterization of the possible functional groups attached to the surface of SNPs.

Determination of Particle Size Distribution (Z-Average Mean) by Zeta Sizer Using DLS Technique

The nanoparticles particle size distribution was studied using a Zeta-sizer Nano ZS (Malvern instruments) in a disposable cell at 25°C, and the results were analyzed using Zeta-sizer 7.01 software, United Kingdom.

Metabolomics Analyses

Metabolic profiling of the methylene chloride-methanolic extract of the soft coral; *Nephthea* sp. and its derived fractions was carried out as described by Abdelmohsen et al.^{31,51} using an Acquity Ultra Performance Liquid Chromatography system connected to a Synapt G2 HDMS quadrupole time-of-flight hybrid mass spectrometer (Waters, Milford, USA). Chromatographic separation was carried out using a BEH C18 column (2.1 × 100 mm, 1.7 µm particle size; Waters, Milford, USA) accompanied with a guard column (2.1 × 5 mm, 1.7 µm particle size). The mobile phase used during the separation consisted of purified water (A) and acetonitrile

(B) with 0.1% formic acid added to each solvent. A gradient elution started at a flow rate of 300 µL/min with 10% B linearly increased to 100% B within 30 min and remained isocratic for the next 5 min before linearly decreasing back to 10% B for the following 1 min. The volume injected was 2 µL and the column temperature was adjusted to 40°C. The obtained raw data were separated into positive and negative ionization mode using MSConvert software. Accordingly, the files were imported to the data mining software MZmine 2.10 for peak picking followed by deconvolution, deisotoping, alignment, and formula prediction. Dictionary of Natural Products (DNP) and Marinlit databases were used for the identification of compounds.^{53,54}

Anti-Inflammatory Activity

The anti-inflammatory activity (IC₅₀ values in µM) of the total extract and different fractions of *Nephthea* sp. against ovine COX-1 and human recombinant COX-2 enzymes was determined by measuring prostaglandin F_{2α} (PGF_{2α}) using a COX Inhibitor Screening Kit (Catalog No 560,131) from Cayman Chemical, Ann Arbor, Michigan, USA following the procedure suggested by the manufacturer.⁵⁵

Molecular Docking Study

The X-ray structures of COX-1 (using the pdb entry 5WBE cocrystallized with mofezolac)⁵⁶ and COX-2 (using the pdb entry 5KIR cocrystallized with rofecoxib)⁵⁷ were retrieved from protein data bank and used in the present docking study. The structure preparation module in MOE 2019.01 (Chemical Computing Group, Montreal, QC, Canada) was applied in the preparation of the protein structures.⁵⁸ All water molecules were removed from the structure. For both COX isoforms, the co-crystallized ligand was defined as the

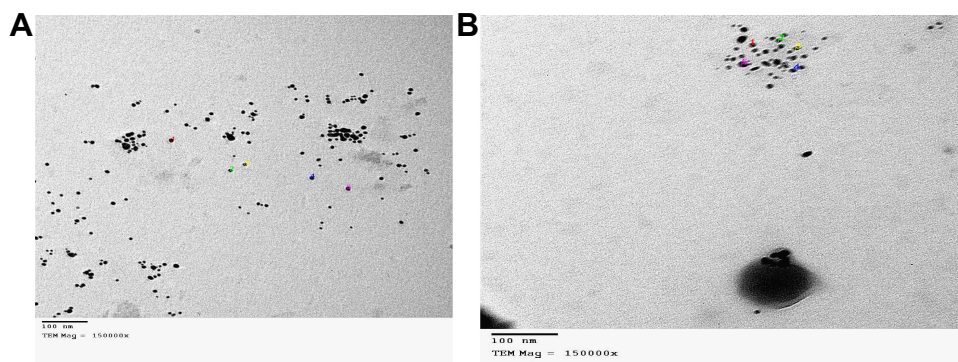


Figure 1 TEM photos of the formed silver nanoparticles of the petroleum ether (A) and ethyl acetate (B) fractions of *Nephthea* sp.

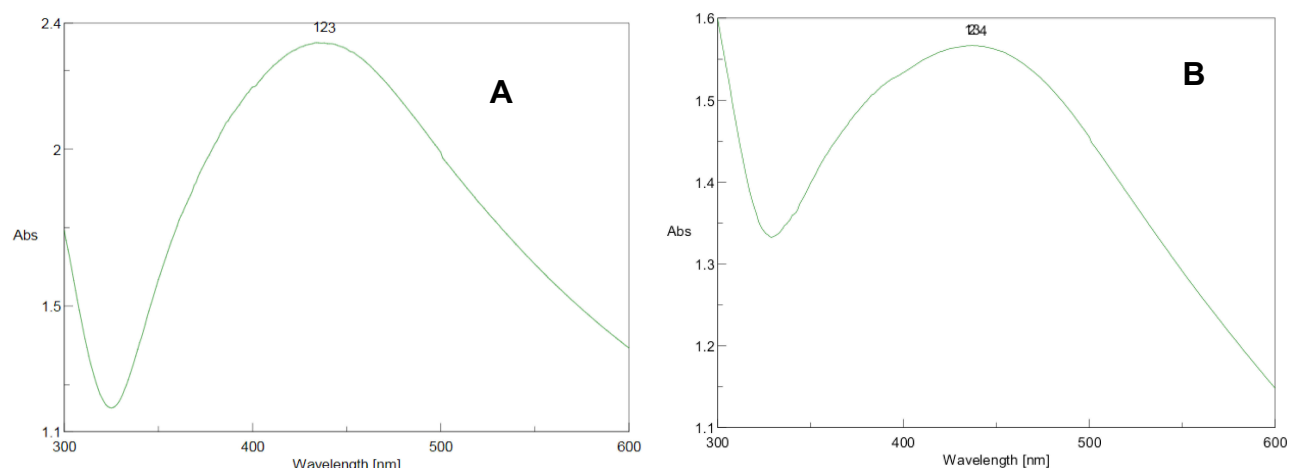


Figure 2 UV-Vis spectra after synthesis of nanoparticles using the petroleum ether (A) and ethyl acetate (B) fractions of *Nephthea* sp.

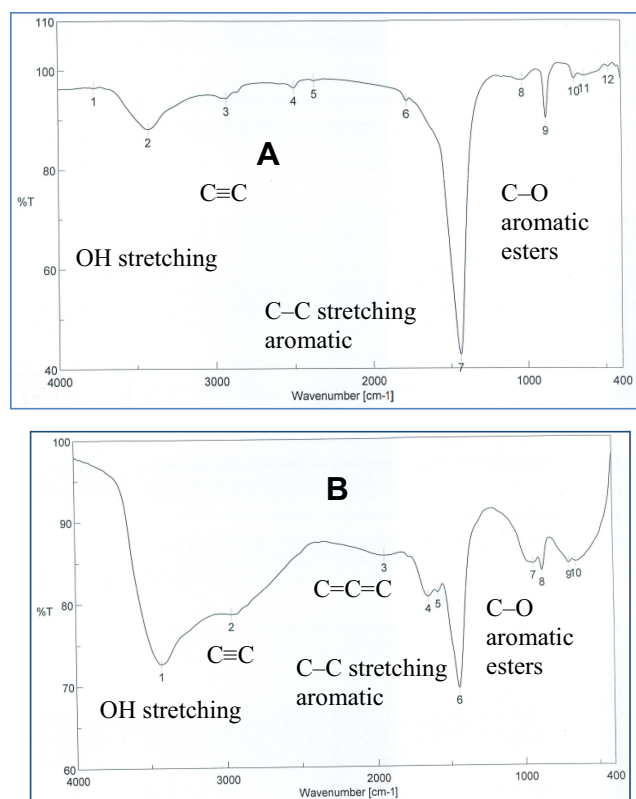


Figure 3 FTIR spectra after synthesis of nanoparticles using the petroleum ether (A) and ethyl acetate (B) fractions of *Nephthea* sp.

center of the binding site. All the identified compounds (1–10) were docked using the rigid-receptor method.⁵⁹ Three hundred docking poses were calculated for each compound. All other options were left at their default standards. The co-crystallized ligand was also docked with other compounds for validation of the docking method. The resulting docking poses were visualized using MOE 2019.01.

Results and Discussion

Synthesis and Characterization of SNPs

Treatment of the petroleum ether and ethyl acetate fractions of *Nephthea* sp. with 1mM AgNO₃ has markedly changed their colors to brown, which is an early sign for SNPs formation as represented in (Figure S1). Such a color transition is due to the excitation of surface plasmon, its vibrations and the reduction of the Ag⁺ to Ag⁰ by some of the secondary metabolites present in the petroleum ether and ethyl acetate fractions.^{52,60,61}

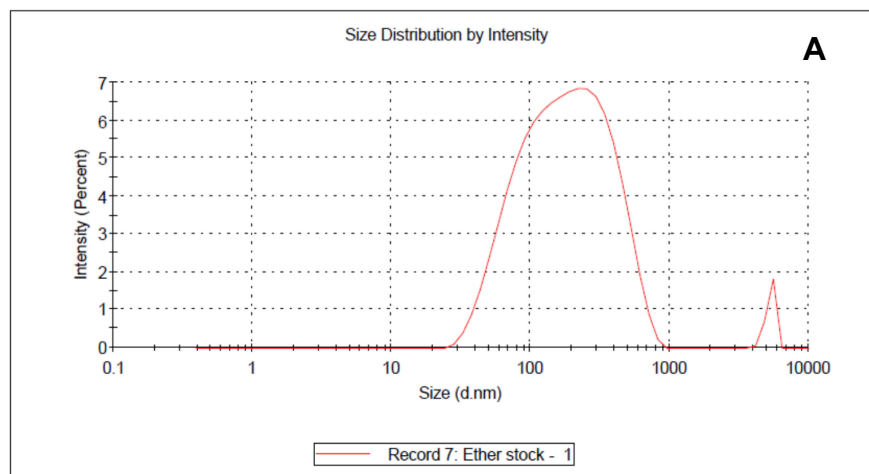
TEM Characterization of the Synthesized SNPs

TEM analysis was used to investigate the size and shape of the petroleum ether and ethyl acetate fractions of *Nephthea* sp. nano-samples. The green synthesized silver nanoparticles were spherical in shape with mean size ranges of 8.59–11.19 and 5.28–8.34 nm for the petroleum ether and ethyl acetate fractions, respectively (Figure 1A and B).

UV-Vis Characterization of the Synthesized SNPs

The formation of silver nanoparticles was depicted by UV-Vis spectrometry as one of the most broadly utilized approaches for structural characterization of silver nanoparticles.⁵² Therefore, the formation and optimization of SNPs were observed by measuring the absorbance in the range of 200–600 nm. Consequently, an absorbance band was observed at 417 nm, which is similar to that reported in the literature (Figure 2).^{62,63}

	Size (d.nm):	% Intensity:	St Dev (d.nm):
Z-Average (d.nm): 157.0	Peak 1: 219.2	97.4	149.7
Pdl: 0.490	Peak 2: 5318	2.6	385.1
Intercept: 0.862	Peak 3: 0.000	0.0	0.000
Result quality: Good			



	Size (d.nm):	% Intensity:	St Dev (d.nm):
Z-Average (d.nm): 178.3	Peak 1: 258.0	93.2	158.1
Pdl: 0.451	Peak 2: 4905	3.9	672.4
Intercept: 0.917	Peak 3: 23.51	2.9	6.527
Result quality: Good			

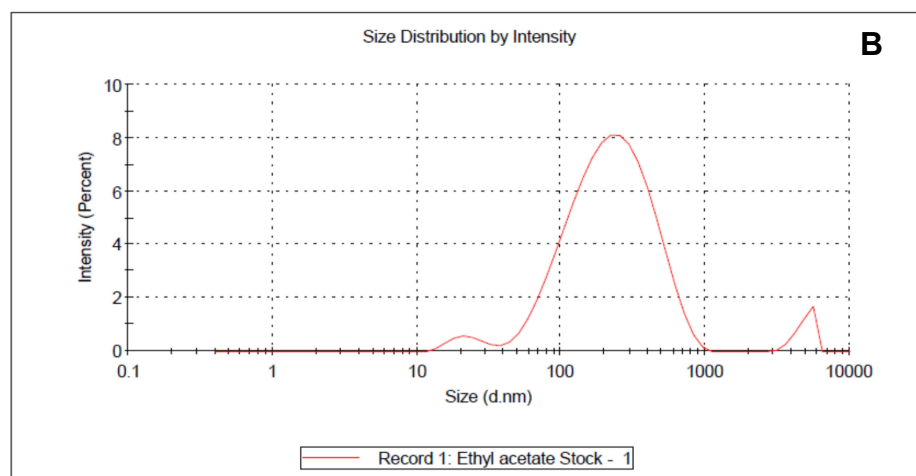


Figure 4 Dynamic light scattering analysis of synthesized SNPs (A) Pet. ether nano extract, (B) ethyl acetate nano extract.

FTIR Characterization of the Synthesized SNPs

FTIR measurements were carried out to explore the biomolecules' functional groups accountable for the reduction of silver ions and capping of SNPs.⁶⁴ The obtained FTIR spectra demonstrated various absorption

bands at 3572.17, 3421.72, 3414, 3390.86, 2083.12, 1913.39, 1643.35, 1635.64, 1392.61, 1284.59, 1246.02, 1222.87, 1076.28, 505.35, 470.63, 450.06, 435.91, and 428.20 cm^{-1} (Figure 3A and B). Among them, the absorption bands in the range of 3200–3500 cm^{-1} were assigned as –OH stretching for

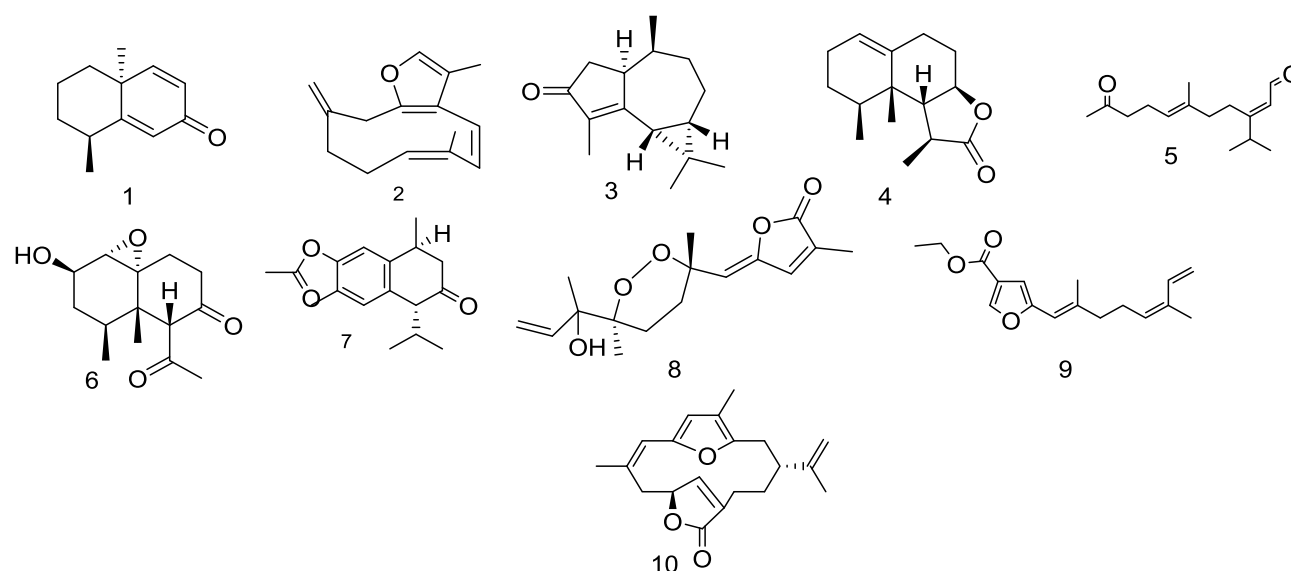


Figure 5 Chemical structures of the dereplicated metabolites from *Nephthea* sp. (Stereochemistry was shown as predicted from MarinLit).

alcohols and phenols. Another absorption band at 2083.12 cm^{-1} could be assigned for the triple bond stretching. Moreover, the absorption band at 1913.39 cm^{-1} was characteristic for an allene group, whereas the absorption bands 1643.35 , 1635.64 cm^{-1}

could be assigned for alkene stretching. The absorption band at 1392.61 cm^{-1} was also characteristic for C–C stretching in aromatic rings, while those at 1284.59 and 1246.02 cm^{-1} were distinctive for C–O stretching of aromatic esters. Furthermore, the absorption bands at

Table 1 In vitro COX-I and COX-2 Inhibitory Activities of the Crude Extract and Different Fractions of *Nephthea* Sp., Along with Their Selectivity Ratio

Extract/Fraction	COX-I (IC_{50} in $\mu\text{g/mL}$)	COX-2 (IC_{50} in $\mu\text{g/mL}$)	Selectivity Ratio (COX2/COX1)
Total extract	33.72	46.75	1.38
Petroleum ether fraction	381.96	27.43	0.07
Ethyl acetate fraction	100.51	141.20	1.40
n-Butanol fraction	254.66	39.33	0.15
Acetone fraction	399.69	36.15	0.09
Petroleum ether nano fraction	494.20 ± 16.34	3.34 ± 0.19	147.96
Ethyl acetate nano fraction	714.47 ± 22.59	4.53 ± 0.24	157.71
AgNO_3	249.86 ± 9.26	4.38 ± 0.26	57.04
Celecoxib	119.97	5.63	0.04
Indomethacin	127.57	52.24	0.40

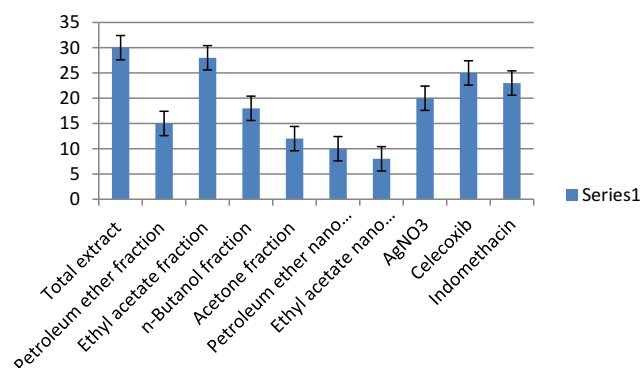


Figure 6 In-vitro anti-COX-I potential of the tested samples.

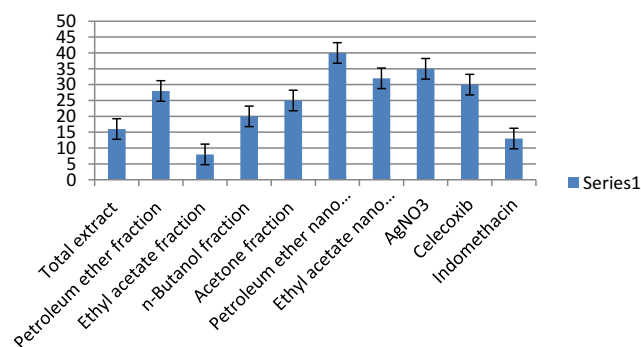


Figure 7 In-vitro anti-COX-2 potential of the tested samples.

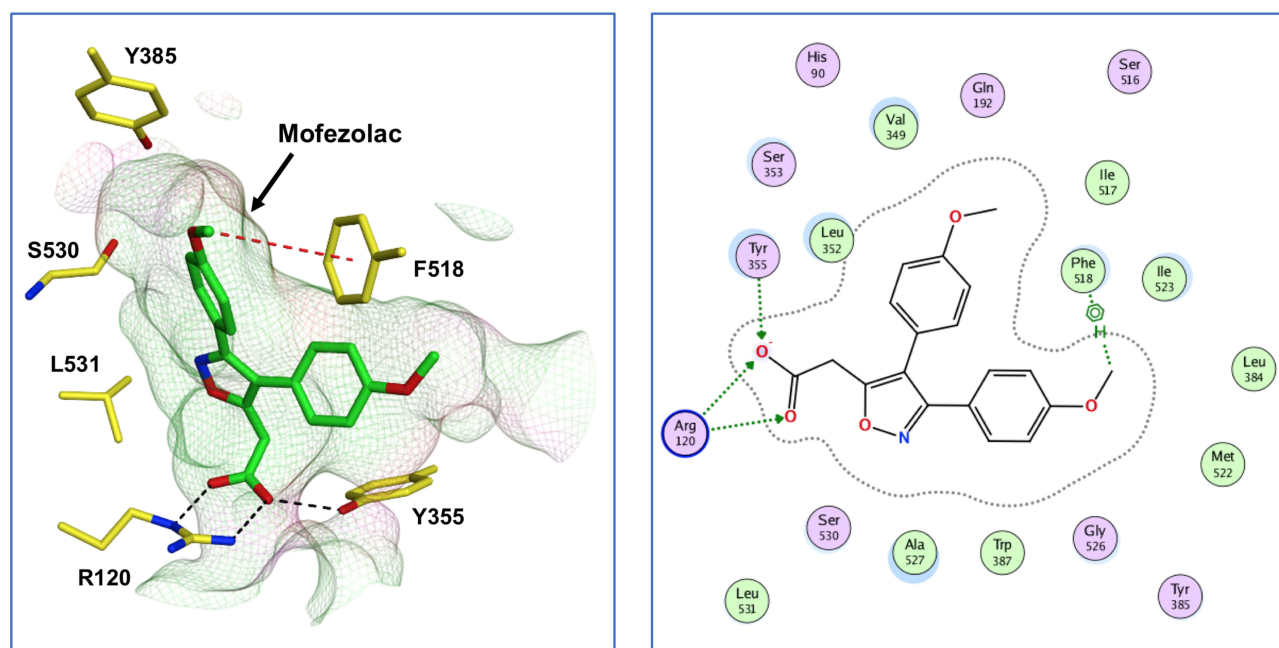


Figure 8 3D and 2D plots of the poses of Mofezolac in the binding pocket of COX-I.

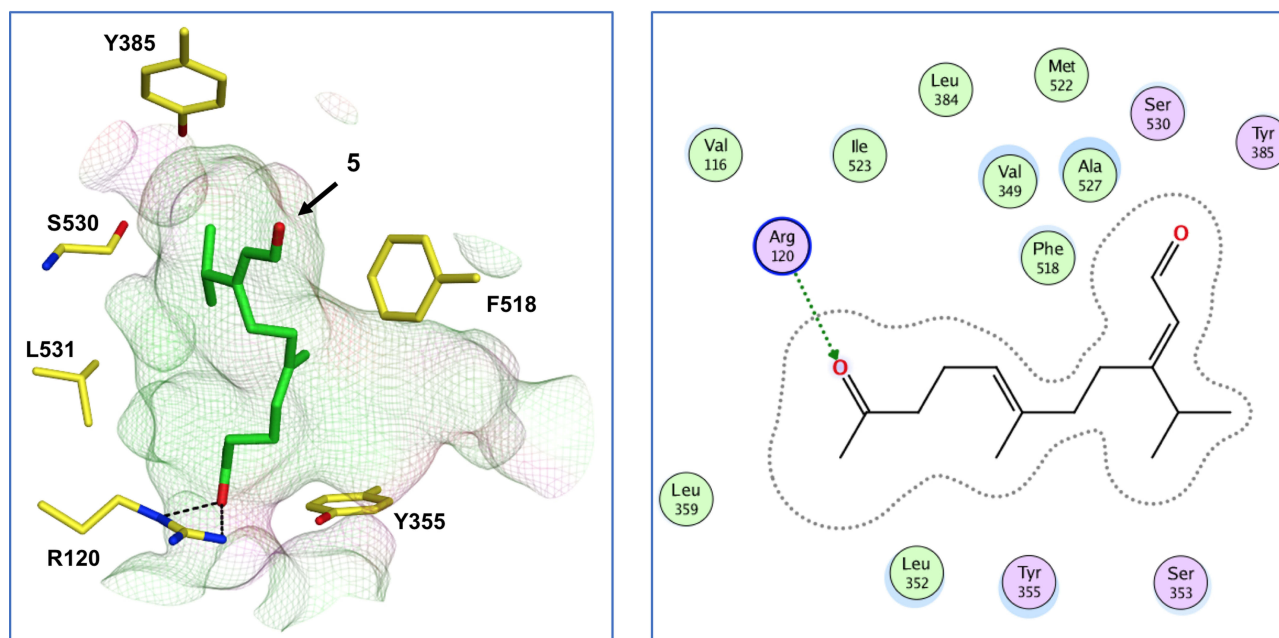


Figure 9 3D and 2D plots of the poses of compound 5 in the binding pocket of COX-I.

1222.87 and 1076.28 cm^{-1} were typical for C–O stretching of secondary and primary alcohols,^{65–67} respectively. In this regard, the observed absorption bands in the FTIR analysis could be mainly attributed to terpenoids having the main functional groups,

including ketones, aldehydes, carboxylic acids, and others. Such bioactive metabolites interact with metal ions (Ag^+) through these functional groups, mediating their reduction to nanoparticles (Ag^0) and increasing the stability of the resulting nanoparticles.^{64,68}

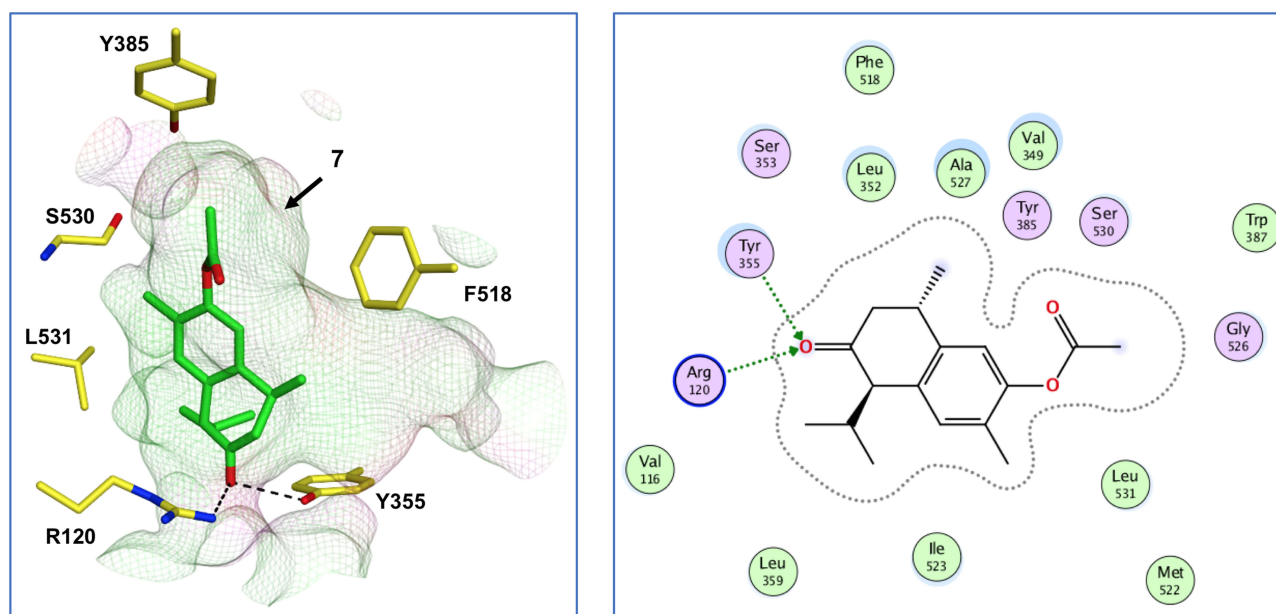


Figure 10 3D and 2D plots of the poses of compound 7 in the binding pocket of COX-I.

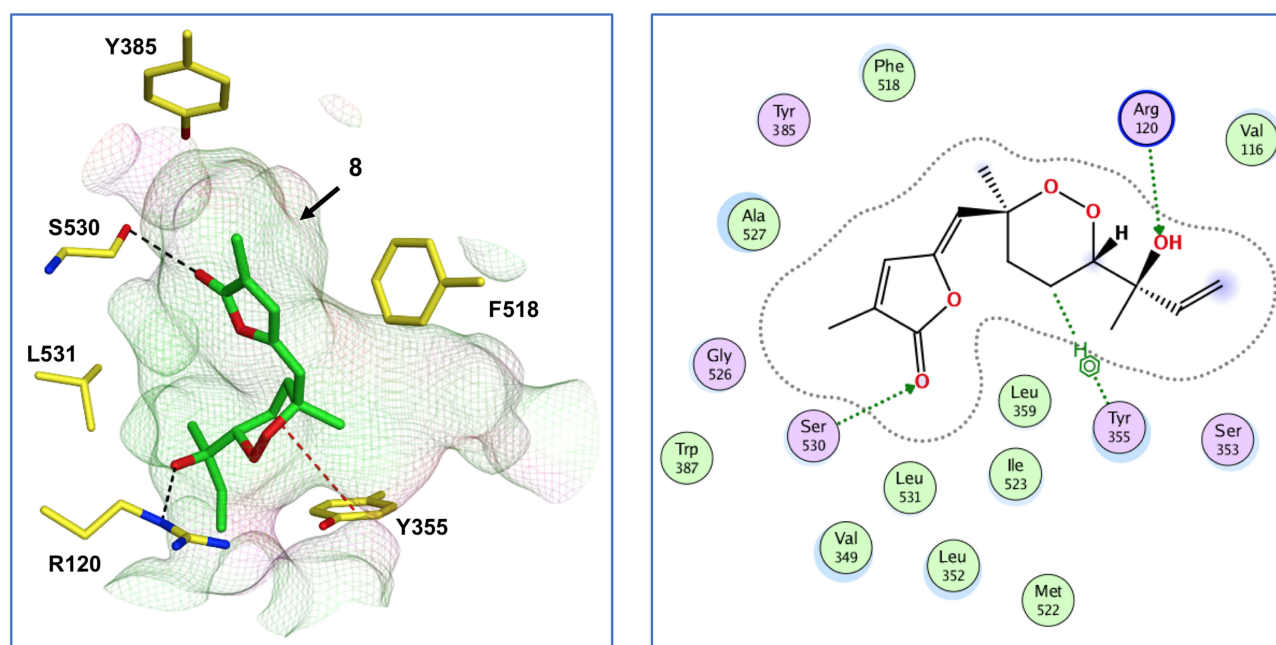


Figure 11 3D and 2D plots of the poses of compound 8 in the binding pocket of COX-I.

Determination of the Nanoparticles Particle Size Distribution (Z-Average Mean) of the Pet. Ether and Ethyl Acetate Samples of *Nephthea* Sp. SNPs

The z-average mean (d.nm) in case of pet. ether nano extract was 157 with a polydispersity index (PDI) 0.490 and in case

of ethyl acetate nano extract with the z-average is 178.3 with a polydispersity index (PDI) 0.451. The morphology and dimensions of the biosynthesized SNPs were initially characterized using TEM image as shown in (Figure 1A and B) with an average size ranging from 8.34 nm to 11.19 nm. Additionally, the mean particle size determined by TEM analysis was significantly smaller than that measured by

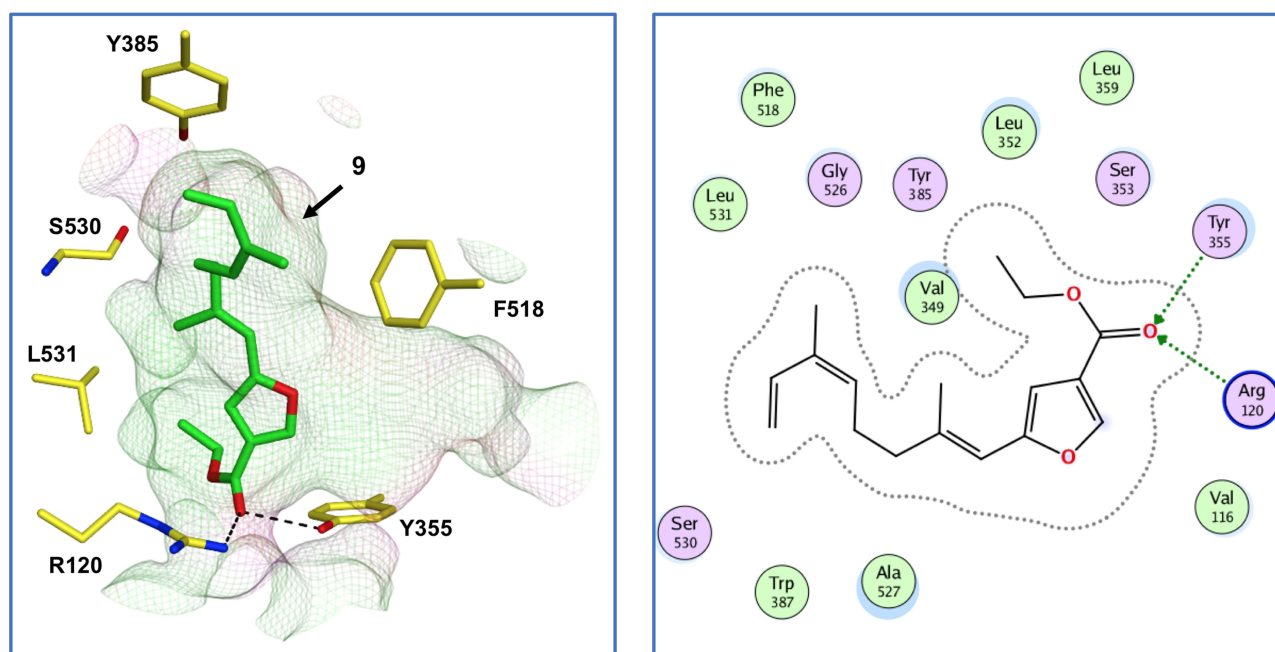


Figure 12 3D and 2D plots of the poses of compound 9 in the binding pocket of COX-1.

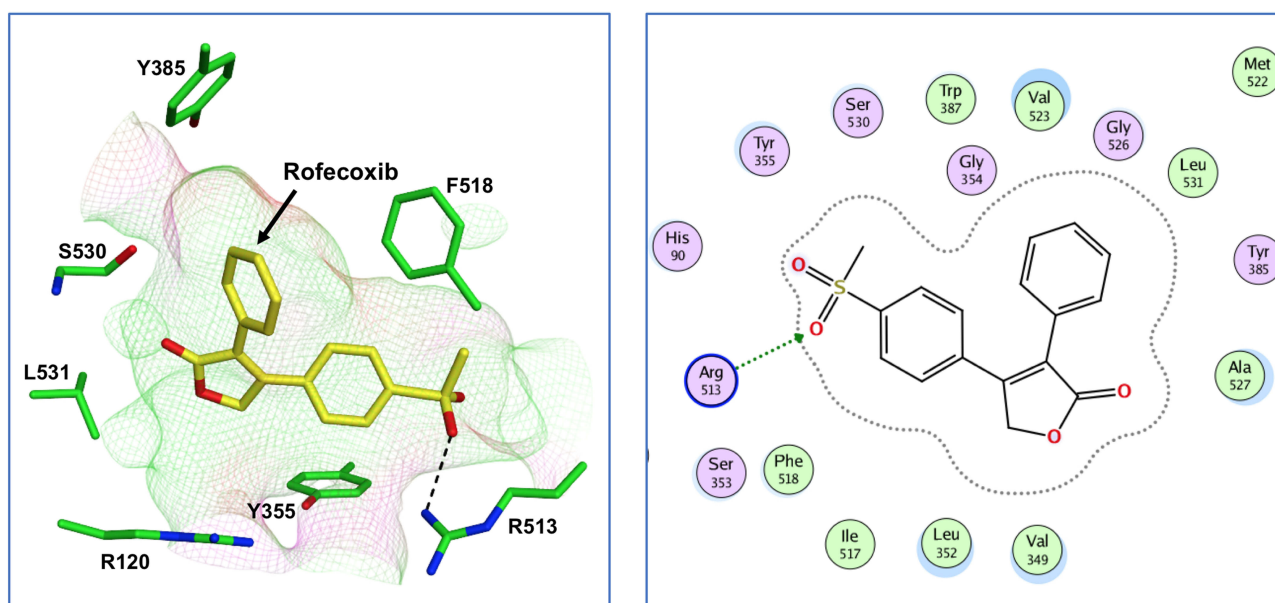


Figure 13 3D and 2D plots of the poses of Rofecoxib in the binding pocket of COX-2.

DLS analysis (Figure 1A and B & Figure 4A and B). This could be possibly due to the adsorption of organic stabilizers from the extract on the surface of SNPs and the aggregation of some small particles.⁶⁹

Metabolomics Profiling of the Soft Coral *Nephthea* Sp

Metabolomics analysis of *Nephthea* sp. using LC–HR–ESI–MS for dereplication purposes has resulted in the identification

of a range of diverse secondary metabolites that were dominated by sesquiterpenoids. The detected compounds (Figure 5, Table S1) were identified by coupling MZmine with some databases, namely Marinlit and DNP. In view of that, the mass ion peak at m/z 175.112 for the suggested molecular formula $C_{12}H_{16}O$ was identified as (4aS, 8S)-5, 6, 7, 8-tetrahydro-4a, 8-dimethylnaphthalen-2(4aH)-one (1). This trinor-udesmadienone sesquiterpene was previously reported from the soft coral *N. erecta*.⁷⁰ Moreover, the mass ion peak at m/z

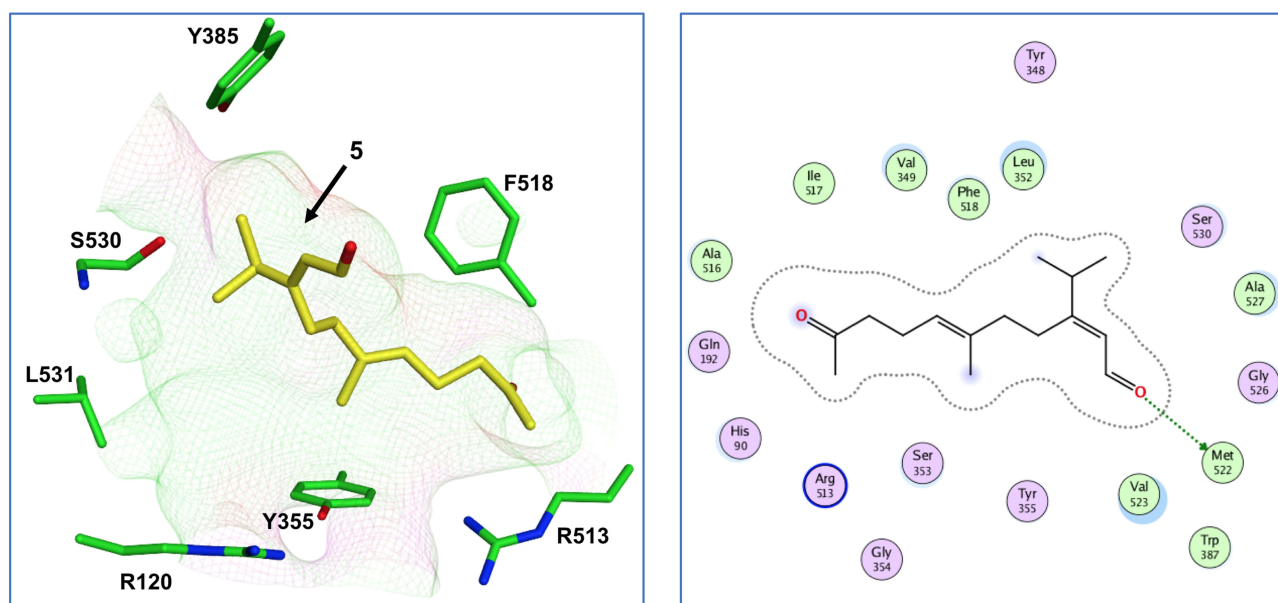


Figure 14 3D and 2D plots of the poses of compound 5 in the binding pocket of COX-2.

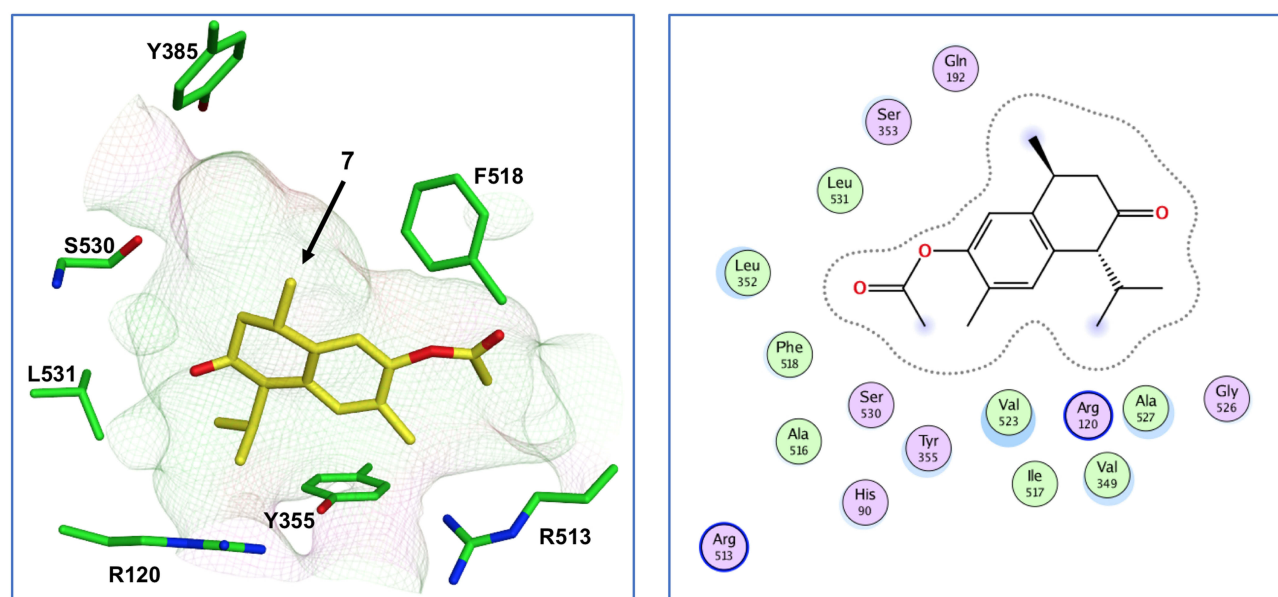


Figure 15 3D and 2D plots of the poses of compound 7 in the binding pocket of COX-2.

215.144 for the predicted molecular formula $C_{15}H_{18}O$ was also dereplicated as the germacranes sesquiterpene furanotriene (**2**), which was formerly obtained from the Formosan soft coral *Lemnalia* sp.⁷¹ Another mass ion peak at m/z 217.159, corresponding to the molecular formula $C_{15}H_{22}O$ was dereplicated as (+)-cyclocolorenone (**3**). This tricyclic sesquiterpene was earlier isolated from different members of the genus *Nephthea*, eg, *N. chabrolii* AUDOIN.⁷² Additionally, another nardosinane sesquiterpene with the molecular formula $C_{15}H_{22}O_2$, in good agreement with the mass ion peak at m/z 233.154, was

characterized as lemnalactone (**4**). This compound was firstly identified from the soft coral *Paralemnalia digitiformis* Macfadyen.⁷³ Similarly, a sec-germacranes sesquiterpene was dereplicated as (2*E*, 6*E*)-3-isopropyl-6-methyl-10-oxoundec-2,6-dienal (**5**), in conformity with the mass ion peak at m/z 235.170 and the molecular formula $C_{15}H_{24}O_2$. This molecule was reported formerly from the soft coral *N. erecta*.²⁶

Furthermore, the mass ion peak at m/z 251.127, corresponding to the suggested molecular formula $C_{14}H_{20}O_4$, was characterized as 1(10)-epoxy-2-hydroxy-12-nornardosin-7,11-

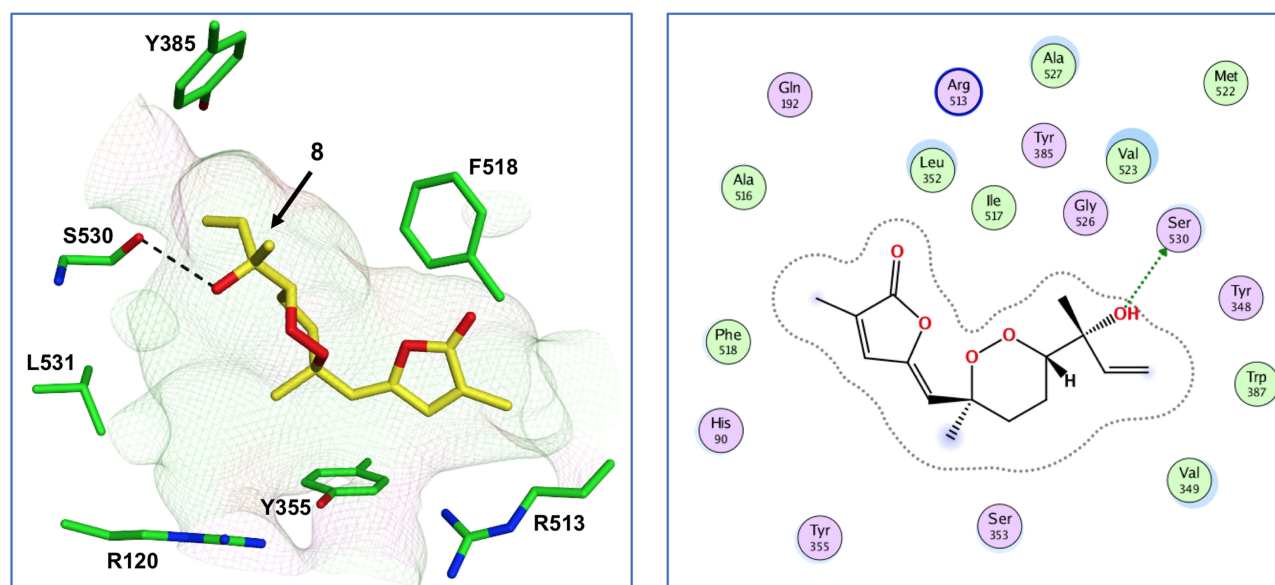


Figure 16 3D and 2D plots of the poses of compound 8 in the binding pocket of COX-2.

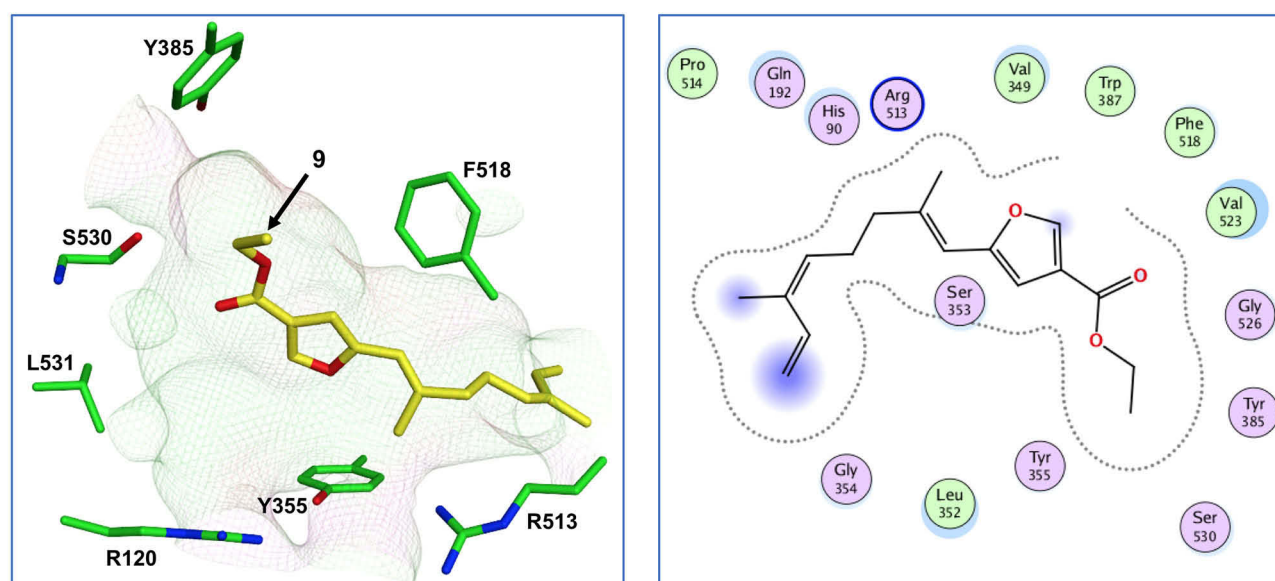


Figure 17 3D and 2D plots of the poses of Sinularioperoxide E in the binding pocket of COX-2.

dione (**6**), a sesquiterpene that was previously obtained from the genus *Lemnalia*, eg. *L. africana* May, which belongs to the family Nephtheidae.⁷⁴ Another compound was dereplicated as 7-acetoxycalamenen-3-one (**7**) on account of the observed mass ion peak at m/z 273.148, and in accordance with the molecular formula $C_{17}H_{22}O_3$. This sesquiterpene was also formerly reported from *Lemnalia cervicornis* May.⁷⁵ In addition to the aforementioned sesquiterpenes, a furanocarboxylate derivative, namely ethyl 5-[(1*E*, 5*Z*)-2, 6-dimethylocta-1, 5, 7-trienyl] furan-3-carboxylate (**8**), was dereplicated from the

mass ion peak at m/z 275.163, in consonance with the molecular formula $C_{16}H_{22}O_5$. This molecule was formerly obtained from the soft corals *Simularia gonatodes* Kolonko⁷⁶ and *Capnella fungiform* Kükenthal.⁷⁷ Additionally, the mass ion peak at m/z 281.138, in keeping with the molecular formula $C_{15}H_{20}O_5$, was dereplicated as the sesquiterpene sinularioperoxide E (**9**), which was purified from *Simularia* sp.⁷⁸ Additionally, a cembrane diterpenoid compound with the molecular formula $C_{20}H_{24}O_3$ was characterized as rubifolide (**10**) from the mass ion peak at m/z 313.164. It was also

previously isolated from the soft coral *Gersemia rubiformis* Ehrenberg.⁷⁹

Anti-Inflammatory Activity

Soft corals of the genus *Nephthea* have been regarded as a pool of a diverse array of secondary metabolites, of which steroids and terpenoids were reported to prevail.⁸⁰ Studies have also shown that these metabolites markedly contribute to the promising anti-inflammatory potential of these soft corals.⁸¹ In this respect, the ability of the total extract and different fractions of *Nephthea* sp., to inhibit the enzymatic activity of COX-1 and COX-2 was evaluated. The potency (IC₅₀ values) of the tested samples was determined and compared to those of the reference drugs; celecoxib and indomethacin. As shown in Table 1, Figures 6 and 7, the obtained results revealed that some of the tested samples exhibited inhibitory activities towards the isoforms of COX enzyme. Among them, only the total extract of *Nephthea* sp. showed COX-1 inhibitory potential with an IC₅₀ value of 33.72 µg/mL, which is more potent than celecoxib and indomethacin, whereas the petroleum ether, ethyl acetate, n-butanol, and acetone fractions exhibited weak activities (IC₅₀ > 100 µg/mL). On the other hand, the petroleum ether fraction displayed the maximum inhibitory actions against COX-2 compared to indomethacin, with an IC₅₀ value of 27.43 µg/mL, followed by the acetone and n-butanol fractions, and the total extract, whereas the ethyl acetate fraction exhibited a weak activity against COX-2 (IC₅₀ > 100 µg/mL).

In the same context, the anti-inflammatory potential of the green synthesized SNPs of the petroleum ether and ethyl acetate fractions were investigated. The petroleum ether fraction demonstrated more potent COX-2 inhibitory actions with an IC₅₀ value of 3.34 µg/mL, followed by the ethyl acetate fraction with IC₅₀ of 4.53 µg/mL. In terms of IC₅₀ values, both the tested nanosamples showed higher inhibitory activities against COX-1 and COX-2 enzymes than the reference anti-inflammatory drugs; celecoxib and indomethacin with IC₅₀ values of 119.97, 5.63, 127.57 and 52.24 µg/mL, respectively.

Since NPs have a large surface area to volume ratio, it is supposed that they are better at blocking pro-inflammatory cytokines and inflammation assisting enzymes when compared to their bulk samples. Moreover, Ag NPs suppress production of pro-inflammatory cytokines like IL-12 and TNF-α and also cause a reduction in COX-2 gene expression at higher concentrations which assist in achieving its anti-

inflammatory potential.⁴⁹ To the best of our knowledge, and based on the available literature survey, this work represents the first study of the anti-inflammatory potential of green synthesized silver nanoparticles using soft corals.

Molecular Docking Study

On account of the interesting results of the in vitro study on the anti-inflammatory potential of *Nephthea* sp., which revealed the direct inhibition of both COX-1 and COX-2, an in silico study was performed to investigate which compounds have the potential to bind in the active sites of these COX isoforms. Molecular docking of the dereplicated compounds (1–10) from this soft coral into both COX-1 and COX-2 has successfully predicted the active compounds and their binding mode within the active sites of both isozymes. The binding free energy (ΔG) in kcal/mol of the characterized compounds to COX-1 and COX-2 in comparison with the co-crystallized ligands is summarized in Table S2. Compounds 5 and 7–9 showed higher binding affinities to both COX isozymes, while the other compounds revealed weak to medium affinities. Interestingly, both compound 5 and mofezolac displayed high and comparable binding affinities to COX-1 protein. These results may suggest that compound 5 is the main chemical principle responsible for the anti-COX-1 properties of *Nephthea* sp. On the contrary, compounds 5 as well as 7–9 exhibited noticeable affinities to COX-2 protein, proposing that more compounds could be adapted in COX-2 than in COX-1 due to the larger active site of COX-2 and its higher hydrophobic nature as compared with COX-1. Likewise, the smaller size of COX-1 pocket compared to the molecular volume of compound 3 did not allow this molecule to be docked to the COX-1 active site.

Figures 8–12 illustrates the binding mode and orientation of the high-affinity compounds (5 and 7–9) within the active site of COX-1. All of these compounds formed at least one hydrogen bond with the key amino acid residue (Arg120). Compound 5 showed the highest binding affinity due to its capacity to form two strong hydrogen bonds with the essential amino acid residue (Arg120) in a similar manner to the co-crystallized ligand (Mofezolac). Moreover, the high binding affinities of compounds 7 and 9 could be explained by their ability to make an additional stronger hydrogen bond with the key amino acid Tyr355. Nonetheless, the moderate binding affinity of compound 8 could be rationalized by its capability to make one more hydrogen bond but with the non-essential amino acid Ser530, in addition to a CH-π interaction with the key residue Tyr355.

Figures 13–17 demonstrates the binding mode and orientation of the high-affinity compounds (5 and 7–9) within the active site of COX-2. All compounds were able to occupy the selectivity pocket of COX-2, but in different degrees and orientations. Such differences were attributed to their differences in hydrophobicity. The fact that Rofecoxib makes only one hydrophilic interaction and 41 hydrophobic contacts with the active site of COX-2 could illustrate their relative affinities to COX-2 protein.⁵⁷ Briefly, compound 8 showed a moderate affinity to COX-2 due to its less hydrophobic nature. Conversely, the other active compounds (5, 7, and 9) are more hydrophobic, and consequently, have more binding affinities to COX-2 than compound 8.

Taking all together, the results of the docking analysis suggested that compounds 5 and 7–9 are more likely responsible for the anti-inflammatory activity of the soft coral through their anti-COX activity.

Conclusion

The present study demonstrated a simple green method for the synthesis of SNPs using the petroleum ether and ethyl acetate fractions of the soft coral *Nephthea* sp. The petroleum ether nano fraction was the most potent COX-2 inhibitor, followed by the ethyl acetate nano fraction. Additionally, the anti-inflammatory potential of the total extract and its derived fractions were investigated showing that the petroleum ether and acetone fractions possess the highest COX-2 inhibitory activities, whereas the total extract showed potent COX-1 inhibitory potential. LC–MS based metabolomics was also applied in unveiling the chemical complexity of marine invertebrates, typified by metabolic profiling of the under investigated soft coral *Nephthea* sp., resulting in the characterization of a group of sesquiterpenes and other metabolites of different structural types. Molecular docking studies of the identified metabolites have pinpointed that compounds (2*E*, 6*E*)-3-isopropyl-6-methyl-10-oxoundec-2,6-dienal (5), 7-acetoxycalamenen-3-one (7), ethyl 5-[(1*E*, 5*Z*)-2, 6-dimethylocta-1, 5, 7-trienyl] furan-3-carboxylate (8), and sinularioperoxide E (9), which were detected at high levels in the petroleum ether, ethyl acetate, and acetone fractions, possess the best COX binding aptitude, suggesting their probable responsibility for the observed COX inhibitory potential of *Nephthea* sp. In view of that, synthesis of silver nanoparticles using natural resources is a better alternative to the chemical synthesis as it is eco-friendly, less toxic for human health and environment with nearly no adverse effect. Additionally, from the previous results of our research, one can affirm that *Nephthea* sp. can play an important role in the bioreduction and stabilization of

silver nanoparticles. Moreover, this soft coral could be regarded as a considerable and interesting pool of bioactive metabolites for the development of potent natural anti-inflammatory remedies.

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Disclosure

The authors report no conflicts of interest in this work.

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