

## In Silico Evaluation of Anti-Inflammatory Phytochemicals from *Nyctanthes arbor-tristis* Linn Using Molecular Docking and Dynamics Approaches

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Received: 23 May 2023; Revised: 16 August 2023; Accepted: 16 August 2023

### ABSTRACT

Pharmacological studies on the leaves, flowers, seeds, and bark of *Nyctanthes arbor-tristis* Linn have confirmed their traditional therapeutic roles in managing diverse health conditions. This research assessed the anti-inflammatory capabilities of 26 plant-derived compounds through molecular docking with AutoDock 4.2, supplemented by Molecular Dynamics Simulations using GROMACS. SwissADME was employed to analyze ADME (absorption, distribution, metabolism, and excretion) profiles. Among these, Arb\_E and Beta-sito exhibited robust binding interactions with targets including COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase. The standard inhibitor celecoxib showed a binding energy of  $-9.29$  kcal/mol, whereas Arb\_E stood out with the highest affinity (docking energy:  $-10.26$  kcal/mol). Beta\_sito also demonstrated substantial binding with  $-8.86$  kcal/mol against COX-2. In simulations of COX-2 complexed with Arb\_E or celecoxib, RMSD values stayed within 0.15 to 0.25 nm, confirming complex stability over the entire duration. Additionally, MM-PBSA calculations indicated that Arb\_E's interaction with COX-2 had the most favorable binding energy at  $-277.602$  kJ/mol. Both compounds presented desirable physicochemical properties and drug-likeness in ADME evaluations, suggesting strong therapeutic promise. Hence, these plant constituents may represent viable candidates for anti-inflammatory therapy and require further validation through in vitro and in vivo testing to advance new drug development.

**Keywords:** *Nyctanthes arbor-tristis* Linn, Natural products, Anti-inflammatory activity, Cyclooxygenase enzyme inhibition, Binding affinity, Molecular docking simulation

**How to Cite This Article:** Tan GY, Lim WM, Ong HX, Koh R. In Silico Evaluation of Anti-Inflammatory Phytochemicals from *Nyctanthes arbor-tristis* Linn Using Molecular Docking and Dynamics Approaches. *Pharm Sci Drug Des.* 2023;3:295-311. <https://doi.org/10.51847/ZfL8Qbas15>

### Introduction

*Nyctanthes arbor-tristis* Linn (NAT), an indigenous Indian medicinal species from the Oleaceae family, is additionally grown for ornamental purposes and known locally as night jasmine or harsingar. Its distribution spans sub-Himalayan zones southward to the Godavari region. Reaching up to 10 m in height, the plant features opposite, simple, rough, hairy leaves in decussate arrangement, with flowers clustered at branch tips. It prefers loamy soil with ample moisture and grows well under full sunlight to partial shade. The blooming period usually spans July to October [1, 2].

Various parts of this plant—leaves, flowers, seeds, and bark—have been subjected to pharmacological testing to substantiate traditional uses against ailments like fever, rheumatism, sciatica, arthritis, malaria, and dermatological issues [2, 3].

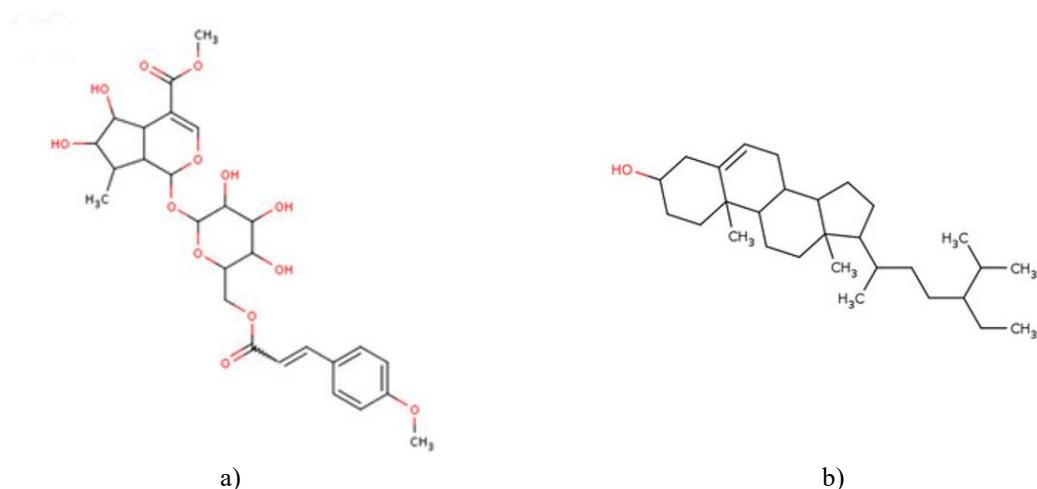
Key bioactive constituents reported include glycosides, flavonoids, oleanic acid, tannic acid, essential oils, carotene, lupeol, friedeline, benzoic acid, and glucose, each contributing to therapeutic effects. In particular, the anti-inflammatory actions of NAT compounds have drawn increasing research focus lately. Inflammation

involves a multifaceted physiological defense against harmful agents such as pathogens, tissue damage, irritants, and associated toxins, triggering immune activation and secretion of pro-inflammatory factors like prostaglandins, cytokines, and chemokines. Persistent inflammation underlies many pathologies, including rheumatoid arthritis, diabetes, atherosclerosis, and cancer [4].

As a result, discovering safe natural modulators of inflammation that minimize side effects remains a priority. Evidence from animal studies and cellular assays has established NAT's anti-inflammatory efficacy [5, 6]. Notably, leaf extracts display marked bioactivity. These leaves contain flavonoid polyphenols like kaempferol, quercetin, rutin, and astragalin, recognized for antioxidant, anti-inflammatory, and antimicrobial benefits. Triterpenoids identified in the leaves, such as ursolic acid,  $\beta$ -sitosterol, oleanolic acid, and lupeol, are associated with anti-inflammatory, antitumor, and antidiabetic properties [7]. PubChem-registered compounds from this species encompass oleanolic acid, friedelin, 6beta-hydroxyloganin, arborside A, arborside B, 6-beta-hydroxyloganin, calceolarioside A, astragalin, sitogluside, methyl (1S,4aS)-6-hydroxy-5-[(E)-3-(4-methoxyphenyl)prop-2-enoyl]oxy-7-methyl-1-[(2S,3R,4S,5S,6R)-3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2-yl]oxy-1,4a,5,6,7,7a-hexahydrocyclopenta[c]pyran-4-carboxylate, arbortristoside B, nyctanthic acid, arbortristoside E, arbortristoside D, arbortristoside C, 7-O-(3,4-dihydrocinnamoyl)nyctanthoside, arborside D, etc.

Certain alkaloids, including nyctanthine and arbortristosides—nitrogenous bases—have shown broad bioactivities encompassing analgesia, spasmolysis, and antimalarial action. Other classes like phenolic acids, lignans, coumarins, fatty acids, and essential oils contribute antioxidant, antibacterial, antifungal, and antiviral effects [8]. The water-soluble fraction obtained from the ethanol extract of NAT leaves has been documented to substantially reduce granuloma formation in cotton pellet assays and edema in carrageenan-challenged rat paws [9]. A methanol extract derived from NAT leaves effectively blocked lipopolysaccharide (LPS)-triggered nitric oxide (NO) release and inducible nitric oxide synthase (iNOS) upregulation in RAW 264.7 macrophage cells, highlighting strong anti-inflammatory capabilities [8]. Additionally, the ethanol extract from NAT leaves diminished secretion of key pro-inflammatory cytokines—including tumor necrosis factor-alpha (TNF- $\alpha$ ), interleukin-1 beta (IL-1 $\beta$ ), and interleukin-6 (IL-6)—in LPS-activated murine peritoneal macrophages. Several isolated bioactive constituents from NAT leaves have also been pinpointed as prospective Janus kinase (JAK) inhibitors, enzymes central to cytokine signaling pathways that drive rheumatoid arthritis progression [5, 10]. Collectively, these observations point to robust anti-inflammatory attributes in NAT leaves, potentially beneficial for managing inflammation-related diseases. That said, more in-depth investigations are essential to pinpoint precise action mechanisms and establish safety data for the plant and its compounds. The objective of this work was to undertake an *in silico* evaluation to validate the anti-inflammatory properties of NAT-derived phytochemicals and emphasize the plant's promising role in future anti-inflammatory drug discovery. Certain compounds extracted from NAT leaves and assessed for anti-inflammatory action in LPS-treated RAW 264.7 macrophages include astragalin—a flavonoid glycoside that curbs NO and iNOS activity [11]. The triterpene  $\beta$ -sitosterol notably lowered IL-6, TNF, and IL-1 output in LPS-exposed mouse peritoneal macrophages. Reports indicate that NAT leaves contain high levels of polyphenolic flavonoids, among them kaempferol, quercetin, astragalin, and rutin [4, 12, 13]. Flavonoids in general are recognized for their antioxidant, anti-inflammatory, and antimicrobial benefits [14]. Alkaloids bearing nitrogen atoms demonstrate a range of bioactivities, such as pain relief, spasm reduction, and antimalarial effects. Specifically, arbortristosides A and B have been shown to suppress JAK function while lowering IL-1 $\beta$ , IL-6, and TNF- $\alpha$  concentrations in LPS-challenged macrophages [15]. Lipophilic triterpenoids like beta-sitosterol, ursolic acid, oleanolic acid, and lupeol [12] exhibit anticancer, antidiabetic, and anti-inflammatory actions [14]. How these natural compounds perform against conventional synthetic anti-inflammatory agents can depend on factors like inflammation characteristics, dosage, delivery method, pharmacokinetic profile, and drug interactions. Even so, multiple reports suggest their anti-inflammatory potency matches or exceeds that of standard medications including indomethacin, diclofenac, ibuprofen, and prednisolone [16-19]. Astragalin, for example, matches indomethacin's suppression of NO in LPS-treated RAW 264.7 cells, whereas  $\beta$ -sitosterol outperforms diclofenac in restraining IL-6 in similarly stimulated peritoneal macrophages [18]. Arbortristosides A and B, in turn, inhibit JAKs more effectively than prednisolone in LPS-exposed RAW 264.7 macrophages. Clinical studies in humans are still required, however, to substantiate both efficacy and tolerability for inflammatory conditions [17]. Tackling ongoing inflammation and enhancing patient well-being demand innovative anti-inflammatory therapies. Increasingly, researchers explore botanical sources for safer alternatives with minimal side effects. Here, we aimed to pinpoint natural compounds capable of targeting diverse inflammatory pathways or receptors to boost treatment outcomes and enable lower therapeutic doses. Accordingly, we performed *in silico* analyses—

encompassing virtual screening, docking, and dynamics simulations—on two NAT phytochemicals: arbortristoside E and beta-sitosterol. Arbortristoside E (PubChem ID:14632884) possesses a molecular weight of 566.5 g/mol and the formula C<sub>27</sub>H<sub>34</sub>O<sub>13</sub>, featuring a sophisticated architecture with esters, hydroxyl groups, and aromatic moieties. Beta-sitosterol (PubChem ID:222284), a phytosterol with a beta-hydroxy substituent, has a molecular weight of 414.7 g/mol and formula C<sub>29</sub>H<sub>50</sub>O. Their structural details are illustrated in **Figure 1**.



**Figure 1.** Two-dimensional structural representations of (a) arbortristoside E and (b) beta-sitosterol. This marks the inaugural examination of arbortristoside E's therapeutic prospects. On this basis, both arbortristoside E and beta-sitosterol emerge as promising anti-inflammatory candidates, potentially delivering synergistic benefits by targeting distinct receptor sites.

## Materials and Methods

### Ligand preparation

Selective nonsteroidal anti-inflammatory drugs (NSAIDs) target the COX-2 isoform responsible for elevated prostaglandin production during inflammation. Given their effectiveness in pain relief and management of inflammation-associated diseases, alongside improved gastrointestinal safety compared to non-selective NSAIDs, COX-2-specific inhibitors remain central to anti-inflammatory drug research. Accordingly, we employed the established selective COX-2 inhibitor celecoxib as a benchmark to gauge the anti-inflammatory potential of plant-derived compounds. Following an initial virtual screening of 26 phytochemicals from *Nyctanthes arbor-tristis*, arbortristoside E (Arb\_E) and beta-sitosterol (Beta\_sito) emerged as the top candidates based on predicted binding affinities.

Two-dimensional structures and SMILES strings for the primary *Nyctanthes arbor-tristis* constituents and celecoxib were retrieved from the PubChem database (<https://pubchem.ncbi.nlm.nih.gov/>) (accessed on 11 October 2023) [20]. These SMILES were subsequently converted to three-dimensional PDB formats using the Novoprolabs server (<https://www.novoprolabs.com/tools/smiles2pdb>) (accessed on 12 October 2023) [21] in preparation for docking and dynamics studies. Energy minimization of the ligands was then performed in Discovery Studio Visualizer version 21.1.0.20298 [22], applying the CHARMM force field with its empirical energy terms [23, 24].

### Receptor preparation

The COX-2 enzyme facilitates prostaglandin biosynthesis, contributing to inflammatory and nociceptive responses. Its human crystal structure (PDB ID: 5F1A) was downloaded from the Protein Data Bank (<https://www.rcsb.org/structure/5F1A>) (accessed on 19 October 2023) [25].

Water molecules (HOH) and heterogeneous atoms (HETATM) were removed from the original PDB file, followed by energy minimization under the CHARMM force field in Discovery Studio Visualizer version 21.1.0.20298 [23].

Binding site identification was carried out in Discovery Studio Visualizer version 21.1.0.20298 [26], focusing on critical residues to define the active pocket for subsequent docking of the selected phytochemicals.

#### *AutoDock 4.2 tool receptor–ligand docking*

In AutoDock 4.2, extraneous elements such as waters and cofactors were stripped from the receptor, followed by addition of polar hydrogens, assignment of charges and atom types, and geometric optimization. For ligands, conformational and tautomeric variants were generated to explore potential binding modes.

A grid box encompassing the active site was configured to map interaction energies, with dimensions of  $60 \times 60 \times 60$  points and  $0.375 \text{ \AA}$  spacing. Center coordinates were set as follows:  $-36.659, -51.728, 2.072$  (COX-1);  $41.585, 25.501, 237.603$  (COX-2);  $96.897, 66.877, 19.023$  (PDE4);  $0.0192, 49.098, 20.118$  (PDE7);  $79.997, -40.055, -38.557$  (IL-17A);  $37.218, -35.236, 4.499$  (IL-17D);  $24.212, 63.416, 44.088$  (TNF- $\alpha$ );  $11.193, 20.924, -9.834$  (IL-1 $\beta$ ); and  $-45.708, -42.479, 0.232$  (prostaglandin E2) [27].

Default settings were retained for the docking algorithm, scoring function, and output parameters. Pose generation and orientation relied on the Lamarckian genetic algorithm (LGA) coupled with an empirical free energy function, expressed as:

$$\Delta G_{\text{binding}} = \Delta G_{\text{Gauss}} + \Delta G_{\text{Repulsion}} + \Delta G_{\text{Hbond}} + \Delta G_{\text{Hydrophobic}} + \Delta G_{\text{Tors}},$$

where  $\Delta G_{\text{Gauss}}$  represents attractive Gaussian dispersion;  $\Delta G_{\text{Repulsion}}$  penalizes short contacts;  $\Delta G_{\text{Hbond}}$  models directional H-bonding (including metal interactions);  $\Delta G_{\text{Hydrophobic}}$  accounts for non-polar contacts; and  $\Delta G_{\text{Tors}}$  scales with rotatable bond count [28].

Upon preparation of receptor, ligand, grid, and parameter files, AutoDock 4.2 was executed with population size (ga\_pop\_size) of 150, maximum energy evaluations (ga\_num\_generation) of 2,500,000, 27,000 generations, mutation rate of 0.02, crossover rate of 0.8, and step size of 0.2. Ten independent LGA runs were performed per system, varying with molecular complexity [29].

Docking outcomes were ranked by score, visualized, and benchmarked against controls using Discovery Studio Visualizer version 20.1.0.19295 [26, 30].

#### *Drug-likeness and ADMET*

The SwissADME web server (<http://www.swissadme.ch>) (accessed on 25 October 2023), provided by the Swiss Institute of Bioinformatics (SIB), Lausanne, Switzerland [31–33], was employed to predict the ADME parameters, drug-likeness, and pharmacokinetic profiles of the chosen phytochemicals. Additional toxicity assessments were performed using the pkCSM online platform (<http://biosig.unimelb.edu.au/pkcs/>) (accessed on 25 October 2023) [34].

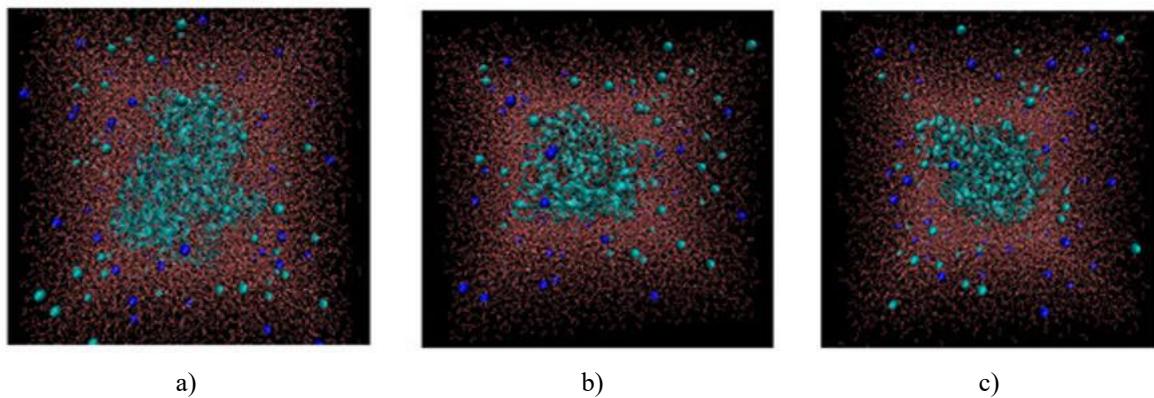
#### *MDS*

A 100 ns molecular dynamics simulation (MDS) was carried out on the COX-2–Arb\_E, COX-2–Beta\_sito, and COX-2–celecoxib complexes with GROMACS version 2018 software [35].

For benchmarking, an additional simulation of apo COX-2 in water was included. The topology for COX-2 was created via the pdb2gmx module, applying the CHARMM27 all-atom force field. Ligand topologies for Arb\_E, Beta\_sito, and celecoxib were acquired from the SwissParam server [36]. Each system was placed in a triclinic simulation box, solvated with water, and neutralized by adding  $\text{Na}^+$  and  $\text{Cl}^-$  ions. A total of 59  $\text{Na}^+$  and 61  $\text{Cl}^-$  ions were introduced to achieve electrical neutrality and a physiological salt concentration of 0.15 M. The fully solvated systems contained 18,793, 18,788, and 18,503 molecules for the COX-2–Beta\_sito, COX-2–Arb\_E, and COX-2–celecoxib complexes, respectively (**Figures 2a–2c**) [37].

Energy minimization was followed by equilibration in two phases: NVT and NPT ensembles. The steepest descent algorithm was run for 5000 steps. These steps ensured stable temperature and pressure control during the production run [38].

Equilibration was conducted at 300 K and 1.0 bar for 100 ps each. Trajectory analyses utilized gmx rms for root-mean-square deviation (RMSD) [39], gmx rmsf for root-mean-square fluctuation (RMSF), gmx gyrate for radius of gyration (Rg) [40] and gmx hbond for intermolecular hydrogen bond counting. Two-dimensional plots were produced with XMGRACE version 5.1 [41].



**Figure 2.** Three-dimensional representations of the solvated and ionized systems: (a) COX-2–Arb\_E, (b) COX-2–Beta\_sito, and (c) COX-2–celecoxib. Protein complexes appear as cyan ribbons at the center, surrounded by water with  $\text{Na}^+$  (blue spheres) and  $\text{Cl}^-$  (cyan spheres). Visualizations were generated using VMD (Visual Molecular Dynamics) version 1.9.4a57 [42].

#### *Molecular mechanics–poisson–boltzmann surface area (MM-PBSA)*

Following the approach described by Kumari *et al.* [43, 44], binding free energies for the selected complexes were estimated using the Molecular Mechanics–Poisson–Boltzmann Surface Area (MM-PBSA) method [45]. This technique, implemented through a tool designed for evaluating solvation in biomolecules and macromolecular assemblies, calculates free energy without the entropic term. It comprises two main contributions: the molecular mechanics potential energy in vacuum ( $\Delta G_{\text{MM}}$ ), encompassing bonded interactions (bond, angle, dihedral) and non-bonded terms such as van der Waals ( $\Delta G_{\text{VDW}}$ ) and electrostatic ( $\Delta G_{\text{Coulomb}}$ ) energies; and the solvation free energy ( $\Delta G_{\text{Solvation}}$ ), which combines polar ( $\Delta G_{\text{Polar}}$ ) and non-polar ( $\Delta G_{\text{Nonpolar}}$ ) components within an implicit solvent model [42]. The MM-PBSA binding free energy is formulated as follows:

$$\Delta G = \Delta G_{\text{MM}} + \Delta G_{\text{Solvation}} \quad (1)$$

Where

$$\Delta G_{\text{MM}} = \Delta G_{\text{Electrostatic pot}} + \Delta G_{\text{VDW}} \quad (2)$$

The solvation energy is the amount of energy necessary to transfer a solute from the void to the solvent and is expressed as the sum of the polar and nonpolar energies (see Equation (3)).

$$\Delta G_{\text{Solvation}} = \Delta G_{\text{Polar}} + \Delta G_{\text{nonpolar}} \quad (3)$$

The polar contribution is closely associated with the formation of permanent dipoles. In contrast, the polar solvation term accounts for permanent dipoles and reflects the solute's charge distribution. For our MM-PBSA computations, the ionic strength was adjusted to 0.150 M through the addition of NaCl. Key setup parameters involved a grid density of 10 points per  $\text{\AA}^2$  and a maximum of 50,000 iterations for the linear Poisson–Boltzmann equation solver.

## Results and Discussion

### *Docking results*

In the present investigation, we assessed the prospective anti-inflammatory binding strengths and molecular interactions of the chosen compound Arb\_E with various key proteins involved in inflammatory pathways, specifically COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase. These targets play crucial roles in diverse physiological and pathological events, such as cellular signaling, immune responses, and nociception. Molecular docking was employed to estimate binding energies and inhibition constants ( $K_i$ ) for Arb\_E against each protein, while also examining hydrogen bonding and hydrophobic contacts with active site residues. Key findings are compiled in **Tables 1 and 2**.

**Table 1.** Docking parameters for Arb\_E with the selected targets: COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase.

Receptors	PDB ID	Binding Energy (kcal/mol)	Inhibition Constant (Ki)	Hydrogen Bond Details	Hydrogen Bond Length (Angstrom)	Residues Involved in Hydrophobic Interaction
<b>Control (Celecoxib)</b>	Cox-2	-9.29	155.52 nM	A:ARG513:HH11 —:UNK0:O	2.04571	Val116,Leu359,Tyr335,Ser353,Leu531,His90,Gln192,ALA516,Leu384,Val523,Phe518,Trp387,Met522,Gly526,Leu352,Ala527,Val349,Ser530,Met113
<b>COX-1</b>	6Y3C	-3.05	5.81 mM	A:ARG513:CD— :UNK0:O	3.00729	
				A:ARG513:CD— :UNK0:N	3.62419	
				A:TRP387:HN— :UNK1:O36	1.64895	
				UNK1:H49— A:ASN382:O	2.56551	
				UNK1:H50— A:ASN382:OD1	2.53999	Ala199,Ala202,Gln203,Thr206,His207,Phe210,Phen381,Asn382,Tyr385,His386,Trp387,His388,Leu390,Met391,Ile444
				UNK1:H71— A:TYR385:O	1.92435	
				UNK1:H70— A:TYR385:O	2.23812	
				A:HIS388:CA— :UNK1:O23	3.75406	
				UNK1:C40— A:PHE210:O	3.26066	
<b>COX-2</b>	5F1A	-10.26	30.07 nM	A:ARG120:HE— :UNK1:O38	2.11946	Val116,Arg120,Phe205,Phen209,Gly227,Val228,Thr348,Val349,Leu352,Ser353,Tyr355,Leu359,Asn375,Ile377,Phen381,Tyr385,Trp387,Phen518,Met522,Val523,Gly526,Ala527,Phe529,Ser530,Leu531,Gly533,Leu534
				A:ASN375:HD22— :UNK1:O32	2.79305	
				A:SER530:HG— :UNK1:O19	2.24954	
				A:SER530:HG— :UNK1:O21	1.89473	
				UNK1:C33— A:GLY533:O	2.89113	
				A:HIS416:HE2— :UNK1:O38	2.03017	
				A:GLN555:HE22— :UNK1:O36	2.64094	Asp413,His416,Ser420,Asn421,Gln422,Leu441,Glut442,His445,Asp484,Meth485,Ser486,Asn533,Thr545,Ile548,Phe552,Gln555,Ser567,Met569,Gln581,Phe584
<b>PDE4</b>	2QYK	-9.00	251.54 nM	A:ASP484:OD1 UNK1:H50— A:GLU442:OE2	1.91855	
				A:SER420:CB— :UNK1:O13	1.92009	
				UNK1:C40— A:ASP413:OD1	3.0371	
				A:HIS256:HE2— :UNK1:O34	3.165	
				A:HIS256:HE2— :UNK1:O35	2.03088	Tyr211,His212,His216,Asp253,His256,Gly258,Asn260,Gln261,Leu281,Glu282,His285,Thr323,Asp362,Asn365,Trp376,Ser377,Val380,Glu383,Phe384,Gln387,Pro400,Leu401,Cys402,Gln413,Phe416
<b>PDE7</b>	1ZKL	-6.74	11.43 uM	A:GLN413:HE22— :UNK1:O32	2.10147	
				UNK1:H69— A:ASP253:OD1	2.53525	
				UNK1:H71— A:GLU282:OE2	2.16071	

<b>IL-17A</b>	5HI4	-5.81	54.74 uM	UNK1:H49— A:GLU383:OE2	2.69909	Leu53,Tyr62,Pro63,Val6 5,Ile66,Trp67,Gln94,Ile9 6,Leu97,Val98,Leu99,Val 1117,Ser118,Val119
				UNK1:C40— A:PRO400:O	2.37041	
				UNK1:H50— A:VAL65:O	1.98348	
				UNK1:H69— A:TYR62:O	2.4814	
				A:PRO63:CD— :UNK1:O35	2.97263	
				A:VAL119:CA— :UNK1:O32	3.01728	
				UNK1:C33— A:TRP67:O	3.37552	
<b>IL-17D</b>	Mod eled from MO DBA SE serve r	-6.70	12.36 uM	UNK1:H69— A:VAL141:O	2.64013	Ala78,Arg80,Tyr96,Tyr1 05,Pro106,Tyr108,Leu10 9,Pro110,Ala112,Thr140, Val141,Val142,Ile163,Pr o164,Val165
				UNK1:C40— A:ALA78:O	2.95779	
				UNK1:C33— A:PRO110:O	3.29094	
				UNK1:C33— A:PRO164:O	3.0518	
				UNK1:C20— A:LEU142:O	3.23102	
<b>TNF-<math>\alpha</math></b>	1A8 M	-4.70	360.94 uM	UNK1:C33— A:GLN67:OE1	3.04695	Pro20,Ala22,Gly24,Lys6 5,Gly66,Gln67,Asp140,L eu142,Phe144,Ala145
<b>IL-1<math>\beta</math></b>	6Y8 M	-4.59	431.16 uM	A:LYS103:HZ2— :UNK1:O7	2.66882	Lys103,Asn108,Lys109, Leu110,Phe146,Thr147, Met148,Gln149,Phe150
				UNK1:C33— A:PHE150:O	3.21082	
				UNK1:H49— A:THR168:OG1	2.63075	
<b>Prostagla ndin E2</b>	4YH L	-7.23	4.98 uM	UNK1:H50— A:THR168:O	1.8278	Ile23,Pro24,Met27,Val72 ,Val75,Thr76,Thr79,Tyr8 0,Leu99,Thr168,Trp169, Cys170,Arg316,Ser319, Val320
				UNK1:C40— A:CYS170:O	3.05882	
				A:TYR24:HN— :UNK1:O7	2.28139	
<b>Prostagla ndin F synthase</b>	1RY 0	-10.19	33.66 nM	A:SER217:HN— :UNK1:O36	2.31396	Thr251,Gln279,Asn280, ALA253,Arg276,Leu219 ,Leu236,Ala269,Leu268, Ala218,Ser221,Gly22,Ty r216,Thr23,Ser51,Lys84, His117
				A:LYS270:HN— :UNK1:O35	2.95418	
				A:LYS270:HZ2— :UNK1:O23	2.7668	
				A:LYS270:HZ3— :UNK1:O23	2.84067	
				UNK1:H49— A:ASP50:OD2	2.45111	
				UNK1:H49— A:ASP50:O	2.87918	
				UNK1:H50— A:TYR55:OH	2.08453	
				UNK1:C20— A:LYS270:O	2.79899	
				UNK1:C33— A:THR251:OG1	3.62729	

**Table 2.** Docking parameters for Beta\_sito with the selected targets: COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase.

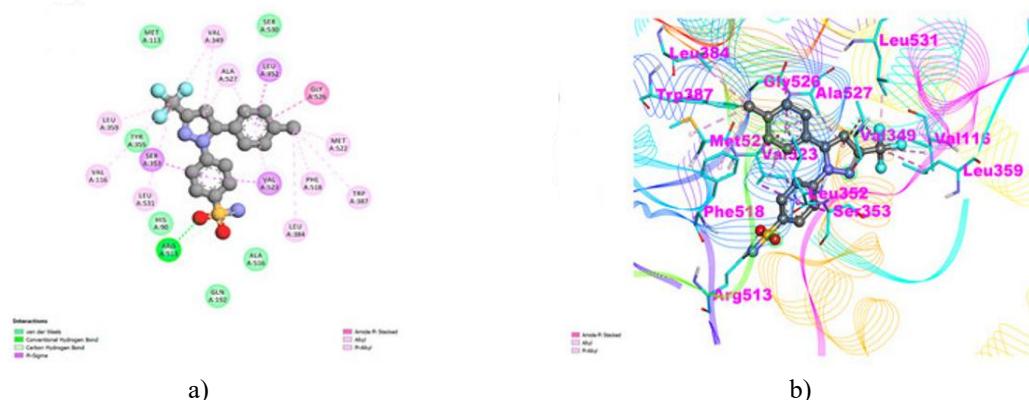
Receptors	PDB ID	Binding Energy	Inhibition	Hydrogen Bond Details	Hydrogen Bond Length (Angstrom)	Residues Involved in Hydrophobic Interaction
Control (Celecox ib)	Cox-2	-9.29	155.52 nM	A:ARG513 :HH11— :UNK0:O	2.04571	
				A:ARG513 :CD— :UNK0:O	3.00729	Val116,Leu359,Tyr335,Ser353,Leu531,His90,Gl n192,ALA516,Leu384,Val523,Phe518,Trp387,M et522,Gly526,Leu352,Ala527,Val349,Ser530,Me t113
				A:ARG513 :CD— :UNK0:N	3.62419	
COX-1	6Y3C	-4.91	253.57 uM	NA	NA	Ala199,Phe200,Ala202,Gln203,Thr206,His207,L eu295,Tyr385,His386,Trp387,His388,Leu390,Met391,Tyr404,Leu408,Ile444
COX-2	5F1A	-8.86	320.37 nM	NA	NA	Ala199,Ala202,Gln203,Thr206,His207,Phe210, His214,Asn382,Tyr385,His386,Trp387,His388,Leu390,Leu391
PDE4	2QYK	-8.66	448.17 nM	NA	NA	Tyr371,His372,Asp413,His416,Asn421,Leu441, Glu442,His445,Thr483,Met485,Asp530,Leu531,Ile548,P he552,Met569,Phe584,Ile588
PDE7	1ZKL	-7.48	3.68 uM	A:HIS256: HE2— :UNK1:O2	2.68409	
				5 UNK1:H67		Tyr211,His212,His216,His252,Asp253,His256,L eu281,Glu282,His285,Thr321,Ile323,Asp362,Val 380,Phe384,Leu401,Gln413,Phe416,Leu420
IL-17A	5HI4	-7.43	3.60 uM	A:ASP253: OD1	2.14352	
				A:TRP67: HN— :UNK1:O2	2.23528	
				5 UNK1:H67		Tyr62,Pro63,Ile66,Trp67,Ile96,Leu97,Val98,Leu 99,Leu112, Val117
IL-17D	Model ed from MOD BASE server	-8.22	947.55 nM	A:TRP67: O	1.86307	
				UNK1:H67		
				— A:VAL165 :O	2.01343	Arg80,Arg81,Phe82,Trp94,Tyr96,Pro106,Tyr108 ,Pro110,Val165
TNF- $\alpha$	1A8M	-7.10	6.20 uM	UNK1:H67	2.0408	Pro20,Lys65,Gly66,Gln67,Asp140,Tyr141,Leu1 42,Asp143,Phe144,Ala145
IL-1 $\beta$	6Y8M	-6.19	29.24 uM	UNK1:H67	2.23593	Leu6,Met44,Phe46,Lys103,Glu105,Asn108,Leu1 10,Thr147,Met148,Gln149,Phe150

<b>Prostaglandin E2</b>	4YHL	-8.58	514.41 nM	NA	NA	Ile23,Pro24,Met27,Thr69,Val72,Ser73,Thr76,Tyr80,Arg316,Ser319,Val320
<b>Prostaglandin F synthase</b>	1RY0	-7.39	3.83 uM	NA	NA	Arg223,Leu236,Gly220,Leu219,Ala218,Ala269,Tyr55,Ser217,Tyr55,Tyr24,Tyr216,Gly22,Asp50,Leu268,Thr23,Lys270,Gln222,Ser221

The reference compound celecoxib, a selective NSAID, exhibited strong affinity for cyclooxygenase-2 (COX-2), recording a binding energy of  $-9.29$  kcal/mol, reflecting robust interaction. Its inhibition constant (Ki) was  $155.52$  nM, indicating effective COX-2 suppression at nanomolar concentrations or below.

**Table 1** further details hydrogen bonding between celecoxib and COX-2: one bond links the carboxylate of ARG513 (COX-2) to the hydroxyl of UNK0 (celecoxib) at  $2.04571$  Å; another connects the same ARG513 carboxylate to the amide of UNK0 at  $3.00729$  Å; and a third involves the ARG513 carboxylate with the amine of UNK0 at  $3.62419$  Å (**Table 1**).

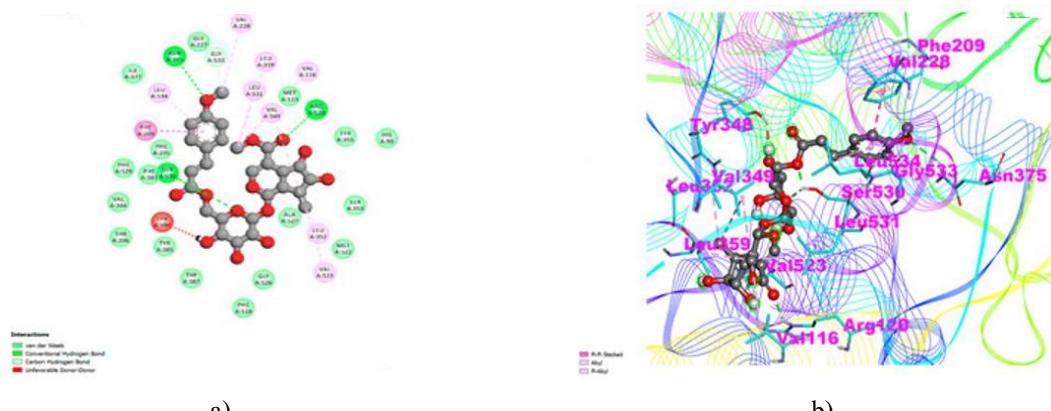
Additionally, extensive hydrophobic contacts contributed to stability, involving COX-2 residues Val116, Leu359, Tyr335, Ser353, Leu531, His90, Gln192, Ala516, Leu384, Val523, Phe518, Trp387, Met522, Gly526, Leu352, Ala527, Val349, Ser530, and Met113 (**Figures 3a and 3b**). Such non-polar interactions enhance complex stabilization by aligning hydrophobic regions of ligand and protein.



**Figure 3.** (a) Two-dimensional interaction diagram and (b) three-dimensional view of celecoxib bound to COX-2.

Compounds targeting COX-1 and COX-2 remain primary choices for developing anti-inflammatory and pain-relieving medications [46].

Arb\_E displayed weak interaction with COX-1, yielding a binding energy of  $-3.05$  kcal/mol and a Ki of  $5.81$  mM. Binding involved hydrogen bonds with Tyr385 and Asn382, plus hydrophobic contacts with Phe210 and Pro400 (**Table 1**). In contrast, Arb\_E demonstrated markedly stronger affinity for COX-2 ( $-10.26$  kcal/mol; Ki:  $30.07$  nM), mediated by three hydrogen bonds to Arg120, Asn375, and Ser530, along with four hydrophobic interactions involving Gly533, Trp67, Pro110, and Pro164 (**Figures 4a and 4b; Table 1**).



**Figure 4.** (a) Two-dimensional interaction diagram and (b) three-dimensional view of Arb\_E bound to COX-2.

The docking outcomes reveal that Arb\_E preferentially inhibits COX-2 over COX-1, a favorable profile that may minimize adverse effects linked to COX-1 blockade, including gastric irritation and ulceration. Notably, Arb\_E also showed strong binding to both COX-2 and prostaglandin E2 (PGE2), a downstream inflammatory mediator produced by COX-2. This dual targeting implies potential synergistic anti-inflammatory effects through reduced PGE2 synthesis.

PDE4 and PDE7 catalyze the hydrolysis of cyclic adenosine monophosphate (cAMP), an important second messenger regulating numerous cellular functions. Agents inhibiting PDE4 and PDE7 have emerged as promising candidates for treating inflammatory disorders, including asthma, chronic obstructive pulmonary disease (COPD), psoriasis, and rheumatoid arthritis [47].

Both compounds investigated here demonstrated strong binding to PDE4, exhibiting a binding energy of  $-9.00$  kcal/mol and a  $K_i$  of  $251.54$  nM. Hydrogen bonding occurred with the PDE4 residues His416, Glu442, Asp484, and Gln555, while four hydrophobic interactions involved Ser420, Asp413, Pro400, and Leu401. In contrast, a moderate yet noteworthy affinity for PDE7 was recorded, with a binding energy of  $-6.74$  kcal/mol and a  $K_i$  of  $11.43$   $\mu$ M. Four hydrogen bonds were detected with PDE7 residues Asp253, Glu282, Glu383, and Gln413. Numerous reports have established that natural plant-derived bioactives can suppress PDE activity to manage diverse inflammatory disorders (**Table 1**). Several promising plant-based PDE inhibitors have been identified, including coumarins (glycocomararin and licoarylcoumarin), agapanthus saponins (saponin, lignin, kobusin, and  $(\pm)$ -schizandrin), terpenes (perianradulcin A, ursolic acid, and quinovic acid), anthraquinones (chrysophanol and emodin), and alkaloids (Sanjoinine-D) [48].

IL-17A and IL-17D belong to the IL-17 cytokine family and play key roles in inflammatory processes, immune regulation, and cellular signaling. IL-17A serves as the primary cytokine produced by Th17 cells, contributing to host protection against pathogens as well as to autoimmune pathologies. IL-17D, though less characterized, is produced by multiple tissues and cell types and has been linked to tumor suppression and antiviral responses [49]. Docking analyses revealed meaningful interactions of the compounds with both IL-17A and IL-17D (binding energies of  $-5.81$  and  $-6.70$  kcal/mol, with  $K_i$  values of  $54.74$  and  $12.36$   $\mu$ M, respectively). For IL-17A, two hydrogen bonds involved Val65 and Tyr62, accompanied by four hydrophobic contacts with Leu53, Pro63, Trp67, and Gln94. For IL-17D, four hydrogen bonds engaged Val141, Glu282, Glu383, and Gln413, with four hydrophobic interactions involving Ala78, Pro110, Pro164, and Cys402 (**Table 1**). The documented anti-inflammatory effects of various phytochemicals acting via IL-17A and IL-17D pathways underscore the relevance of these observations. These results indicate that the examined natural compound can engage both IL-17A and IL-17D, potentially modulating inflammatory signaling cascades. Further experimental validation is required to elucidate its biological impact on these cytokines.

Tumor necrosis factor-alpha (TNF- $\alpha$ ) and interleukin-1 beta (IL-1 $\beta$ ) are major pro-inflammatory cytokines orchestrating numerous immune and inflammatory reactions [19]. They contribute to pathologies such as rheumatoid arthritis, ulcerative colitis, Alzheimer's disease, and Crohn's disease. Targeted inhibitors of TNF- $\alpha$  and IL-1 $\beta$  have been successfully developed as therapeutics for these conditions [50].

The compounds displayed notable binding to TNF- $\alpha$  ( $-4.70$  kcal/mol;  $K_i$ :  $360.94$   $\mu$ M). Specifically for IL-1 $\beta$ , interaction yielded a binding energy of  $-4.59$  kcal/mol and  $K_i$  of  $431.16$   $\mu$ M, without hydrogen bond formation. Only one hydrogen bond was observed with Lys103 of IL-1 $\beta$ , alongside one hydrophobic contact with Phe150. Overall, these findings suggest moderate inhibitory potential against TNF- $\alpha$  and IL-1 $\beta$ . Binding affinities of the compounds to TNF- $\alpha$  and IL-1 $\beta$  were weaker than those of their endogenous ligands to TNFR1 and IL-1 receptor 1, respectively, implying minimal disruption of physiological cytokine signaling.

Prostaglandin F synthase (PGFS), an enzyme in the aldo-keto reductase (AKR) superfamily, converts prostaglandin D2 (PGD2) to prostaglandin F2 $\alpha$  (PGF2 $\alpha$ ). Interaction showed a binding energy of  $-10.19$  kcal/mol and  $K_i$  of  $33.66$  nM. Ten hydrogen bonds were formed, and hydrophobic interactions involved residues Thr251, Gln279, Asn280, ALA253, Arg276, Leu219, Leu236, Ala269, Leu268, Ala218, Ser221, Gly22, Tyr216, Thr23, Ser51, Lys84, and His117 (**Table 1**).

In addition, we examined the binding profiles of beta-sitosterol—a phytosterol known for cholesterol reduction and anti-inflammatory activity—against the same panel of targets: COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase. These proteins participate in inflammation, pain sensation, immune modulation, and cellular signaling. Outcomes are presented in **Table 2**.

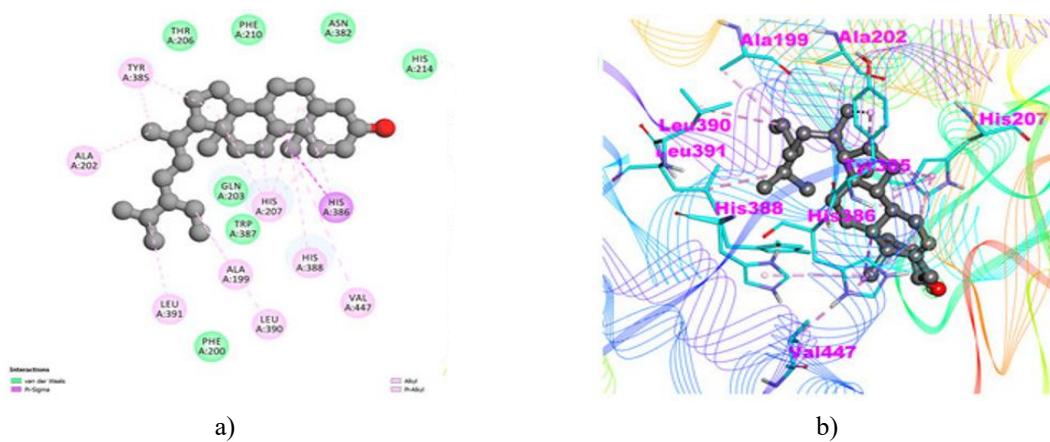
COX-1 and COX-2 enzymes convert arachidonic acid into prostaglandins, mediators of inflammation, pain, fever, and other processes. Cyclooxygenase inhibitors remain cornerstone treatments for inflammation and analgesia.

Beta-sitosterol exhibited moderate affinity for COX-1 ( $-4.91$  kcal/mol;  $K_i: 253.57$   $\mu\text{M}$ ), relying solely on multiple hydrophobic contacts without hydrogen bonds, thereby maintaining complex stability.

Stronger binding was seen with COX-2 ( $-8.86$  kcal/mol;  $K_i: 320.37$  nM) (Table 2). Again, no hydrogen bonds formed, but 18 hydrophobic interactions with various COX-2 residues were noted. The docking configuration for beta-sitosterol in COX-2 is illustrated in Figures 5a and 5b. These data position beta-sitosterol as a preferential COX-2 inhibitor, a property that could limit COX-1-related adverse effects like gastrointestinal bleeding and ulceration [51, 52]. Furthermore, beta-sitosterol outperformed prostaglandin E2 (PGE2), the endogenous COX-2 substrate, in binding affinity [53], suggesting competitive inhibition and reduced prostaglandin synthesis.

PDE4 and PDE7 hydrolyze cyclic adenosine monophosphate (cAMP), a critical second messenger. Their inhibitors hold therapeutic promise for conditions including rheumatoid arthritis, COPD, asthma, and psoriasis [54]. Beta-sitosterol bound robustly to PDE4 ( $-8.66$  kcal/mol;  $K_i: 448.17$  nM) (Table 2), stabilized by 17 hydrophobic contacts without hydrogen bonds. Affinity for PDE7 was also substantial ( $-7.48$  kcal/mol;  $K_i: 3.68$   $\mu\text{M}$ ), featuring two hydrogen bonds with His256 and Asp253 [55, 56] (Table 2).

IL-17A and IL-17D, part of the IL-17 cytokine family, regulate inflammation, immunity, and signaling. IL-17A, the hallmark cytokine of Th17 cells, influences pathogen defense and autoimmunity [57].



**Figure 5.** (a) Two-dimensional interaction map and (b) three-dimensional visualization of Beta\_sito docked with COX-2.

The cytokine IL-17D, which receives comparatively less research attention, is produced by numerous cell types and tissues and has roles in suppressing tumors and combating viral pathogens. Beta\_sito displayed robust affinity toward IL-17A ( $-7.43$  kcal/mol binding energy;  $K_i: 3.60$   $\mu\text{M}$ ) (Table 2), establishing one hydrogen bond with Trp67 and 11 hydrophobic interactions across various residues. Likewise, it bound strongly to IL-17D ( $-8.22$  kcal/mol;  $K_i: 947.55$  nM) (Table 2), forming a hydrogen bond with Val165 alongside nine hydrophobic contacts involving multiple residues (Table 2). Such outcomes point to Beta\_sito's ability to target both IL-17A and IL-17D, possibly altering their associated signaling cascades. That said, the precise functional impacts of Beta\_sito on these cytokines remain undetermined and require additional studies.

TNF- $\alpha$  and IL-1 $\beta$  represent key pro-inflammatory cytokines driving diverse immune and inflammatory pathways. These mediators are implicated in disorders including rheumatoid arthritis, Crohn's disease, ulcerative colitis, and Alzheimer's disease. Specific blockers of TNF- $\alpha$  and IL-1 $\beta$  have been engineered into effective anti-inflammatory therapies. Beta\_sito revealed strong interaction with TNF- $\alpha$  ( $-7.10$  kcal/mol;  $K_i: 6.20$   $\mu\text{M}$ ), supported by a single hydrogen bond to Gln67 and ten hydrophobic engagements with assorted residues. Its binding to IL-1 $\beta$  was less pronounced but still relevant ( $-6.19$  kcal/mol;  $K_i: 29.24$   $\mu\text{M}$ ) (Table 2), featuring one hydrogen bond with Met148 and nine hydrophobic links to other residues. Taken together, this positions Beta\_sito as an effective TNF- $\alpha$  blocker with moderate activity against IL-1 $\beta$ , potentially dampening their contributions to inflammation. Intriguingly, Beta\_sito outperformed the native receptors TNFR1 and IL-1R1 in binding strength to TNF- $\alpha$  and IL-1 $\beta$ , respectively, raising the possibility of disrupting endogenous cytokine pathways [58-60].

Docking with prostaglandin F synthase (PGFS) produced a binding energy of  $-7.39$  kcal/mol and  $K_i$  of  $3.83$   $\mu\text{M}$ . Hydrogen bonding was absent, but complex stability relied on hydrophobic contributions from residues Arg223,

Leu236, Gly220, Leu219, Ala218, Ala269, Tyr55, Ser217, Tyr55, Tyr24, Tyr216, Gly22, Asp50, Leu268, Thr23, Lys270, Gln222, and Ser221 (**Table 2**).

#### ADMET results

ADME encompasses the core processes of absorption, distribution, metabolism, and excretion that shape a molecule's fate within the organism. Celecoxib is forecasted to possess high gastrointestinal absorption and capability to traverse the blood–brain barrier (BBB). It is also flagged as a P-glycoprotein (Pgp) substrate—an active efflux mechanism—and as an inhibitor of key metabolizing enzymes CYP1A2, CYP2C19, and CYP2C9. Its skin permeability metric ( $\log K_p$ ) stands at  $-6.21$ , reflecting limited transdermal potential. In comparison, Arb\_E is projected to show poor gastrointestinal uptake and no BBB penetration, without Pgp substrate properties or CYP inhibition. Its markedly low  $\log K_p$  of  $-9.95$  highlights negligible skin permeation. Beta\_sito mirrors low gastrointestinal absorption and lacks BBB permeability, Pgp involvement, or CYP inhibitory effects, yet its  $\log K_p$  of  $-2.2$  denotes reasonably better skin penetration. These insights aid in tailoring compounds toward specific therapeutic needs—for instance, steering clear of Pgp substrates or CYP inhibitors when central nervous system activity is targeted, or selecting candidates with higher (less negative)  $\log K_p$  for topical applications.

As a clinically approved agent for managing pain and inflammation, celecoxib has a molecular weight of 381.37 g/mol, four rotatable bonds, seven acceptors and one donor for hydrogen bonding, and a TPSA of  $86.36 \text{ \AA}^2$ . Its consensus  $\log P$  of 3.4 aligns well with optimal ranges for drug candidates. Compliance with all major filters—Lipinski, Ghose, Veber, Egan, and Muegge—predicts favorable oral bioavailability and stability. The compound earns a bioavailability score of 0.55 (satisfactory) and a synthetic accessibility rating of 2.74, implying straightforward chemical synthesis.

To our knowledge, Arb\_E remains untested in clinical settings. It possesses a molecular weight of 566.55 g/mol, 10 rotatable bonds, 5 hydrogen bond acceptors, and 13 hydrogen bond donors. Its topological polar surface area measures  $190.67 \text{ \AA}^2$ , with a consensus  $\log P$  of  $-0.14$ . The compound breaches Lipinski's rule regarding hydrogen bond acceptors but complies with the remaining criteria. Consequently, it is likely to exhibit limited oral bioavailability and metabolic stability, consistent with its low bioavailability score of 0.11. Its synthetic accessibility score stands at 6.51, indicating considerable synthetic complexity.

Beta-sitosterol, a plant-derived sterol, is recognized for its notable antioxidant and anti-inflammatory activities. It has a molecular weight of 414.71 g/mol, six rotatable bonds, one hydrogen bond acceptor, and one hydrogen bond donor. Its polar surface area is  $20.23 \text{ \AA}^2$ , and the consensus  $\log P$  is 7.19. It infringes Lipinski's rule on molecular weight while adhering to the others, pointing to potential challenges in oral bioavailability and metabolic stability. The bioavailability score is 0.55, considered modest, and its synthetic accessibility is 6.3, reflecting relative difficulty in synthesis.

Its molecular weight, rotatable bonds, TPSA, and consensus  $\log P$  all fall within optimal ranges, with full adherence to the Lipinski, Ghose, Veber, Egan, and Muegge filters. It also benefits from a favorable bioavailability score and easier synthesis. Although Arb\_E and beta-sitosterol display certain drug-like features, they may serve as starting points for developing new anti-inflammatory agents.

As an established therapeutic for pain and inflammation, celecoxib is forecasted to exhibit mutagenicity, albeit below the toxicity threshold. Its maximum tolerated dose (MTD) is  $0.021 \log(\text{mg/kg/day})$ , also below the threshold. It shows no predicted inhibition of hERG I or hERG II channels, which regulate cardiac repolarization. The oral rat acute toxicity (LD50) is 2.027, exceeding the toxicity cutoff, while the chronic toxicity (LOAEL) is 0.963, falling below it. No hepatotoxicity or skin sensitization is anticipated, nor toxicity toward *T. pyriformis* or fathead minnows.

Arb\_E, an unexplored candidate in humans, is not forecasted to be mutagenic. Its MTD is  $-0.151 \log(\text{mg/kg/day})$ , below the threshold. No hERG I or II inhibition is predicted. The LD50 in oral rat studies is 3.197 (above threshold), and LOAEL is 3.25 (above threshold). Hepatotoxicity, skin sensitization, and toxicity to *T. pyriformis* or minnows are not expected.

Beta-sitosterol, known for anti-inflammatory and antioxidant effects, is similarly non-mutagenic in predictions. Its MTD is  $-0.621 \log(\text{mg/kg/day})$ , below the threshold. No hERG inhibition is foreseen. Oral rat LD50 is 2.552 (above threshold), while LOAEL is 0.855 (below threshold). It is not projected to cause hepatotoxicity, skin sensitization, or harm to *T. pyriformis* or minnows.

Overall, celecoxib emerges as the least concerning in terms of predicted toxicity, remaining below thresholds across categories. Arb\_E and beta-sitosterol raise minor flags but largely stay below thresholds in most areas.

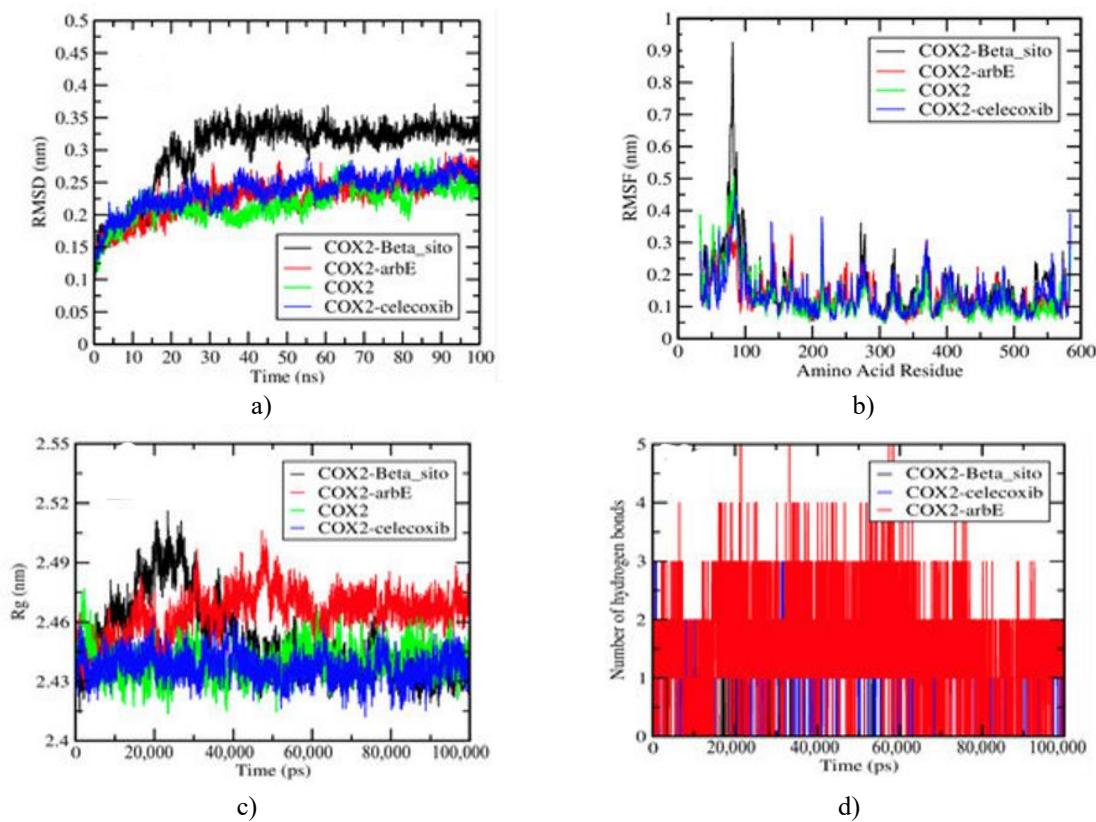
Importantly, these are computational estimates only; real-world performance may vary, underscoring the need for empirical validation through experimental testing.

#### Molecular dynamics and simulation analysis

Following completion of the simulations, trajectory data from GROMACS 2018 were processed using XMGRACE version 5.1. Two-dimensional plots were generated to evaluate root-mean-square fluctuation (RMSF), root-mean-square deviation (RMSD), radius of gyration (RoG), and hydrogen bonding over a 100 ns timeframe.

The Beta\_sito–COX-2 complex exhibited the highest RMSD, reaching 0.3 nm, while maintaining stable trajectories. In contrast, apo COX-2 (in water), COX-2–Arb\_E, and COX-2–celecoxib complexes displayed deviations between 0.15 and 0.25 nm (**Figure 6a**). The COX-2 and COX-2–Arb\_E systems averaged around 0.2 nm. RMSF values across complexes spanned 0.1 to 0.9 nm, with most averaging near 0.1 nm except for notable peaks in the 70–100 residue segment (**Figure 6b**).

Radius of gyration metrics reflect structural compactness and folding stability, providing insight into protein integrity when bound to ligands. Values ranged from 2.43 to 2.52 nm across systems. Apo COX-2, Beta\_sito-bound, and celecoxib-bound complexes clustered near 2.46 nm. The Arb\_E complex registered slightly elevated values above 2.46 nm, with a generally steady profile aside from minor variations between 20 and 40 ns (**Figure 6c**).



**Figure 6.** Trajectory-derived plots. (a) RMSD trajectories for the COX-2–Beta\_sito complex (black), COX-2–Arb\_E complex (red), apo COX-2 in water (green), and COX-2–celecoxib complex (blue). (b) RMSF profile illustrating per-residue fluctuations. (c) Radius of gyration (Rg) graph depicting the structural compactness and folding of COX-2 when bound to Beta\_sito, Arb\_E, or celecoxib. (d) Graph displaying the count of intermolecular hydrogen bonds across the 100 ns simulation for the selected complexes.

Hydrogen bonding is critical for stabilizing ligand–protein complexes and serves as a key metric in evaluating interaction strength and thermodynamic properties [61]. The hydrogen bond analysis revealed that the COX-2–Arb\_E complex maintained five hydrogen bonds throughout the simulation, whereas the COX-2–Beta\_sito complex sustained only one. The COX-2–celecoxib complex, in comparison, formed three hydrogen bonds (**Figure 6d**).

#### MM-PBSA results

We conducted a comparative binding free energy assessment for the ligands Arb\_E, Beta\_sito, and celecoxib within their respective COX-2 complexes (COX-2–Arb\_E, COX-2–Beta\_sito, and COX-2–celecoxib), with results compiled in **Table 3**. The calculated binding free energies ( $\Delta G_{bind}$ ) showed that Arb\_E achieved the most favorable value of  $-277.602$  kJ/mol, surpassing Beta\_sito ( $-214.385$  kJ/mol) and celecoxib ( $-193.635$  kJ/mol). Net differences highlighted substantial advantages:  $-83.967$  kJ/mol (Arb\_E versus celecoxib),  $-63.217$  kJ/mol (Arb\_E versus Beta\_sito), and  $-20.75$  kJ/mol (Beta\_sito versus celecoxib), underscoring stronger binding energetics for Arb\_E and Beta\_sito relative to the reference compound.

**Table 3.** Components of binding free energy for the selected complexes derived from MM-PBSA calculations.

S.N0.	Ligands	Van der Wall Energy (kJ/mol)	Electrostatic Energy (kJ/mol)	Polar Salvation Energy (kJ/mol)	SASA Energy (kJ/mol)	Binding Energy (kJ/mol)
1.	Arb_E	$-300.730$ $+/-13.113$	$-22.633$ $+/-9.119$	$47.260$ $+/-188.830$	$-28.499$ $+/-0.977$	$-277.602$ $+/-39.964$
2.	Beta_sito	$-232.379$ $+/-11.525$	$-0.160$ $+/-2.069$	$39.170$ $+/-34.210$	$-21.016$ $+/-1.008$	$-214.385$ $+/-36.906$
3.	Celecoxib	$-220.267$ $+/-0.184$	$-59.621$ $+/-0.124$	$103.2250$ $+/-0.94$	$-16.972$ $+/-0.011$	$-193.635$ $+/-0.573$

Through molecular docking, we examined the binding profiles of Beta\_sito—a phytosterol recognized for its anti-inflammatory effects—against multiple targets: COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase. The results position Beta\_sito as a preferential COX-2 inhibitor over COX-1, a dual inhibitor of PDE4 and PDE7, a strong inhibitor of TNF- $\alpha$ , and a moderate inhibitor of IL-1 $\beta$ . High affinities were also observed for IL-17A and IL-17D, although the physiological consequences on these cytokines remain to be clarified. Overall, Beta\_sito holds promise as a therapeutic candidate for inflammatory conditions, pending further validation of its *in vivo* effects.

#### Conclusion

In silico methodologies have greatly advanced drug discovery and development, especially within the field of anti-inflammatory research. The intricate architecture of biological systems poses difficulties in accurately modeling and predicting drug impacts. Additionally, limited experimental validation data and potential unsuitability of certain compounds or targets for computational analysis present further challenges. Despite these limitations, computational strategies have successfully identified promising hit compounds, advancing them through the drug development pipeline and occasionally to market approval. Ongoing efforts focus on enhancing model accuracy and dependability by integrating more empirical evidence and refining algorithmic approaches. Molecular docking was applied to evaluate the binding affinities and interaction patterns of the novel compound with multiple targets: COX-1, COX-2, PDE4, PDE7, IL-17A, IL-17D, TNF- $\alpha$ , IL-1 $\beta$ , prostaglandin E2, and prostaglandin F synthase. The compound demonstrated selectivity for COX-2 inhibition over COX-1, dual inhibition of PDE4 and PDE7, and moderate binding to IL-17A and IL-17D. Conversely, weaker affinities were observed toward TNF- $\alpha$  and IL-1 $\beta$ , suggesting minimal influence on their pro-inflammatory pathways. Overall, the compound exhibits promise as a therapeutic agent for inflammatory disorders. Subsequent investigations are essential to corroborate these computational outcomes experimentally. Thus, the examined natural compounds emerge as prospective anti-inflammatory candidates, warranting additional *in vitro* and *in vivo* testing to facilitate the creation of new anti-inflammatory therapeutics. The provided insights may guide the pharmaceutical sector in pursuing novel anti-inflammatory drug development.

**Acknowledgments:** None

**Conflict of Interest:** None

**Financial Support:** None

**Ethics Statement:** None

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