Identification of potential human pancreatic α-amylase inhibitors from natural products by molecular docking, MM/GBSA calculations, MD simulations, and ADMET analysis

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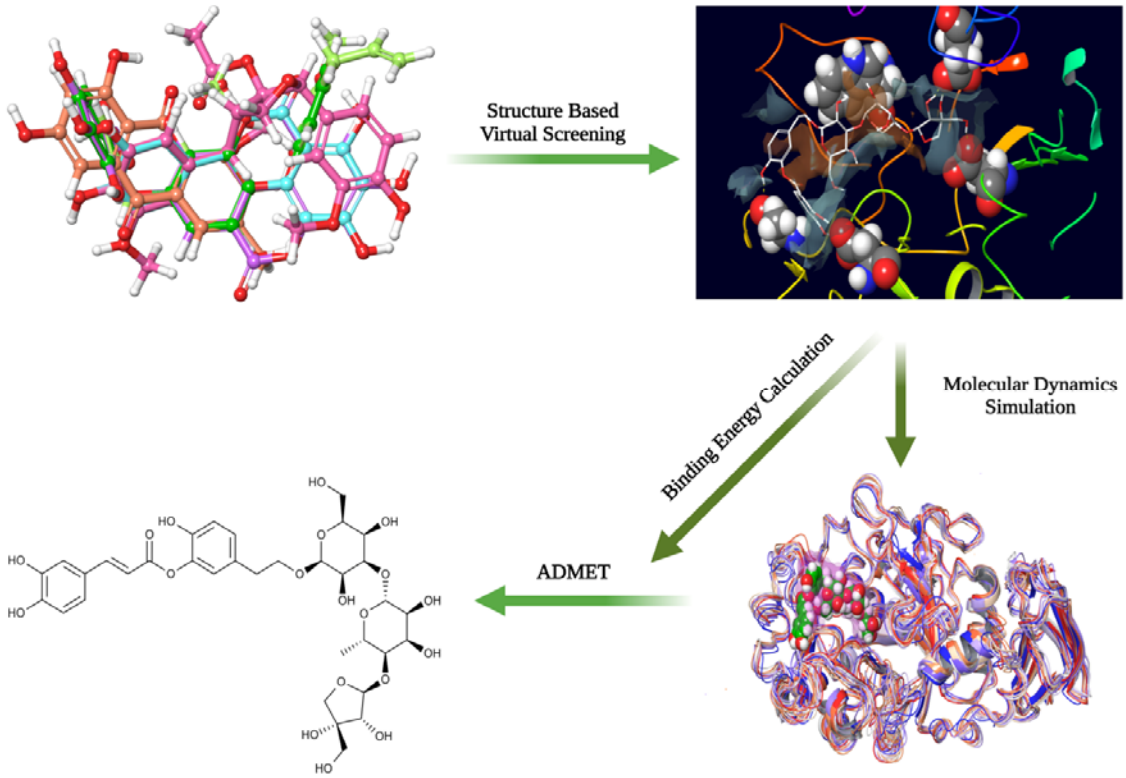
Graphical Abstract



Abstract

Human pancreatic α-amylase (HPA), which works as a catalyst for carbohydrate hydrolysis, is one of the viable targets to control type 2 diabetes. The inhibition of α-amylase lowers blood glucose levels and helps to alleviate hyperglycemia complications. Herein, we systematically screened the potential HPA inhibitors from an in-house library of natural products by molecular modeling. The modeling encompasses molecular docking, MM/GBSA binding energy calculations, MD simulations, and ADMET analysis. This research identified newboulaside B, newboulaside A, quercetin-3-O-β-glucoside, and sasastilboside A as the top four potential HPA inhibitors from the library of natural products, whose Glide docking scores and MM/GBSA binding energies range from -9.191 to -11.366 kcal/mol and -19.38 to -50.29 kcal/mol, respectively. Based on the simulation, among them, newboulaside B was found as the best HPA inhibitor. Throughout the simulation, with the deviation of 3Å (acarbose = 3Å), it interacted with ASP356, ASP300, ASP197, THR163, ARG161, ASP147, ALA106, and GLN63 via hydrogen bonding. Additionally, the comprehensive ADMET analysis revealed that it has good pharmacokinetic properties having not acutely toxic, moderately bioavailable, and non-inhibitor nature toward cytochrome P450. All the results suggest that newboulaside B might be a promising candidate for drug discovery against type 2 diabetes.

Keywords: Type 2 Diabetes, Human Pancreatic α-Amylase, Natural Products, Molecular Modeling, Newboulaside B

1. Introduction

Type 2 diabetes, associated with hyperglycemia, is a long-term endocrine metabolic disorder. It is most prevalent and caused by aberrant insulin activity. It causes various chronic complications. Despite medical improvements, it is still one of the leading causes of death in adults [1,2].

Delaying the digestion of carbohydrates ameliorates hyperglycemia impacts. Multiple enzymes, including human pancreatic α-amylase (HPA) and α-glucosidase, are involved in the hydrolysis of carbohydrates. According to the study, in the HPA, catalytic residues (ASP197, GLU233, and ASP300) are found in an eight-stranded parallel beta-barrel in domain A (1-99, 169-404). In carbohydrate hydrolysis, ASP197 acts as a nucleophile, and GLU233 and ASP300 may act as acid/base catalysts. Therefore, one of the proven scientific methods to manage type 2 diabetes is the inhibition of HPA by ligand, which lowers postprandial blood glucose levels [3–5].

A wide variety of oral anti-diabetic medications, including acarbose and miglitol, were used by doctors to treat type 2 diabetes. The undesirable, serious side effects, however, are becoming apparent. Therefore, the need for efficient, affordable, and low-toxic anti-diabetic medications is urgent [6–9].

To treat diabetes, ancient people relied on medications from natural sources [10]. Therefore, natural products derived from these sources may be an appealing strategy for controlling type 2 diabetes [11]. The research is ramping up to explore a potent HPA inhibitor. The *in vitro* study shows that different natural products exhibit α-amylase inhibition activity. There have been several *in vitro* studies on natural products up to this moment, but an efficient HPA inhibitor is still lacking. Therefore, to identify the potential HPA inhibitor from natural products, structure-based molecular modeling was employed. The modeling comprises molecular docking, MM/GBSA binding energy calculations, molecular dynamics

simulations, and absorption, distribution, metabolism, excretion, and toxicity (ADMET) analysis.

This computational study proposed newboulaside B as the potential HPA inhibitor from natural products. The study also suggests a possible binding mode of the inhibitor with HPA.

2. Material and methods

2.1 Curation and preparation of ligands

Based on *in vitro* data on α-amylase, an in-house library of 39 ligands (including acarbose as the standard ligand) was created to screen a potential HPA inhibitor. Supplementary data contains information about the ligands (**Table S1**). The ligand structures were sketched in Maestro's 2D sketcher and converted to a low-energy 3D state using Schrödinger's LigPrep module [12]. The OPLS4 force field was employed to generate a low-energy state structure [13]. Additionally, at pH 7.0 ± 2.0, Epik produced tautomeric and ionization states and generated a maximum of 32 conformers per ligand.

2.2 Protein preparation and target validation

The structure of HPA was obtained from the RCSB protein data repository and prepared using Schrödinger's Protein Preparation Wizard module (**Table S2**) [14,15]. It was preprocessed with Prime, which assigned bond ordering, added hydrogen atoms, and filled missing loops and side chains; Epik was then run at pH 7.0 ± 2.0 [16]. Additionally, after removing hetero groups, it was optimized by optimizing hydrogen bonding and minimized by employing the OPLS4 force field [17]. The prepared protein quality and its ligand binding region were assessed and validated by the SiteMap application [18]. By incorporating catalytic residues (ASP197, GLU233, and ASP300) receptor grid was created. Further, the cognate ligand was re-docked to validate the target.

2.3 Molecular docking and MM/GBSA binding energy calculation

Glide, in extra precision mode (XP), was used in the molecular docking of natural products

with HPA [19]. Schrödinger's prime module was employed to calculate the MM/GBSA binding energy of protein and ligand complexes. The implicit VSGB solvation model [20] and OPLS4 force field were employed to calculate the binding energy.

2.4 Molecular dynamics simulation

A common technique in drug discovery is rigid receptor-based molecular docking. However, pitfalls exist in it. Therefore, to study the molecular dynamics behavior of the protein-ligand complex, the 200 ns molecular dynamics simulation was performed using the Academic Desmond 2019 GPU version [21]. The molecular system was solvated using the explicit solvation model (SPC) under orthorhombic periodic boundary conditions with a buffer region of 10 Å. The default OPLS_2005 force field was used [22]. Na^+ and Cl^- ions were used in the system builder to neutralize the system. The system was made more relaxed by doing a short-duration simulation and minimization. The Noose-Hoover thermostat method and Martyna-Tobias-Klien barostat method were employed in the NPT ensemble to maintain the temperature and pressure at 300 K and 1.01325 bar, respectively. A multiple-time step RESPA integrator was used in the dynamics study of bonded, near, and far bonded interactions.

2.5 ADMET analysis

QikProp of Schrödinger was used to calculate the pharmacokinetic characteristics of the best ligand [23]. Additionally, using admetSAR, ProTox-II, pkCSM, and the SwissADME web server, the hit's ADMET properties were analyzed [24–27].

3. Results and discussion

3.1 Protein preparation and target validation

Before performing molecular docking, human pancreatic α-amylase (HPA) was prepared and validated. The catalytic region's validity was confirmed using SiteMap. It predicted SiteScore, Dscore, volume, and balance of the most likely ligand-binding (catalytic) area to

be 0.985, 1.010, 341.285, and 0.751, respectively, which meet the almost threshold. TRP58, TRP59, TYR62, GLN63, HIE101, TYR151, LEU162, LEU165, ARG195, ASP197, ALA198, LYS200, HIS201, GLU233, VAL234, ILE235, HIE299, ASP300, and HIE305 residues were found in this area, confirming the catalytic region as the ligand-binding region (**Table S3, Fig S1**). Further, the target, RMSD of less than 2 Å, was validated by re-docking the cognate ligand (**Fig S1**). As a result, the SiteMap calculation, and cognate ligand re-docking all support the target protein's feasibility for further modeling.

3.2 Molecular docking and MM/GMBSA binding energy calculation

In this study, 38 molecules and acarbose were docked with HPA using Glide XP (extra precision mode). Then, MM/GBSA was employed to predict the binding energy between the protein and ligand complex. Based on the docking pose and score, the molecular docking showed that newboulaside B, newboulaside A, quercetin-3-O-β-glucoside, and sasastilboside A are the best molecules (**Table 1)**. Among them, according to the literature, newboulaside B, newboulaside A, and sasastilboside A are all new molecules [28,29]. The MM/GBSA approach, among them, showed that newboulaside B is the best binding molecule.

The newboulaside B docking score and MM/GBSA binding energy with HPA were predicted to be -11.366 kcal/mol (acarbose = -12.581 kcal/mol) and -50.29 kcal/mol (acarbose = -59.77 kcal/mol), respectively. It interacted with active site residues (ASP197 and ASP300) as well as additional binding site residues (ASN105, ALA106, ASP147, THR163, and ARG195) via hydrogen bonding, according to the molecular docking (**Fig 1a, Fig 1b**).

The binding of HPA by newboulaside B was aided more by hydrogen bonds (-6.93) and hydrophobic enclosure reward (-0.25) than in the binding of HPA by acarbose (**Fig 1c, Fig 1d**). In comparison to other parameters, in the binding, the hydrogen bond contribution was found significant. So, we speculate that inhibition of HPA by newboulaside B might be due to the formation of hydrogen bonding with active site residues ASP197 and ASP300.

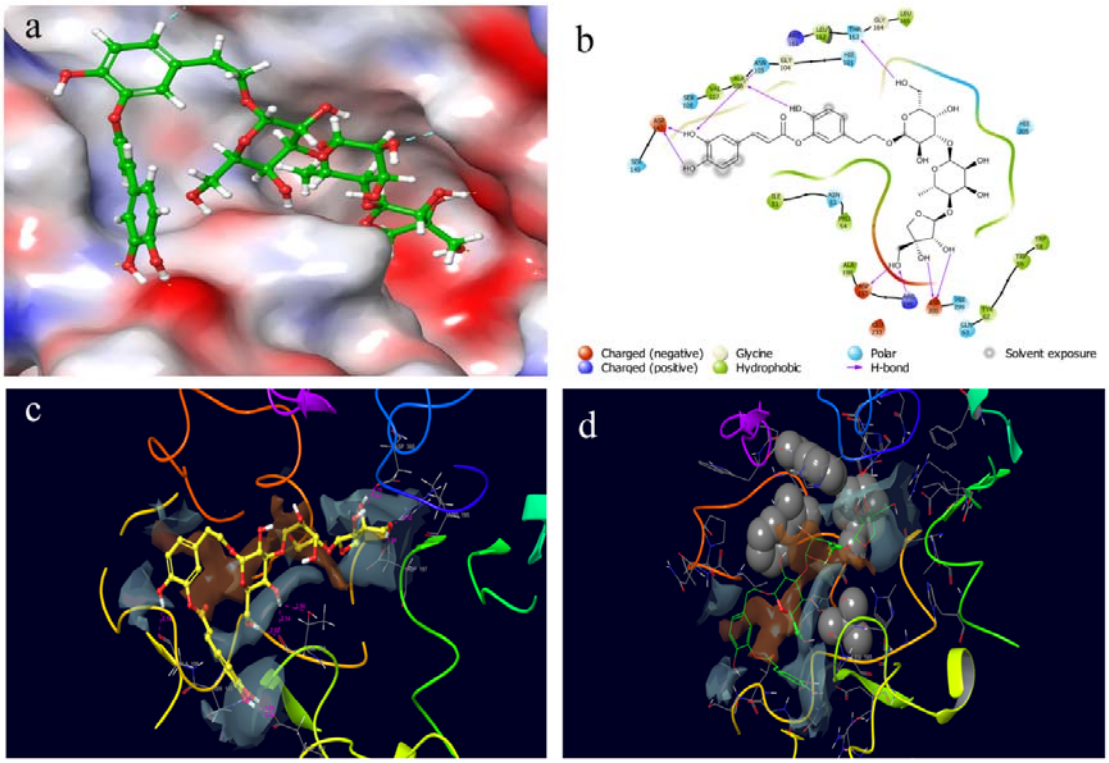


Fig 1. Docked poses and molecular interactions of newboulaside B in the binding site of HPA: (a) 3D molecular surface diagrams, and (b) 2D ligand interactions of newboulaside B with HPA. **Glide XP molecular docking contributing term in the HPA and newboulaside B complex:** (c) HBOND (hydrogen bond) between HPA and newboulaside B (pink interaction) and (d) PhobEn (hydrophobic enclosure reward) of HPA (CPK gray), and PhobEn of newboulaside B (green ball and stick). The hydrophobic/hydrophilic map is represented as gray/brown patches.

When the ligand changes, it undergoes structural remodeling, resulting in a change in binding affinity. The docking score and MM/GBSA binding energy of the HPA newboulaside A complex were predicted to be -10.533 kcal/mol and -19.38 kcal/mol, respectively. ASN53, TRP59, GLN63, ASP197, GLU233, and HIE305 interacted with newboulaside A via hydrogen bonding (**Fig 2a, Fig 2b**). TRP59, THR163, GLU233, and HIE305 formed hydrogen bonds with quercetin-3-O-*β*-glucoside, while TRP59 interacted via pi-pi interaction, with a docking score of -10.038 kcal/mol, and the MM/GBSA binding energy of -

19.65 kcal/mol, respectively (**Fig 2c, Fig 2d**). Similarly, THR163, ARG195, GLU233, HIE299, and ASP300 interacted with sasastilboside A via hydrogen bond, with a docking score of -9.191 kcal/mol and the MM/GBSA binding energy of -36.58 kcal/mol, respectively (**Fig 2e, Fig 2f**).

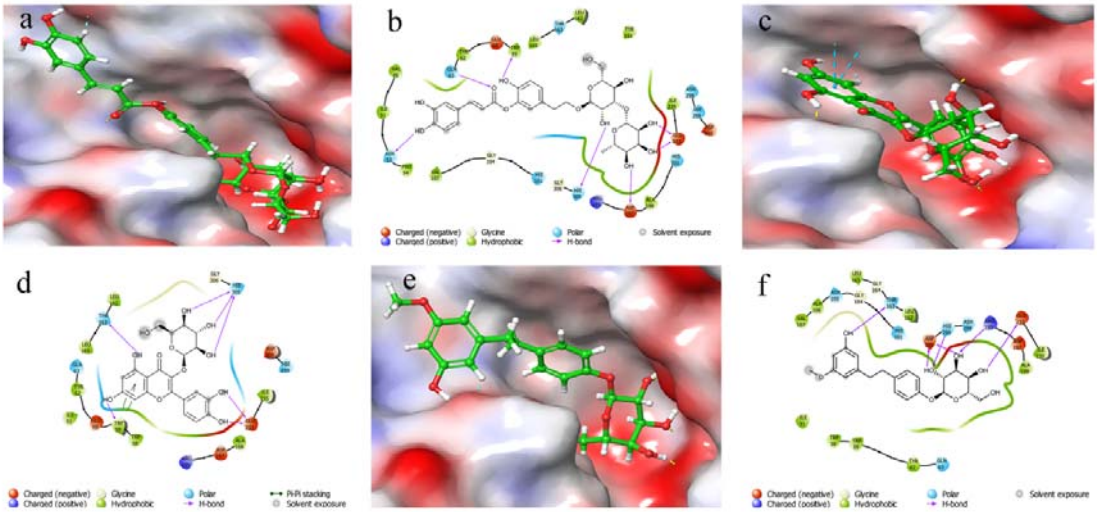


Fig 2. Docked poses and molecular interactions of HPA with inhibitors: 3D molecular surface diagrams and 2D ligand interactions of newboulaside A (a) and (b), quercetin-3-O-*β*-glucoside (c) and (d), and sasastilboside A (e) and (f), respectively. The hydrogen bonds are represented as pink lines.

Table 1. Glide molecular docking and MM/GBSA binding energy of ligands

SN	Compound	docking score (kcal/mol)	glide gscore (kcal/mol)	MM/GBSA dG Bind (kcal/mol)
1	acarbose	-12.581	-12.832	-59.77
2	newboulaside B	-11.366	-11.514	-50.29
3	newboulaside A	-10.533	-10.68	-19.38
4	quercetin-3-O-*β*-glucoside	-10.038	-10.067	-19.65
5	sasastilboside A	-9.191	-9.192	-36.58
6	ligularoside A	-8.910	-8.91	-23.11

7	mangiferin	-8.895	-9.274	-33.56
8	daucosterol	-8.411	-8.411	-22.33
9	kaempferol-3-O-*β*-glucoside	-8.031	-8.06	-28.07
10	rhododendron	-7.436	-7.436	-26.13
11	valoneic acid dilactone	-7.48	-7.687	-39.38
12	DDBT	-7.174	-7.275	-20.65
13	myricetin	-7.095	-7.132	-34.03
14	peruviose E	-6.894	-6.894	-23.57
15	peruviose B	-6.888	-6.888	-26.28
16	peruviose D	-6.881	-6.881	-44.62
17	chrysoeriol	-6.655	-6.695	-10.06
18	*α*-viniferin	-6.464	-6.464	-44.5
19	1-acetoxypinoresinol	-5.451	-5.451	-29.28
20	emodin	-5.23	-5.323	-17.72
21	momilactone B	-5.129	-5.129	-6.6
22	*β*-sitosterol	-4.972	-4.972	-28.93
23	3□-geranylchalconaringenin	-4.863	-5.362	-12.56
24	diosgenin	-4.786	-4.786	-33.8
25	momilactone A	-4.772	-4.772	-29.36
26	lupenone	-4.658	-4.658	-33.24
27	rostratazine B	-4.582	-4.582	-19.18
28	ursolic acid	-4.42	-4.426	-22.29
29	norchelerythrine	-4.414	-4.415	-36.82
30	cycloeucalenone	-4.314	-4.314	-6.33
31	skimmianine	-4.151	-4.164	-39.66

32	sesamine	-4.147	-4.147	-31.28
33	gedunin	-4.057	-4.057	-17.86
34	chaylbemide B	-4.038	-4.038	-8.13
35	oleanolic acid	-3.866	-3.872	-5.88
36	dehydrodieugenol B	-3.623	-3.633	-40.32
37	trans-fagaramide	-3.616	-3.616	-5.16
38	chaylbemide C	-3.452	-3.452	-11.23
39	chaylbemide A	-2.716	-2.716	-16.86

Key: DDBT - 2-(4-(3,5-dihydroxyphenoxy)-3,5-dihydroxyphenoxy) benzene-1,3,5-triol

3.3 Molecular dynamics simulation

Molecular docking predicts the binding mode between a protein and a ligand. However, it is riddled with flaws and unable to foretell the stability and dynamic behavior of the molecule during the binding process. Understanding these by experimental means is also tedious. However, by simulating molecular activity in a computational setting, we can forecast experimentally challenging molecular behavior. Therefore, the top four HPA ligand (acarbose, newboulaside B, newboulaside A, quercetin-3-O-*β*-glucoside, and sasastilboside A) complexes from molecular docking were subjected to the 200 ns of 1000 frame molecular dynamics simulation to confirm the hit.

Monitoring of protein secondary structure elements (SSE) revealed that the majority of strands and helices contributed 100% throughout the simulation and accounted for 33.84 percent of the total composition; the time versus residue index plot also revealed that strands near the binding pocket (ASP197, GLU233, and ASP300) contributed almost time, indicating the structure of HPA's stability. However, due to the loop, there may be a little more fluctuation around residues 130 and 370 (**Fig S2**).

The molecular dynamics simulation anticipated that newboulaside B would be remarkably

stable with HPA. The backbone of HPA in the newboulaside B complex was deviated by less than 2 Å. After a sharp initial deviation to 1.75 Å, it nearly stabilized. Throughout the simulation, newboulaside B deviated around 1.5 Å (acarbose = 1.5 Å) in its alignment with itself and approximately 3 Å (acarbose = 3 Å) in its alignment with the protein (**Fig 3a**).

In the interaction region, the C-alpha residues of the HPA newboulaside B complex fluctuated about 1 Å, but in the HPA acarbose complex, after residue 300, they fluctuated largely (**Fig 3c, Fig 3d**). Throughout the simulation, newboulaside B fluctuated less than 1 Å (acarbose = 1.2 Å) in its alignment with itself and less than 1.8 Å (acarbose = 2 Å) in its alignment with protein (**Fig S3a, Fig S3b**). The stability of other compounds, such as newboulaside A, quercetin-3-O-*β*-glucoside, and sasastilboside A, was predicted to be much less than that of acarbose and newboulaside B. The observed RMSD of their fitting with protein was found more than 3.5 Å (**Fig 3b**). As a result, among top compounds, acarbose, and newboulaside B's stability with HPA may be comparable, as indicated by the aforementioned comparative deviations and fluctuations.

A minimum of 10 protein-ligand interactions, of which at least 5 were significant, were observed between HPA and acarbose as well as HPA and newboulaside B throughout the simulation (**Fig 4a, Fig 4c**). Acarbose interacted with ASP300, ASP197, and THR163 via hydrogen bonds over 70% of the simulated duration (**Fig 4b**). Whereas, newboulaside B interacted with residues (ASP197, ASP147, and ALA106) over 90% of the simulation period via hydrogen bonding. Further, catalytic residue (ASP300) also interacted via multiple hydrogen bonding (**Fig 4d**).

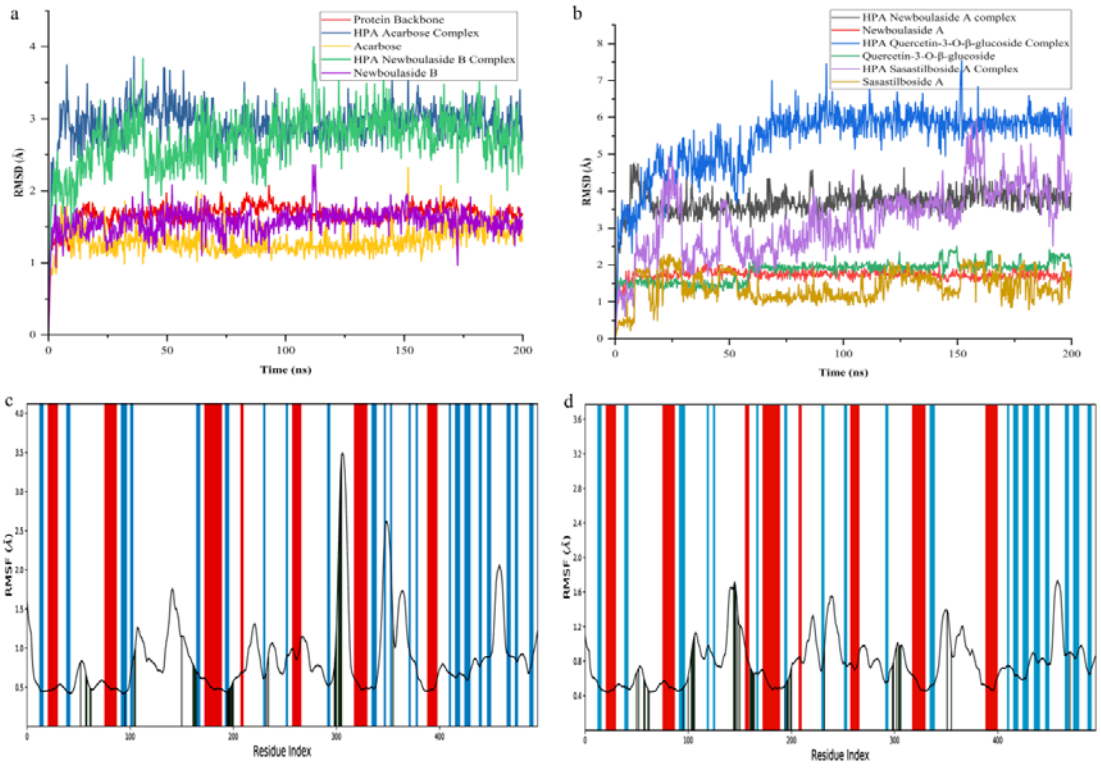


Fig 3. RMSD and RMSF analysis of MD simulation trajectory: The RMSD plot obtained for HPA (a) acarbose and newboulaside B complex, and (b) newboulaside A, quercetin-3-O-*β*-glucoside, and sasastilboside A complex. The RMSF plot was obtained for HPA (c) acarbose complex, and (d) newboulaside B complex. The strand, helix, and loop region of HPA are represented as blue, red, and white, respectively.

The timeline charts also showed that at least three bonds in the HPA complex of acarbose and newboulaside B are almost unbroken and interacted significantly throughout the simulation. THR163, ASP197, and ASP300 interacted via more or less uninterrupted bonding with acarbose, while TRP59 and GLU233 interacted via partial bonding (**Fig S4a**). Similarly, newboulaside B interacted via nearly continuous bonding with ALA106, ASP147, and ASP197, and partial bonding with GLN63, ARG161, THR163, ASP300, and ASP356 (**Fig S4b**). These interactions might help to prevent them from diffusing out from the ligand-binding pocket. This evidence substantiates the hypothesis that newboulaside B inhibits HPA. However, newboulaside A, quercetin-3-O-*β*-glucoside, and sasastilboside A demonstrated

fewer interactions with active site residues than newboulaside B, according to the protein-ligand interaction analysis (**Fig S5a, Fig S5c, Fig S5e**). Further, the HPA complexes of these three were more unstable than the complex of newboulaside B, according to the ligand-protein interaction diagram of MD simulation (**Fig S5b, Fig S5d, Fig S5f**). Overall, they exhibited significantly poorer interactions with HPA than acarbose and newboulaside B, as evidenced by the high deviations and weak interactions.

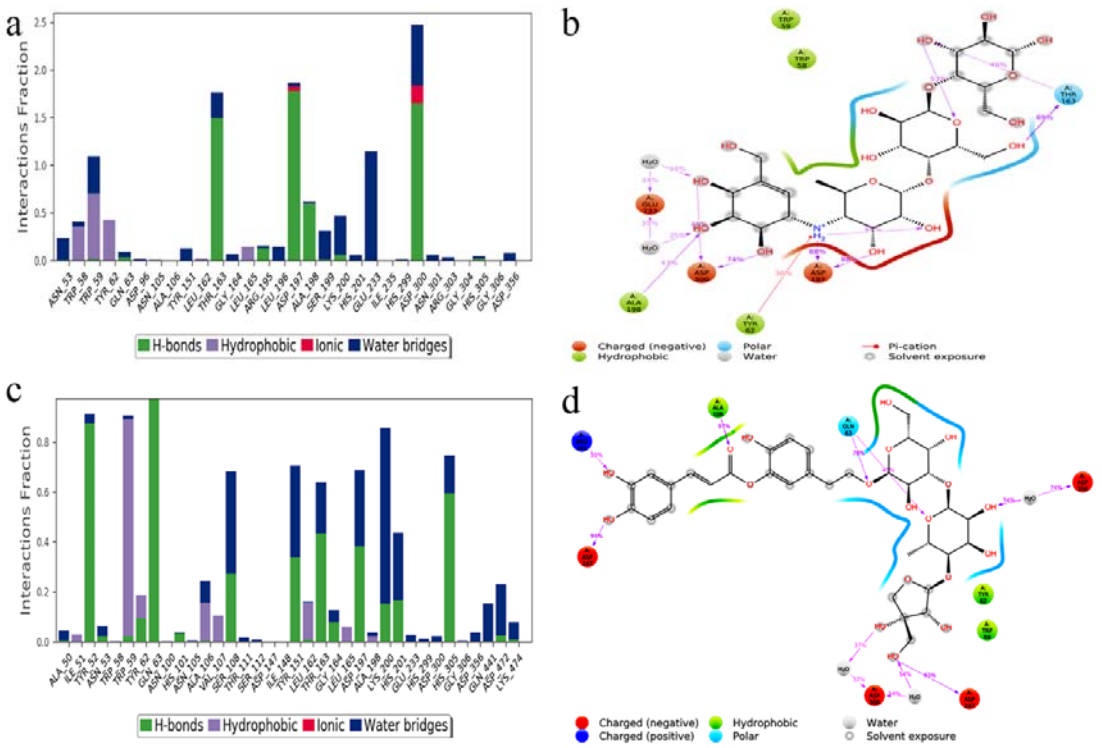


Fig 4. Analysis of inhibitor's molecular interaction and type of contact with HPA after MD simulations: Normalized stacked bar chart of HPA binding site residues interacting with (a) acarbose and (c) newboulaside B via hydrogen bonds, hydrophobic and ionic interactions, and water bridges. Detailed schematic interaction of (b) acarbose and (d) newboulaside B atoms with the binding site residues of HPA. Interactions happening more than 30% of the simulation times are shown.

The outcome of the HPA newboulaside B complex's molecular docking and MM/GBSA binding energy is supported by the molecular dynamics simulation, too. Thus, based on

comparative stability, binding affinity, and interactions with acarbose, newboulaside B is expected to be effective in inhibiting HPA.

Existing knowledge also reinforces our computational analysis. *Newbouldia laevis* (P. Beauv.), which is used in African traditional medicine to treat a variety of illnesses such as sickle cell, diarrhea, inflammation, aches, tumors, skin problems, hypertension, and diabetes, is reported to be the natural source of newboulaside B [30]. Ethanolic extracts and aqueous root extracts of the plant exhibited anti-diabetic activity in streptozocin-induced diabetic Wistar rats and alloxan-induced diabetic rats, respectively [31,32]. Ethanolic extracts and aqueous leaf extracts of the plant reported antioxidant activity in diabetic rats and insulin-inducing activity [33,34]. The methanolic extract of the plant suppressed induced diabetes by 60.2 percent [35].

Two new caffeic acid glycosides (newboulaside A and newboulaside B) isolated from ethanolic extracts of the *Newbouldia laevis*'s leaves inhibited α-amylase with IC_{50} values of 4.95 and 4.44 µg/mL, respectively (acarbose IC_{50} = 4.05 µg/mL) [28]. The aforementioned computational data also supports the binding nature of these compounds to HPA.

3.4 ADMET analysis

The drug should be highly selective and have as few side effects as possible. Due to effectiveness and unavoidable side effects, the therapeutic candidate has a high attrition rate at the late stage. ADMET problems arise due to the complexity of the biological system. The *in silico* study can help to reduce the risk of a drug candidate failure. As a result, as post-processing, identified hit (newboulaside B) drug-likeness and ADMET properties were analyzed comprehensively.

The ethanolic extract of *Newbouldia laevis* was proven to be safe in terms of acute toxicity [36]. The assessment of the ethanolic extract of the plant revealed a low toxicity profile [37]. This finding supports the traditional uses of the plant against diabetes. However, research on

the pure molecule was lacking. As a result, several models, including QikProp, admetSAR, ProTox-II, pkCSM, and SwissADME, were utilized to analyze the hit's pharmacokinetic properties (**Table S4 - Table S8**).

The QikProp computed lipophilicity (QPlogPo/w) of the hit -2.995 (-2.0 to 6.5), which indicates that the hit is more hydrophilic; this low lipophilicity may decrease absorption and distribution due to the lipoid nature of the cell membrane. Similarly, it predicted that hit is aqueous soluble with solubility value -2.52(-6.5 to 0.5) [38,39]. The water solubility of the hit is due to the hydroxyl group, which contributes to absorption. The hit is comparable to acarbose, according to molecular modeling; however, it defies recognized drug-likeness, it is partly due to its large molecular size.

The SwissADME projected that the hit would have poor intestinal absorption. Similarly, it predicted the hit as less skin permeable with LogKp value of -12.08 cm/s (acarbose = -16.30 cm/s). The pkCSM predicted CNS permeability (logPS) -5.747 (logPS<-3), which indicates that the hit is impermeable to CNS. The strong polarity, high molecular weight, and poor lipophilicity of this compound may be the cause of its limited absorption. QikProp's low human serum albumin binding value of the hit (-2.173) indicates the unbound molecule can easily reach the target [40]. As a result of the large molecular size, the hit may be moderately bioavailable on average.

The ProTox-II model projected the hit toxicity would be class V (slightly toxic), with an LD_{50} value of 5000 mg/kg, and also predicted that it is inactive for carcinogenicity, mutagenicity, and cytotoxicity. Additionally, it was evaluated with negative mitochondrial, carcinogenicity, and nephrotoxicity by the admetSAR, which indicates it is not acutely toxic.

The hit was predicted as negative skin sensitization by the admetSAR, which reveals that the molecule would not show a cutaneous inflammatory reaction. It also predicted that the hit would not inhibit CYP 2D6, CYP 1A2, CYP 2C19, CYP 2C9, and CYP 3A4. This property

helps to metabolize xenobiotics and reduce the adverse consequences of drug-drug interactions. Similarly, the admetSAR projected that the hit would be the non-inhibitor of OCT2, OATP2B1, and MATE1. Non-inhibition of OCT2, OATP2B1, and MATE1 help to distribute and excrete the second drug and reduces drug-drug interaction detrimental. Overall ADMET profile of newboulaside B might be good. However, further wet-lab research is necessary to support pharmacokinetics predictions.

4. Conclusions

The results of the current study imply that the computational approach effectively explores the potent human pancreatic α-amylase (HPA) inhibitor. Herein, the computational workflow, with almost similar binding affinity and stability to acarbose, identifies newboulaside B as the potential molecule for HPA inhibition. The study also shows a good ADMET profile for the molecule and reinforces prior reports. To further validate the outcome, wet-lab testing must be performed. The data presented here can be helpful for drug discovery against type 2 diabetes.

Data Accessibility

The data are provided in the electronic supplementary material.

Author's Contribution

Santosh Basnet: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing-original Draft, Funding Acquisition, Software, Validation; **Madhav Prasad Ghimire:** Resources for the Simulation, Technical Support in the Simulation, Writing Reviewing and Editing, Formal Assessment; **Tika Ram Lamichhane:** Technical Support in the Simulation, Writing Reviewing and Editing, Formal Assessment; **Rajendra Adhikari:** Resources for the Simulation, Technical Support in the Simulation, Writing Reviewing and Editing, Formal Assessment; **Achyut Adhikari:** Conceptualization, Supervision, Writing Reviewing and Editing, Funding Acquisition, Software, Project

Administration and Formal Assessment

Compliance with ethics requirement

There are no animal models used in this research.

Competing interest

The authors declare that there are no competing interests.

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Supplementary Information

Table S1-Table S8 and Fig S1-Fig S5's data are provided in the supplementary material.

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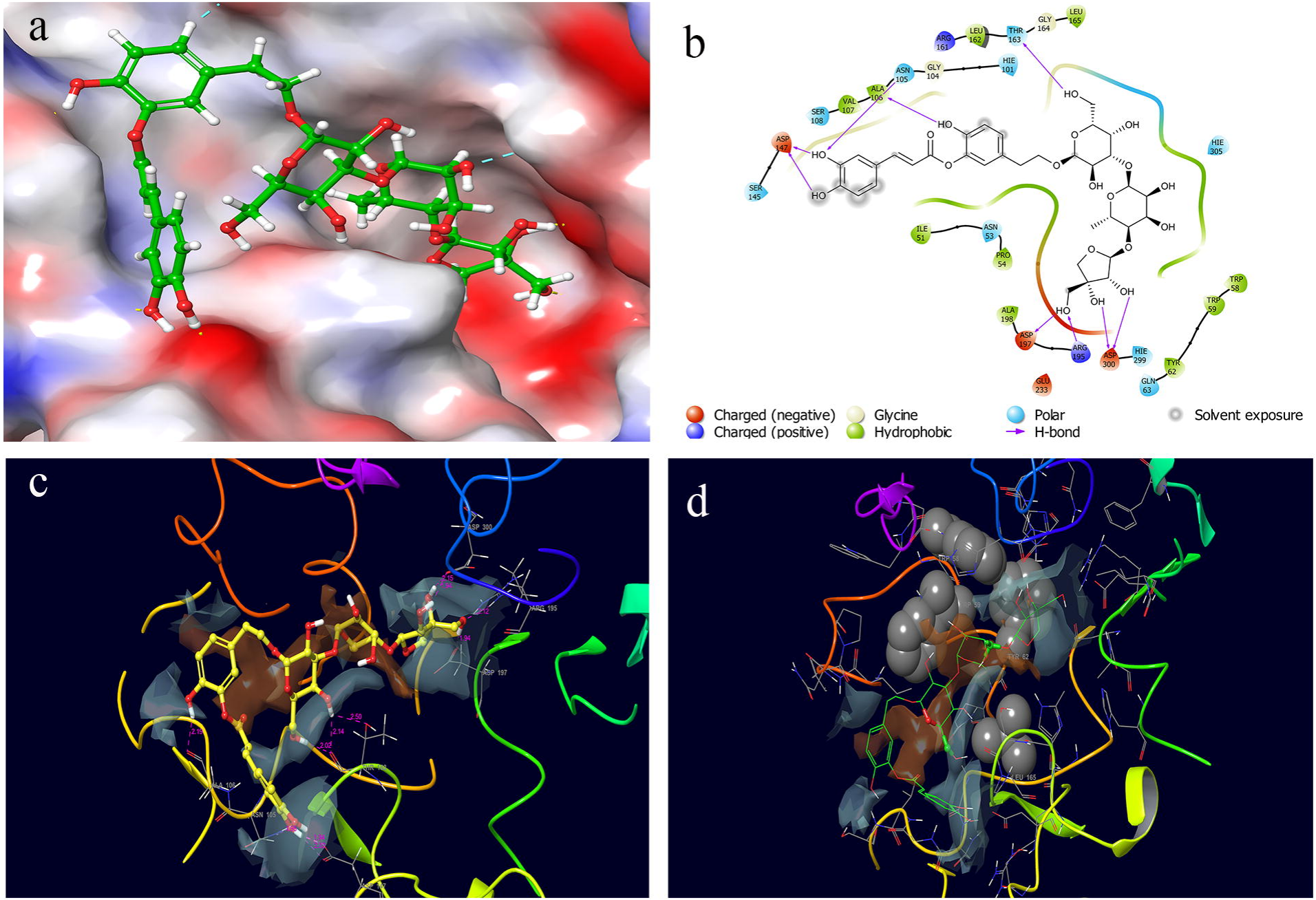
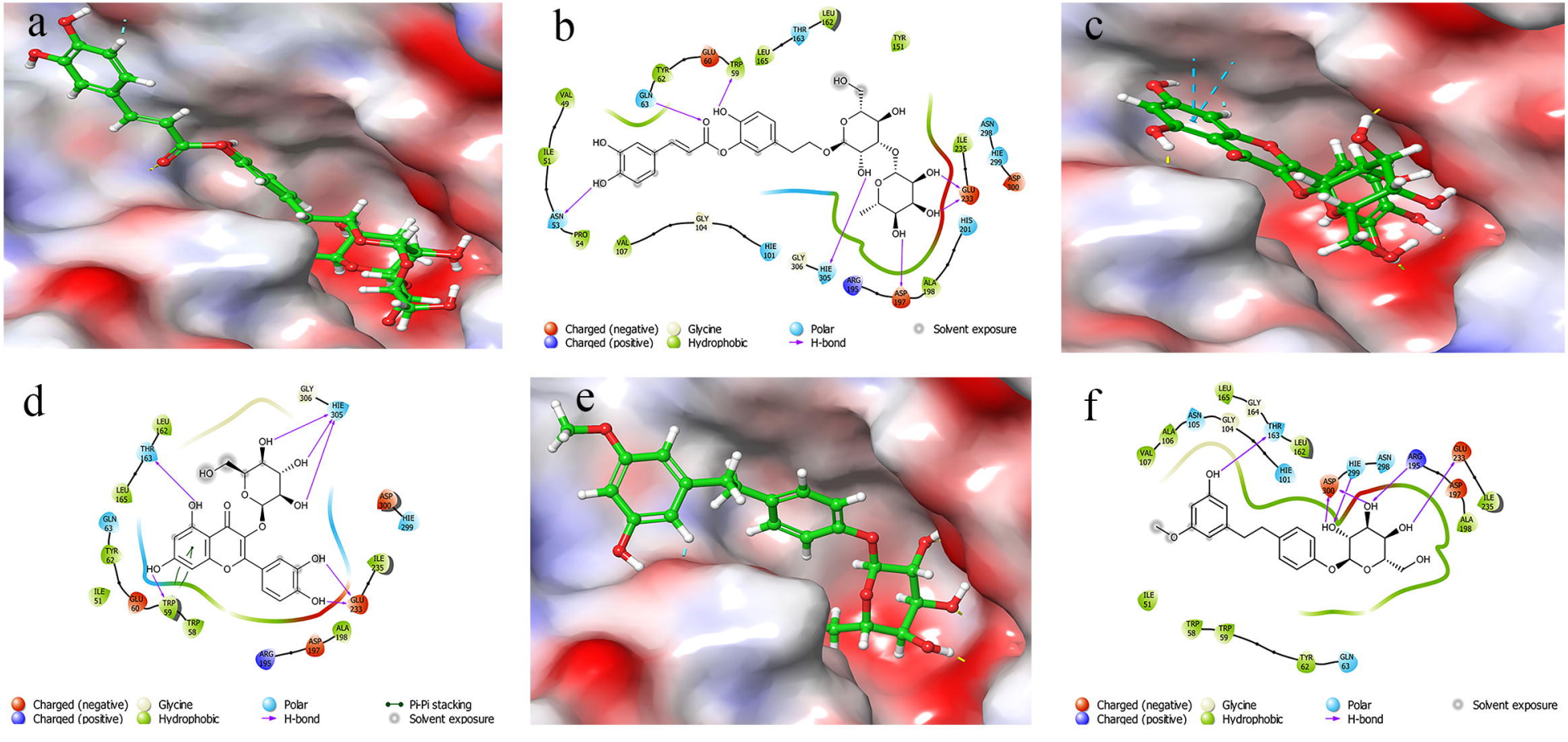
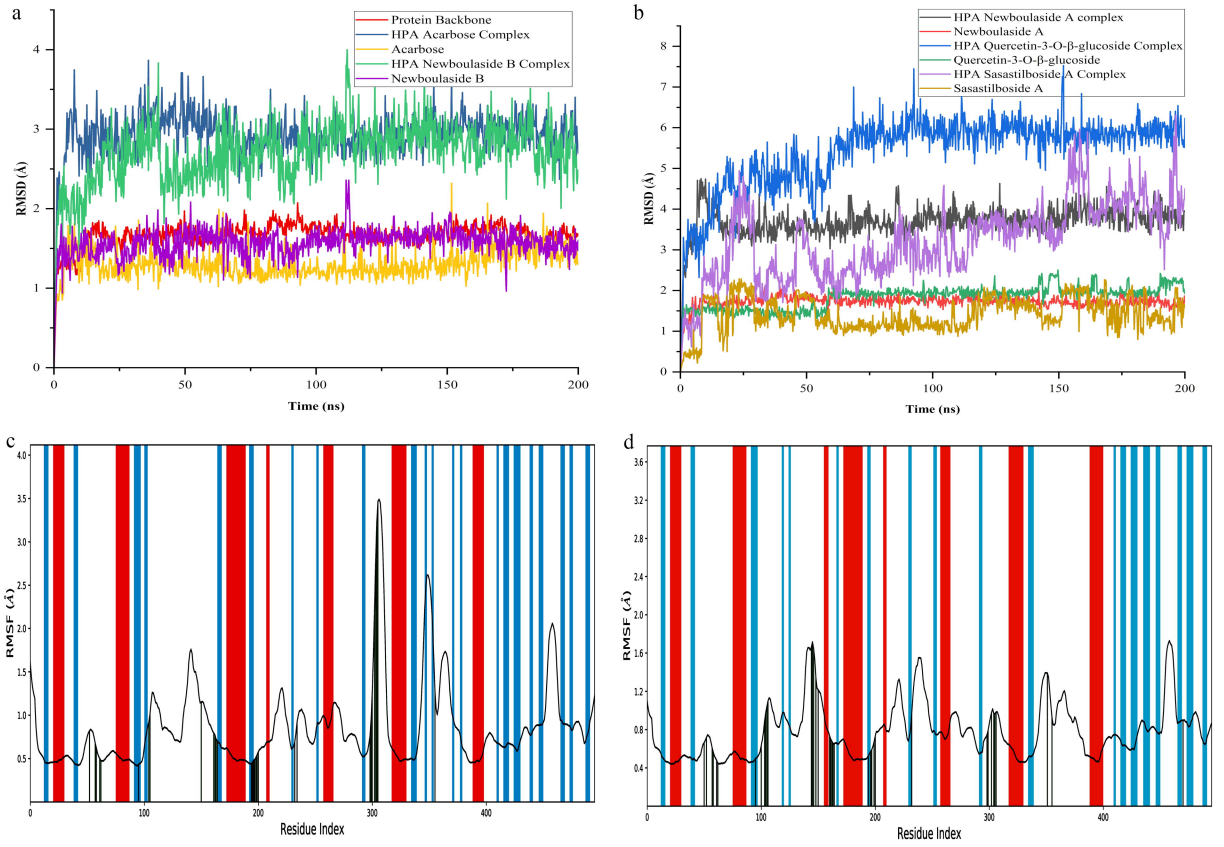
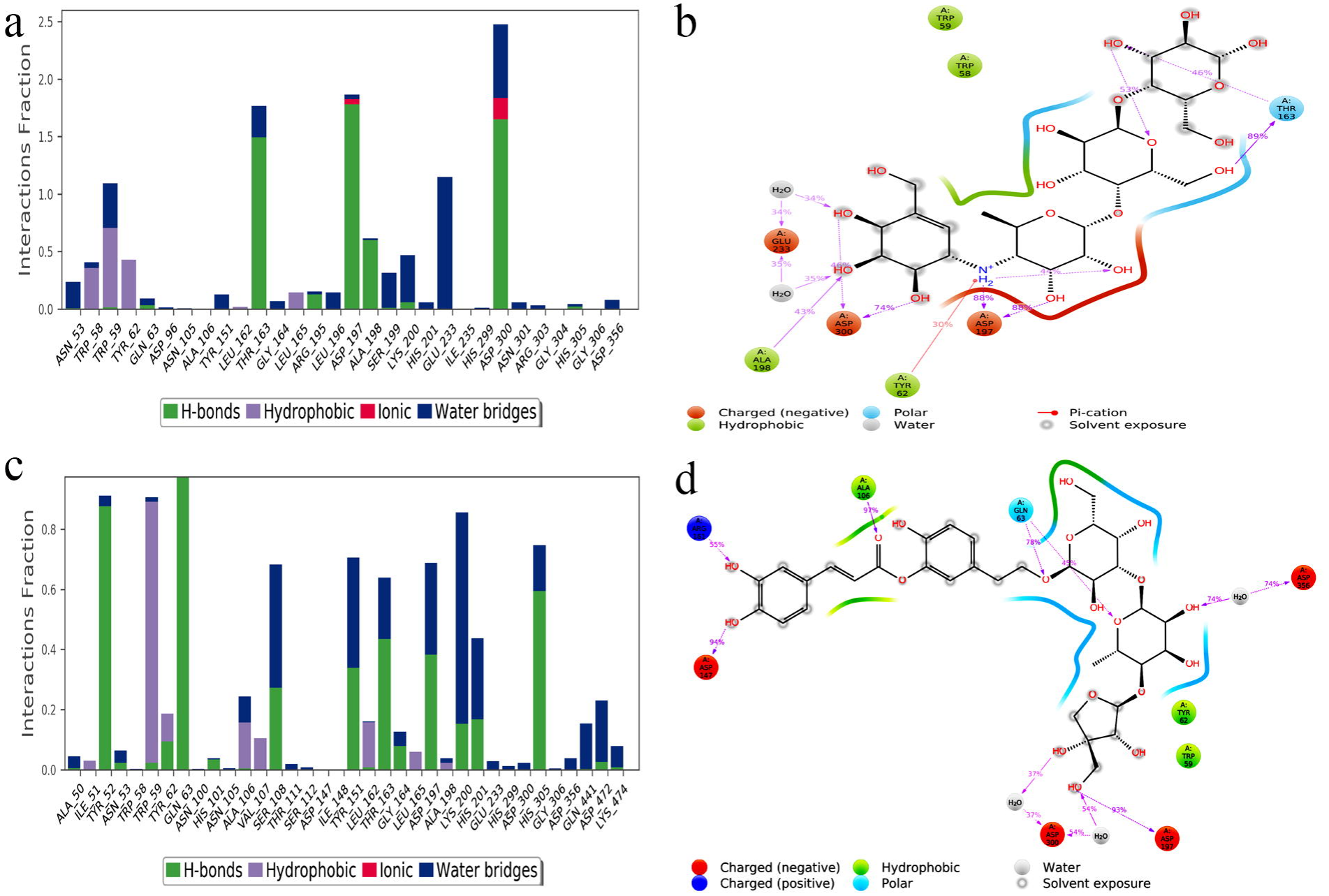
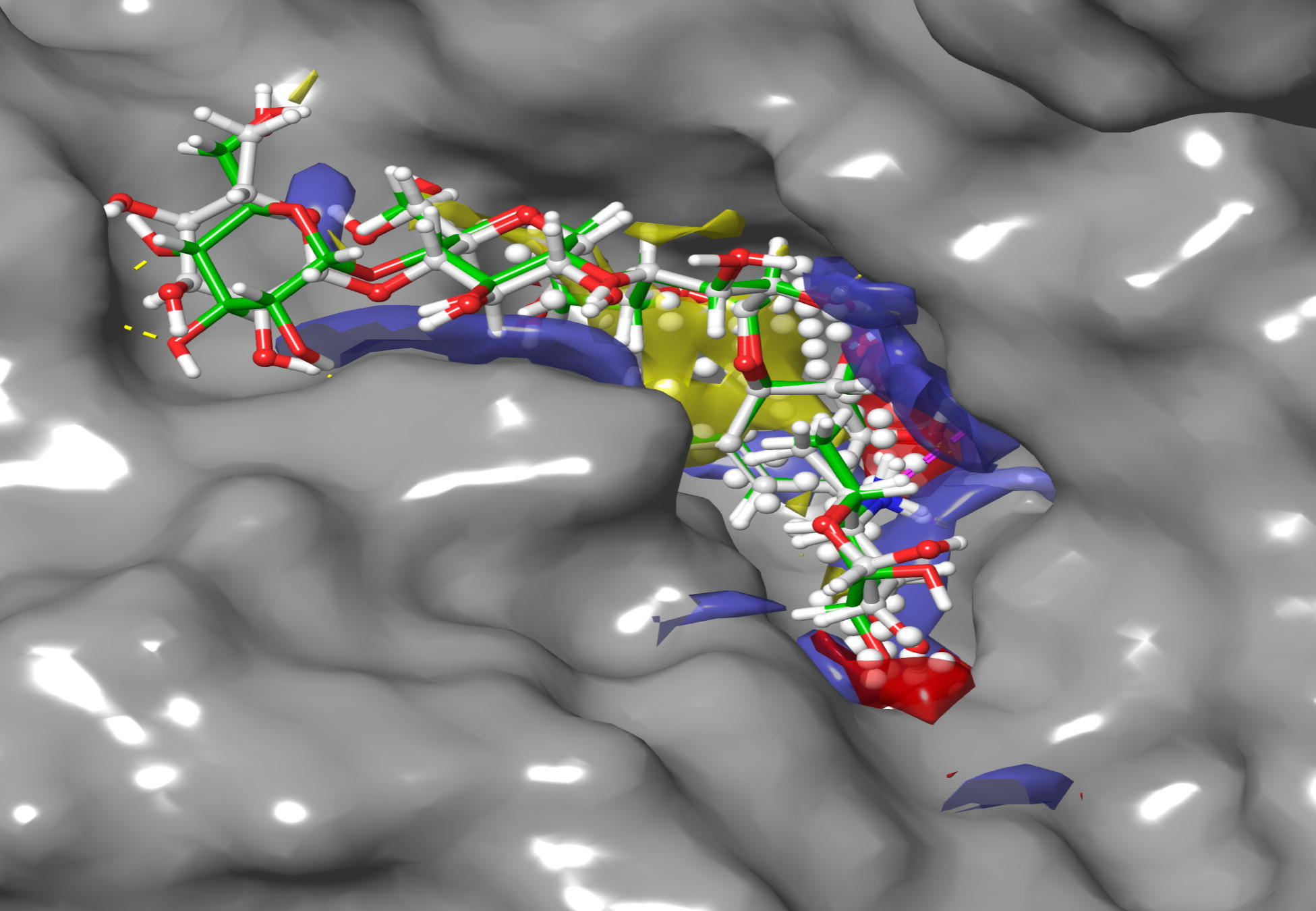
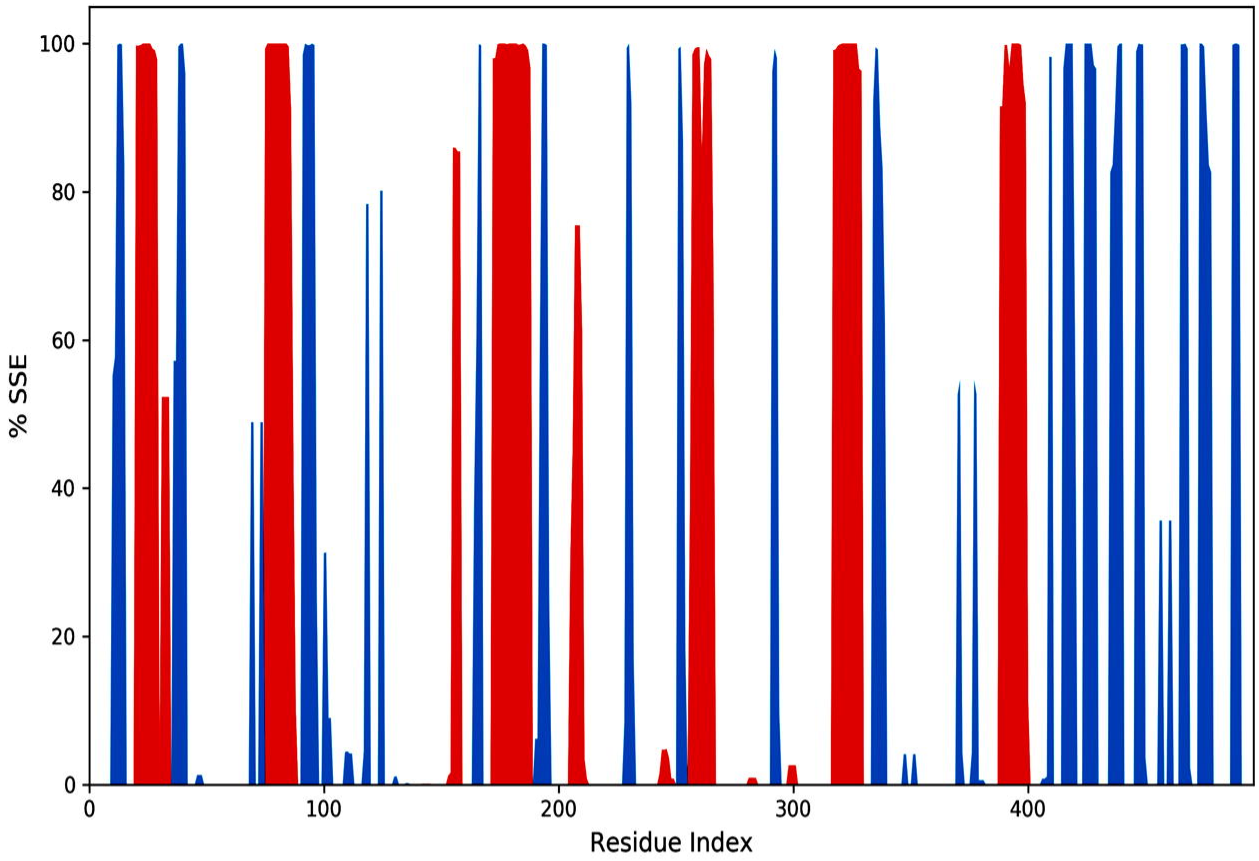

a
b
c
d
Charged (negative)
Charged (positive)
Glycine
Hydrophobic
Polar
H-bond
Solvent exposure


a
b
c
d
e
f
Charged (negative)
Charged (positive)
Glycine
Hydrophobic
Polar
H-bond
Solvent exposure
Pi-Pi stacking


a
Protein Backbone
HPA Acarbose Complex
Acarbose
HPA Newboulaside B Complex
Newboulaside B
RMSD (Å)
Time (ns)
b
HPA Newboulaside A complex
Newboulaside A
HPA Quercetin-3-O-β-glucoside Complex
Quercetin-3-O-β-glucoside
HPA Sasastilboside A Complex
Sasastilboside A
RMSD (Å)
Time (ns)
c
RMSF (Å)
Residue Index
d
RMSF (Å)
Residue Index


a
Interactions Fraction
2.5
2.0
1.5
1.0
0.5
0.0
ASN_53
TRP_58
TRP_59
TYR_62
GLN_63
ASP_96
ASN_105
ALA_106
TYR_151
LEU_162
THR_163
GLY_164
LEU_165
ARG_195
LEU_196
ASP_197
ALA_198
SER_199
LYS_200
HIS_201
GLU_233
ILE_235
HIS_299
ASP_300
ASN_301
ARG_303
GLY_304
HIS_305
GLY_306
ASP_356
H-bonds
Hydrophobic
Ionic
Water bridges
b
A: TRP 59
A: TRP 58
A: THR 163
A: GLU 233
A: ASP 300
A: ASP 197
A: ALA 198
A: TYR 62
Charged (negative)
Hydrophobic
Polar
Water
Pi-cation
Solvent exposure
c
Interactions Fraction
0.8
0.6
0.4
0.2
0.0
ALA_50
ILE_51
TYR_52
ASN_53
TRP_58
TRP_59
TYR_62
GLN_63
ASN_100
HIS_101
ASN_105
ALA_106
VAL_107
SER_108
THR_111
SER_112
ASP_147
ILE_148
TYR_151
LEU_162
THR_163
GLY_164
LEU_165
ASP_197
ALA_198
LYS_200
HIS_201
GLU_233
HIS_299
ASP_300
HIS_305
GLY_306
ASP_356
GLN_441
ASP_472
LYS_474
H-bonds
Hydrophobic
Ionic
Water bridges
d
A: ALA 106
A: GLN 63
A: ARG 195
A: ASP 356
A: ASP 197
A: TYR 62
A: TRP 59
A: ASP 300
Charged (negative)
Charged (positive)
Hydrophobic
Polar
Water
Solvent exposure




% SSE
Residue Index
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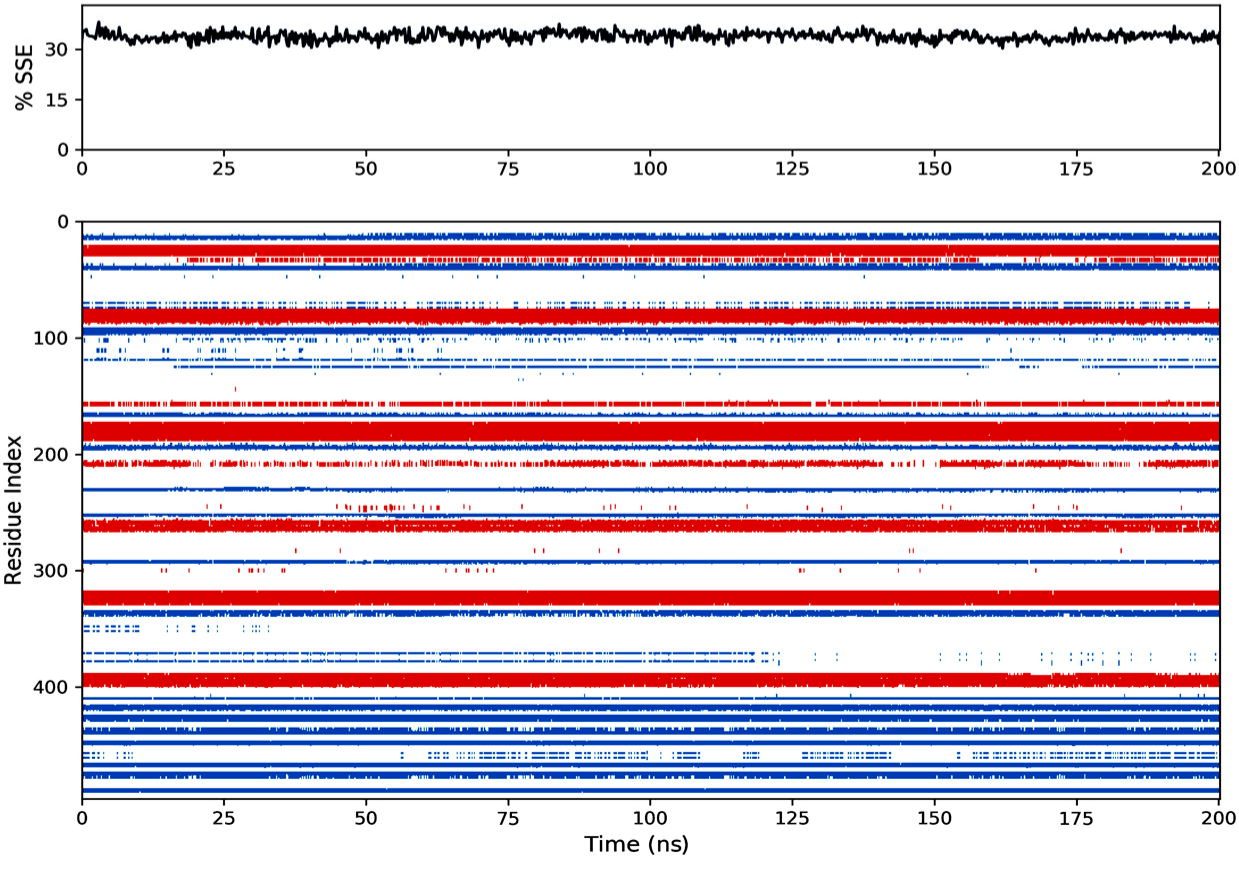
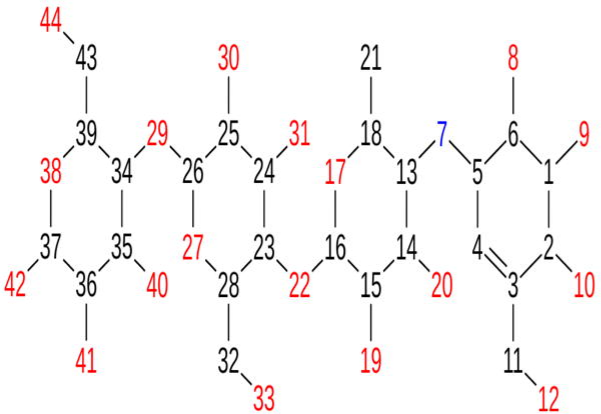
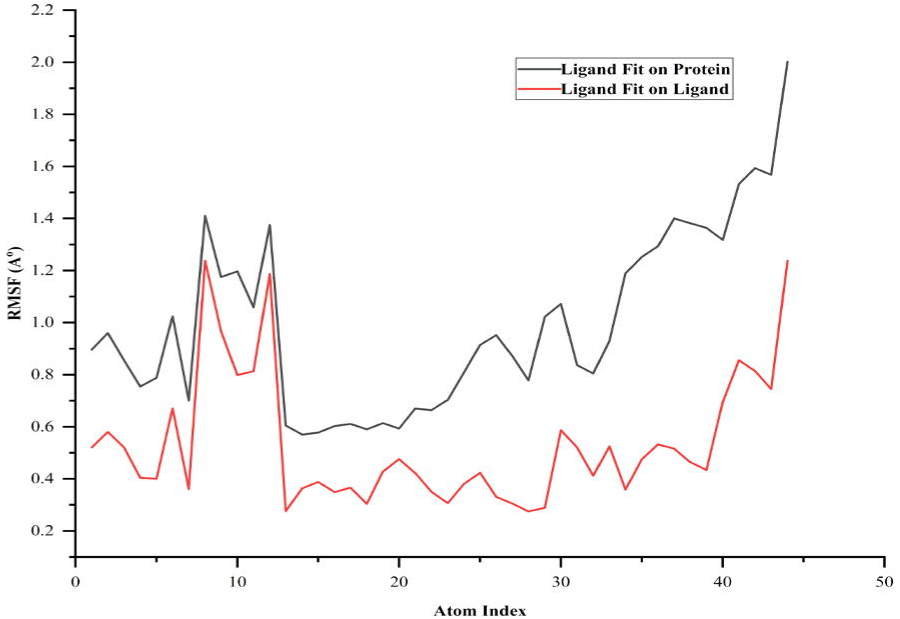
20
40
60
80
100
0
100
200
300
400

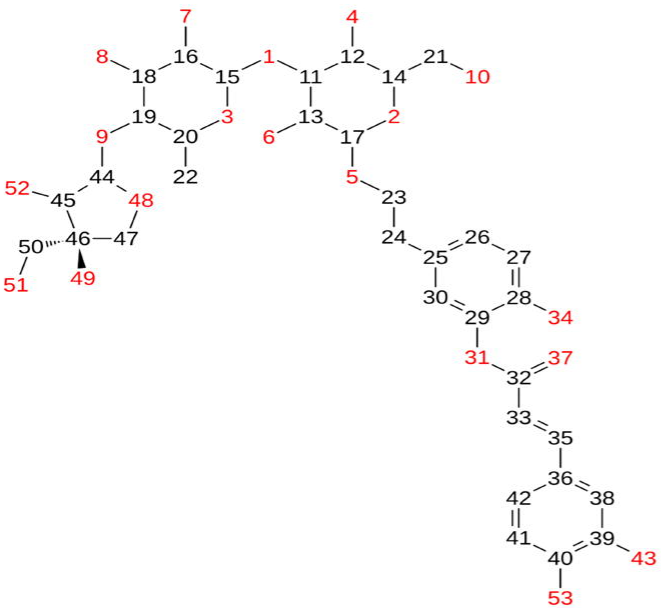

% SSE
0
15
30
0
25
50
75
100
125
150
175
200
Residue Index
0
100
200
300
400
Time (ns)

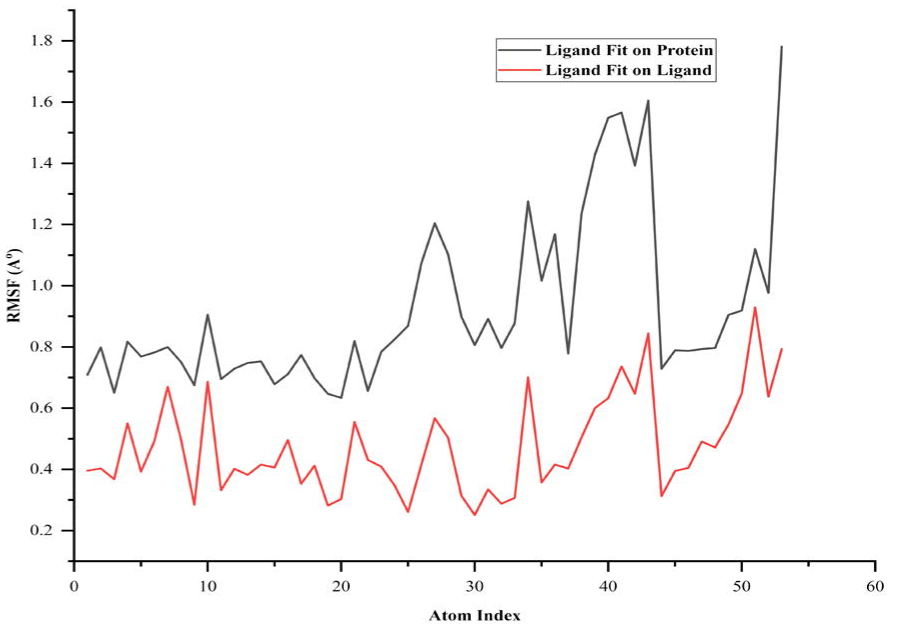
a



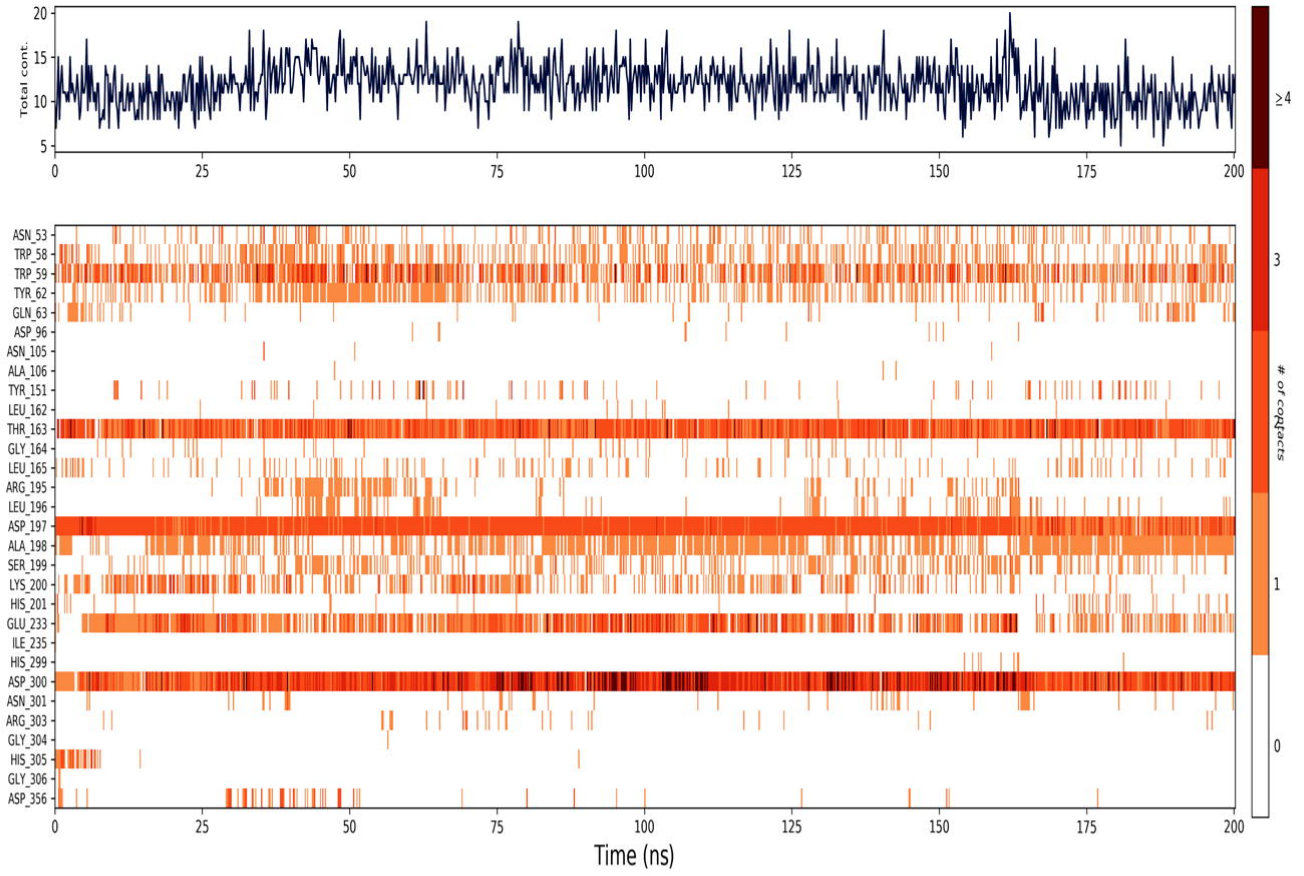

Ligand Fit on Protein
Ligand Fit on Ligand
RMSF (A°)
Atom Index

b

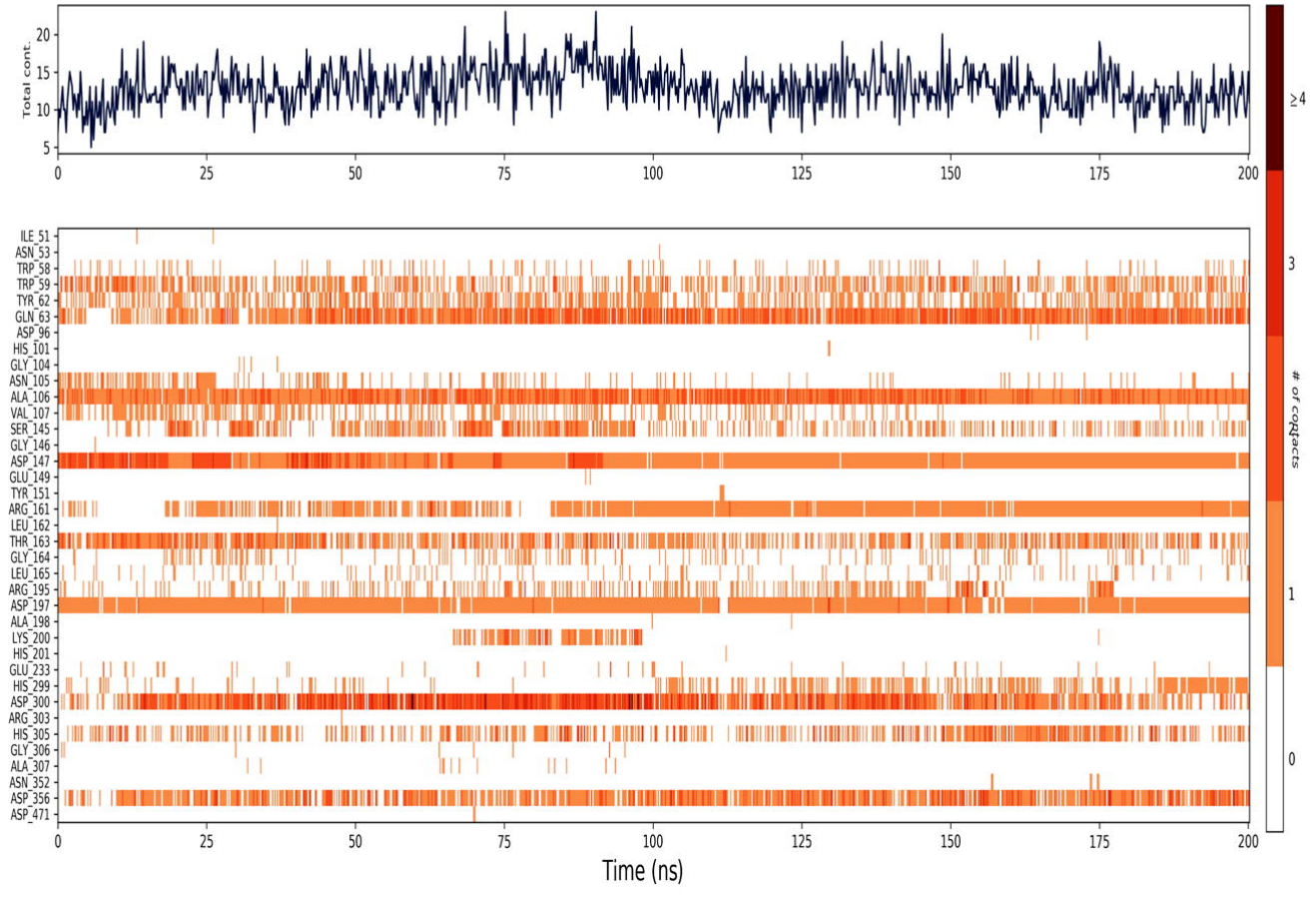



Ligand Fit on Protein
Ligand Fit on Ligand
RMSF (A°)
Atom Index

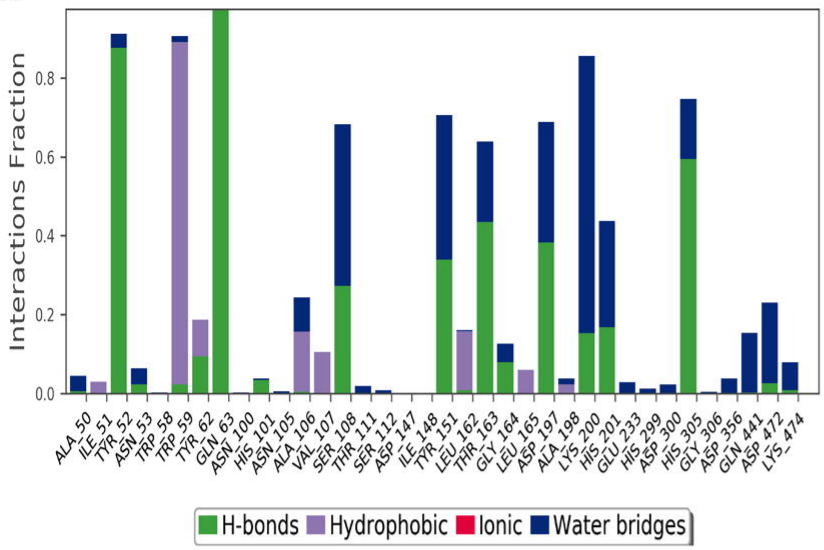
a


Total cont.
20
15
10
5
0
25
50
75
100
125
150
175
200
ASN_53
TRP_58
TRP_59
TYR_62
GLN_63
ASP_96
ASN_105
ALA_106
TYR_151
LEU_162
THR_163
GLY_164
LEU_165
ARG_195
LEU_196
ASP_197
ALA_198
SER_199
LYS_200
HIS_201
GLU_233
ILE_235
HIS_299
ASP_300
ASN_301
ARG_303
GLY_304
HIS_305
GLY_306
ASP_356
Time (ns)
≥4
3
1
0
# of contacts

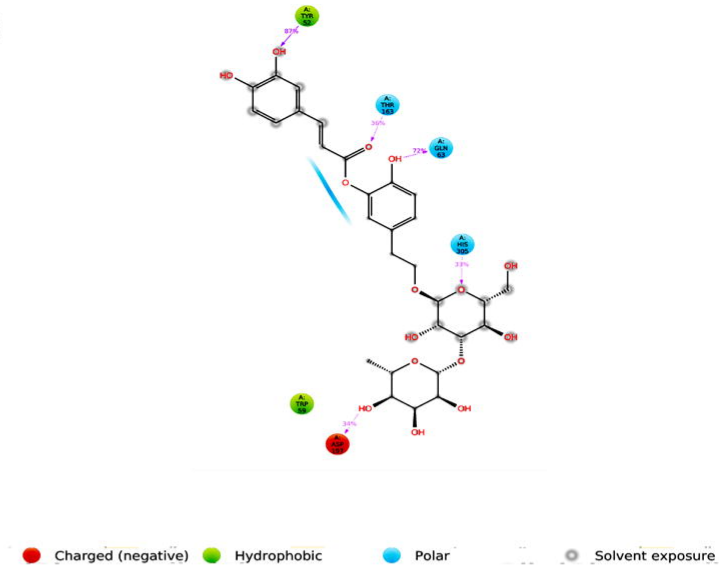
b


Total cont.
20
15
10
5
0
25
50
75
100
125
150
175
200
ILE_51
ASN_53
TRP_58
TRP_59
TYR_62
GLN_63
ASP_96
HIS_101
GLY_104
ASN_105
ALA_106
VAL_107
SER_145
GLY_146
ASP_147
GLU_149
TYR_151
ARG_161
LEU_162
THR_163
GLY_164
LEU_165
ARG_195
ASP_197
ALA_198
LYS_200
HIS_201
GLU_233
HIS_299
ASP_300
ARG_303
HIS_305
GLY_306
ALA_307
ASN_352
ASP_356
ASP_471
Time (ns)
≥4
3
1
0
# of contacts

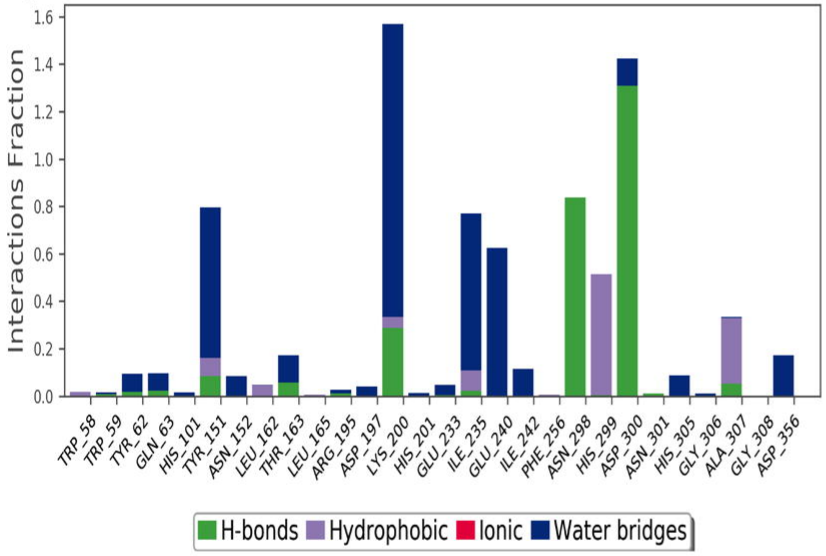
a


Interactions Fraction
0.0
0.2
0.4
0.6
0.8
ALA_50
ILE_51
TYR_52
ASN_53
TRP_58
TRP_59
TYR_62
GLN_63
ASN_100
HIS_101
ASN_105
ALA_106
VAL_107
SER_108
THR_111
SER_112
ASP_147
ILE_148
TYR_151
LEU_162
THR_163
GLY_164
LEU_165
ASP_197
ALA_198
LYS_200
HIS_201
GLU_233
HIS_299
ASP_300
HIS_305
GLY_306
ASP_356
GLN_441
ASP_472
LYS_474
H-bonds
Hydrophobic
Ionic
Water bridges

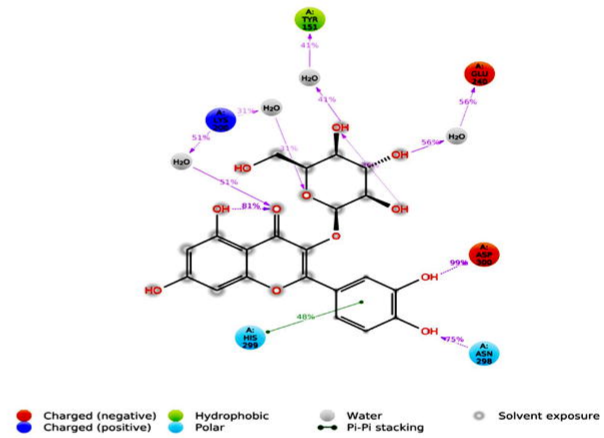
b


Charged (negative)
Hydrophobic
Polar
Solvent exposure

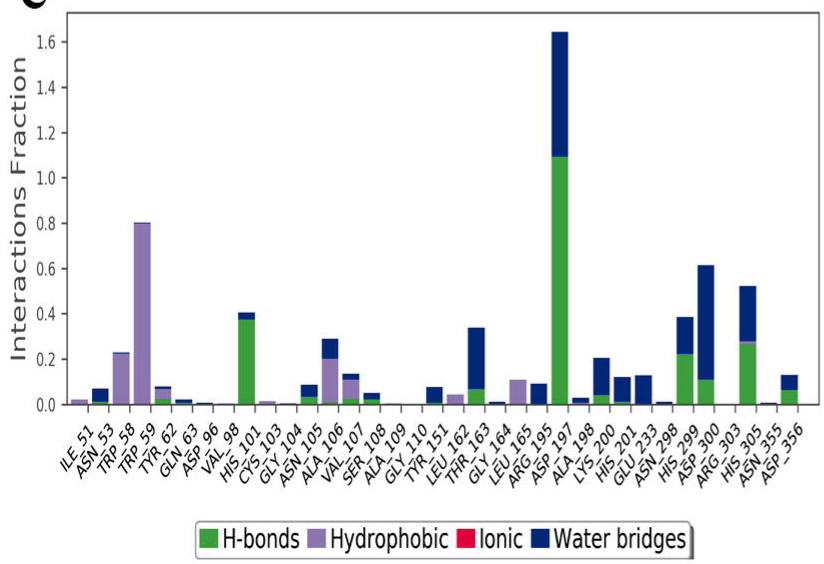
c


Interactions Fraction
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
TRP_58
TRP_59
TYR_62
GLN_63
HIS_101
TYR_151
ASN_152
LEU_162
THR_163
LEU_165
ARG_195
ASP_197
LYS_200
HIS_201
GLU_233
ILE_235
GLU_240
ILE_242
PHE_256
ASN_298
HIS_299
ASP_300
ASN_301
HIS_305
GLY_306
ALA_307
GLY_308
ASP_356
H-bonds
Hydrophobic
Ionic
Water bridges

d


Charged (negative)
Charged (positive)
Hydrophobic
Polar
Water
Pi-Pi stacking
Solvent exposure

e


Interactions Fraction
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
ILE_51
ASN_53
TRP_58
TRP_59
TYR_62
GLN_63
ASP_96
VAL_98
HIS_101
CYS_103
GLY_104
ASN_105
ALA_106
VAL_107
SER_108
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GLY_110
TYR_151
LEU_162
THR_163
GLY_164
LEU_165
ARG_195
ASP_197
ALA_198
LYS_200
HIS_201
GLU_233
ASN_298
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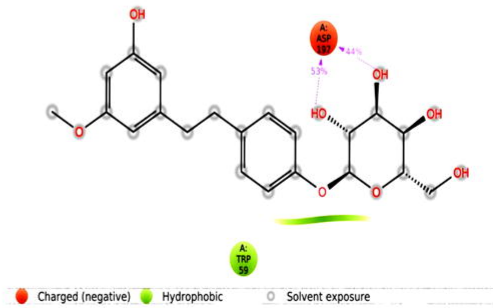
ASP_356
H-bonds
Hydrophobic
Ionic
Water bridges

f


Charged (negative)
Hydrophobic
Solvent exposure