



Interaction of B₁₂N₁₂ nano-cage with cysteine through various functionalities: A DFT study



Masoud Bezi Javan^a, Alireza Soltani^{b,*}, E. Tazikeh Lemeski^{c,**},
Afsaneh Ahmadi^b, Sahar Moazen Rad^b

^a Physics Department, Faculty of Sciences, Golestan University, Gorgan, Iran

^b Golestan Rheumatology Research Center, Golestan University of Medical Sciences, Gorgan, Iran

^c Department of Chemistry, Gorgan Branch, Islamic Azad University, Gorgan, Iran

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ABSTRACT

The adsorption behavior of amino acid cysteine over the pure B₁₂N₁₂ nano-cluster has been investigated using density functional theory (DFT) and time-dependent density functional theory (TD-DFT) calculations. Interaction between the cluster and the amino acid has been explored through all the four functional groups; hydroxyl (-OH), carboxyl (-COOH), amine (-NH₂), and thiol (-SH) of the acid. The zwitterionic form of the amino acid has also been taken into consideration while studying the adsorption of amino acid on the cluster surface. The nature of interaction between the two has been exhaustively explored in terms of adsorption energy, nearest atom distance, optical and electronic properties as well as vibrational frequencies analysis. The affinity of cluster to bind more than one amino acid has been established for amino acids that are present as dipeptide as well as for two distinct cysteine molecules.

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1. Introduction

Amino acids, the fundamental building blocks of peptides and proteins, are the two major construction units in the living systems that reflect the chemical properties of complex biomolecules. Their conjugate structures with different nano-materials are being widely explored as a new class of materials having fascinating applications in biosensors and other medical diagnosis [1–3]. The basic unit of amino acids constitutes of two functional groups i.e. amine and carboxyl groups that could act as linkers for their interaction with nanomaterials. L-cysteine (SHCH₂CH(NH₂)COOH), is one of the smallest σ -amino acid and is the only amino acid found in nature with potent thiol functional group in addition to amine and carboxyl groups. The ionic forms of L-cysteine in different phases are controlled by these three functional groups. In gas phase, L-cysteine is mainly present in its non-ionic form while in both aqueous and solid phases its zwitterionic state is the most stable. In bio-molecules, L-cysteine amino acid is mostly present on the border of large proteins as it can provide a link to anchor these proteins to inorganic supports [4–8]. Therefore, L-cysteine can be considered as the most distinguished member of the family of amino acids and is likely to be very crucial in understanding interactions between nanomaterials and bio-molecules owing to the presence of three functional groups that render better control and flexibility in comparison to the rest of the amino acids [9,10].

* Corresponding author.

** Corresponding author.

E-mail addresses: Alireza.soltani46@yahoo.com (A. Soltani), elham_tazike@yahoo.com (E. Tazikeh Lemeski).

Smaller size, large number of functional groups and strong affinity of sulfur with different metals have expanded the applications of amino acids containing S atoms in developing new techniques [11,12]. The interactions of L-cysteine with various metals and metal oxides have already been investigated both experimentally and theoretically [13,14]. A variety of metals like Ag (111) [13], Au (111) [15], Pt-doped graphene etc. have proven to provide a suitable surface to L-cysteine to get adsorbed through a thiolate (R–S–M) linkage [16]. In addition, several metal oxides such as rutile and anatase forms of TiO₂ [17,18], quartz [19], kaolinite [20] etc. have also been critically examined by many researchers to investigate their interactions with L-cysteine. It has been observed from the theoretical studies that L-cysteine amino acid has strong affinity towards these metals and metal oxides and got chemically adsorbed mainly through –SH group rather than NH₂ and –COOH groups [21–25].

In the present era of nanotechnology, numerous nanomaterials have replaced the bulk materials in wide range of applications owing to their unprecedented properties. Out of several inorganic nanomaterials, boron nitride (BN) nano-clusters analogous of carbon nano-clusters have gained a great attention of researchers due to their wide range of excellent properties such as high temperature and oxidation stability, low dielectric constant, high thermal conductivity and the constant band gap with semiconductor nature in comparison to that of carbon [26–28]. Recent investigations on structures and stability of fullerene like cages of (BN)_n nanostructures suggested the most stable cluster is where n = 12 i.e. B₁₂N₁₂ consisting of six tetragon rings and eight hexagon rings [29,30]. In addition, BN nano-clusters exhibit excellent adsorbent properties which have been validated both experimentally and theoretically by numerous scientists [31–38]. The sensitivity of electronic properties of B₁₂N₁₂ nano-clusters towards adsorption of several toxic molecules like CO, HCN, SCN[−] etc makes them a potential sensor towards them [39,40]. Moreover, the adsorption and decomposition of some aromatic molecules such as pyridine, methanol, methylamine, phenol etc [41–44], and the adsorption of common biomolecules including nucleobases; adenine, uracil and cytosine, drugs; caffeine, nicotine and amphetamine has also been studied over the surface of B₁₂N₁₂ nano-cluster in earlier reports [45–47]. The objective of the present study is to investigate the adsorption of cysteine over B₁₂N₁₂ nano-cluster's surface through theoretical calculations performed within the formalism of density functional theory (DFT).

2. Computational methods

The geometries of bare B₁₂N₁₂ nano-cluster, cysteine molecule and their adsorbed complexes with different orientations have been fully optimized by using Becke, 3-parameter, Lee-yang-Parr (B3LYP) level of theory in conjunction with 6-311 + G** basis set [48,49]. In addition, molecular electrostatic potential (MEP), frontier molecular orbital (FMO), density of states (DOS), and natural bond orbital (NBO) analysis have also been performed to evaluate other important parameters for critical investigation with Gaussian 03 software [50]. All optimization calculations have been carried out within DFT formalism implemented in GAMESS electronic structural package [51]. Incompleteness of basis set originates the basis set superposition errors (BSSE) during the investigation of weak intermolecular interactions in the present calculations which have been resolved by estimating the BSSE energy for all the complex systems using counter poise correction method [52]. Moreover, Time-dependent density functional theory (TD-DFT) has also been performed by incorporating M06-2X method with 6-311 + G** standard basis set [53]. The accuracy of calculations was further ascertained by reperforming the optimizations with another functional i.e. B3PW91 that yielded the same qualitative results. The adsorption energies (E_{ad}) of cysteine upon the pure BN nano-cages are represented by:

$$E_{ad} = E_{\text{cluster-cysteine}} - (E_{\text{cluster}} + E_{\text{cysteine}}) + E_{\text{BSSE}} \quad (1)$$

where E_{cluster} is the total energy of the pure B₁₂N₁₂ nano-cluster. E_{cluster-cysteine} is the total energy of cysteine adsorbed over the bare B₁₂N₁₂ cluster and E_{Molecule} represents the total energy of an isolated cysteine molecule.

3. Results and discussion

The adsorption of cysteine amino acid on the surface of the B₁₂N₁₂ nano-cluster has been considered through four different interaction sites i.e. amine, thiol, carbonyl, and hydroxyl linkage with the cluster. It can be noted that cysteine amino acid exists as zwitterion in both aqueous and solid phase. Both O-centered and S-centered zwitterionic forms of cysteine amino acid in addition to its neutral form have been taken into consideration while investigating while interactions with the nanocluster. The optimized geometries of the bare B₁₂N₁₂ nano-cluster and cysteine amino acid along with their partial charges and their DOS plots are depicted in Fig. 1.

3.1. Adsorption via neutral functional groups

Four optimized geometries obtained while studying adsorption of neutral form of cysteine molecule on the cluster are shown in Fig. 2 along with the corresponding DOS and IR activity plots. Out of the four geometries that consider interaction through different functional groups of the amino acid, the most favorable interaction attributed in terms of adsorption energy and bond lengths (Table 1) is through amine functional group of cysteine with the B atom of the cluster. According to Eq. (1),

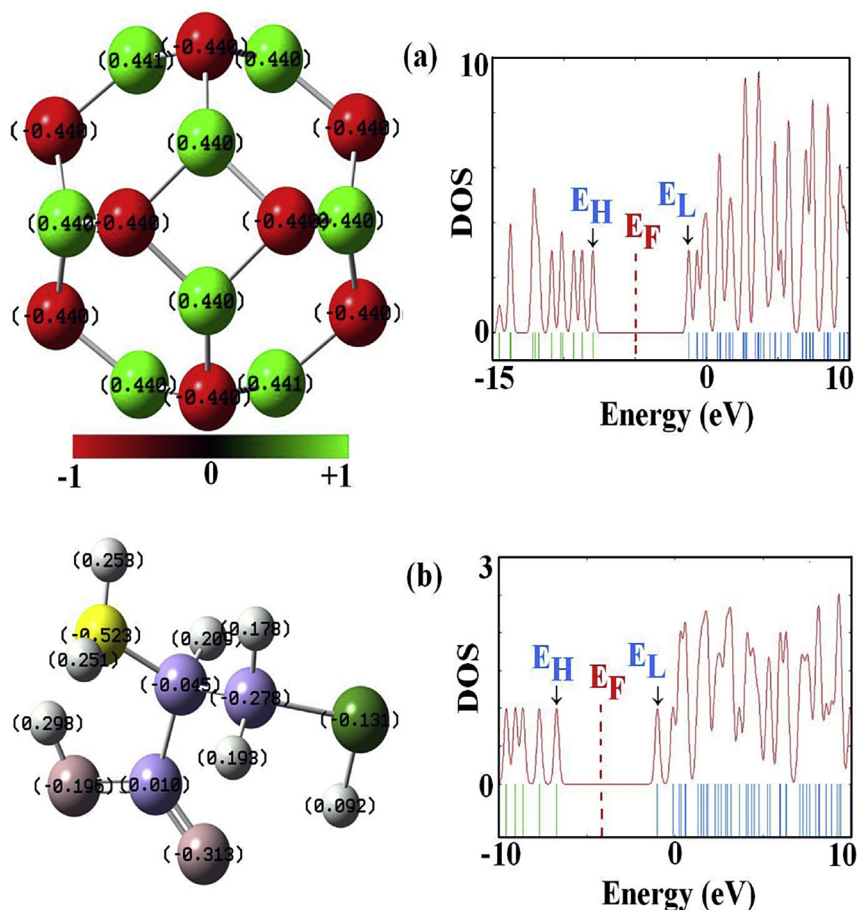


Fig. 1. The charge distribution and DOS plot of (a) pure $B_{12}N_{12}$ nano-cage and (b) neutral form of cysteine amino acid.

the negative sign of adsorption energy indicates exothermic nature of adsorption for all the interaction sites. Out of the four functional groups considered in the present study, amine has the highest nucleophilicity followed by carbonyl and hydroxyl groups, thiol being the least nucleophilic. In the heteroatom cluster considered in the present study, B is the electrophilic centre with 0.44e partial positive charge while N is the nucleophilic centre with the same amount of partial negative charge (Fig. 1). It is heartening to note that the trend of adsorption stability is completely congruent to the nucleophilic character of the functional groups; the adsorption energy is the highest in magnitude when interaction is through amine group and is least for the interaction through thiol group of the amino acid. The lone pair of electrons in the amine (NH_2) is well reciprocated by the vacant orbital concentrated on the B atom of the cluster. This also explains the observed fact that cysteine is adsorbed on the cluster surface through bonding with B rather than N atom of the cluster. It thus infers molecules attached with basic functional groups are highly prone to bind to the cluster surface. The change in structural parameters of the cluster provide further evidence to the fact that there are bonded interactions between the amino acid and the cluster, the B–N bond lengths in all the four states (Fig. 2) are significantly longer after adsorption in comparison to pristine $B_{12}N_{12}$ nano-cluster (see Table 1). In agreement with the earlier observations, the maximum change in bond length observed for amine linked cysteine adsorption. The elongated B–N bond (1.486 Å to 1.567 Å) of the cluster indicates that sp^2 hybridization of the pristine cluster has transformed to sp^3 hybridization.

3.2. Adsorption via zwitterionic state

Depending upon the nature of anionic part of the zwitterions, cysteine exhibit two types of zwitterions; S-Zwitterion ($-NH^{3+}$ and S^-) and O-Zwitterion ($-NH^{3+}$ and COO^-) corresponding to $-SH$ and $-COOH$ acidic groups respectively. The adsorption behavior of both the zwitterions has been examined over the surface of $B_{12}N_{12}$ nano-cluster (see Table 2). The most stable and fully optimized geometries are picturized in Fig. 3. To evaluate the feasibility, extent and nature of adsorption of both the zwitterions over the surface of $B_{12}N_{12}$ nano-cluster, adsorption energy values have been calculated using Eq. (1). While the Zwitterionic forms of cysteine have higher adsorption energy in comparison with its neutral form, the O-

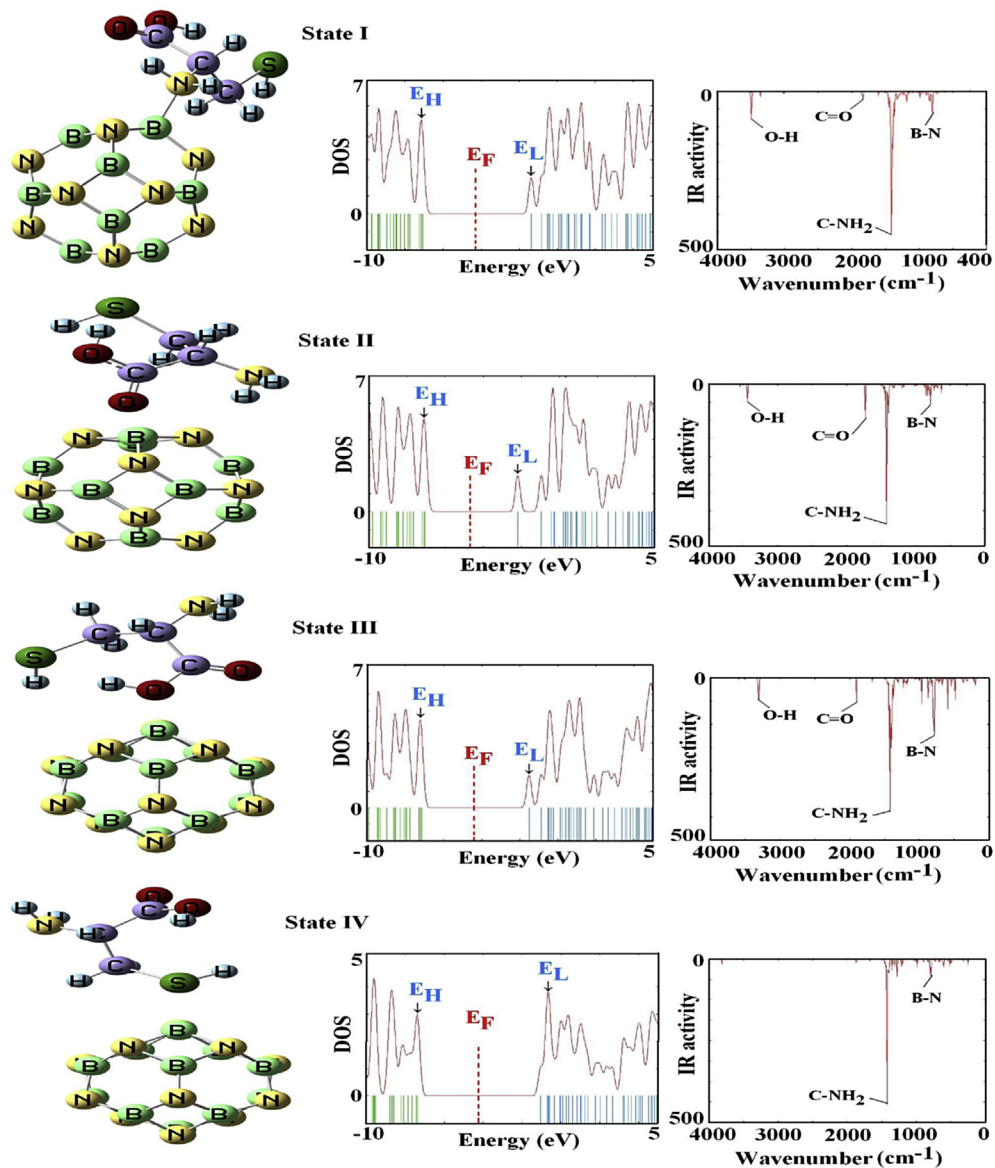


Fig. 2. Optimized geometry, DOS plot and IR activity of neutral form of cysteine amino acid interacting with cluster through: State I-amine group, State II-carbonyl group, State-III-hydroxyl group, State-IV-thiol group.

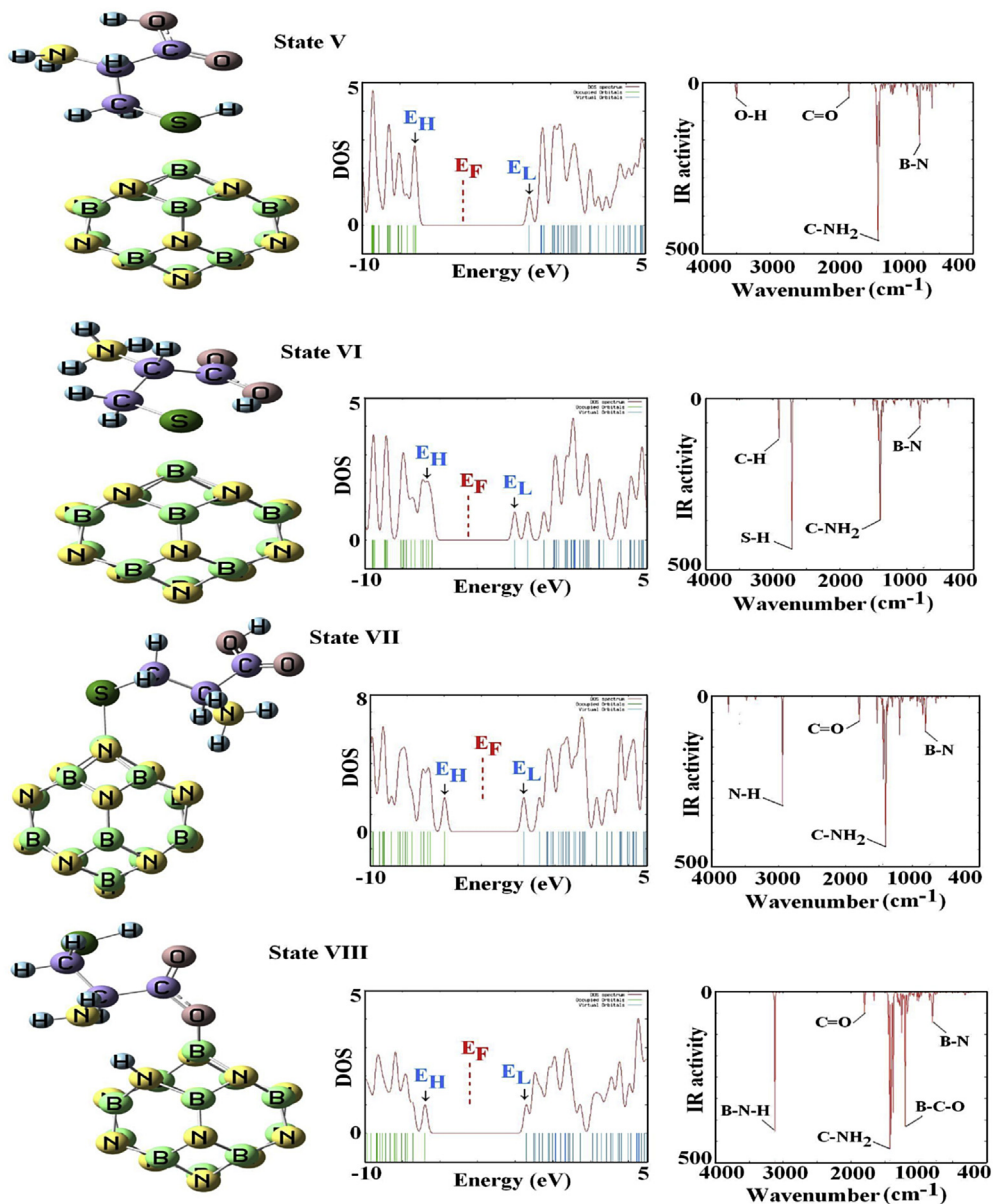
Table 1

The geometric and electronic parameters of cysteine molecule over $B_{12}N_{12}$ nano-cage by B3LYP and B3PW91 methods.

Property	B3LYP				B3PW91			
	I	II	III	IV	I	II	III	IV
B-N/Å	1.56	1.56	1.54	1.53	1.56	1.57	1.54	1.53
N-H/Å	1.02	1.02	1.01	1.01	1.02	1.01	1.014	1.01
C-O/Å	1.20	1.22	1.18	1.19	1.20	1.23	1.18	1.19
O-H/Å	0.97	0.97	0.99	0.96	0.98	0.98	0.99	0.96
S-H/Å	1.34	1.34	1.34	1.35	1.34	1.34	1.34	1.35
D/Å	1.64	1.65	1.76	2.11	1.6	1.60	1.76	2.14
N-B-N/ $^{\circ}$	91.9	92.07	94.20	94.24	92.22	92.28	94.18	94.10
E_{HOMO}/eV	-7.08	-7.04	-7.15	-7.35	-7.19	-7.11	-7.14	-7.41
E_{LUMO}/eV	-1.37	-2.19	-1.51	-1.03	-1.28	-2.22	-1.53	-1.03
E_g/eV	5.71	4.85	5.64	6.32	5.91	4.89	5.61	6.38
ΔE_g (%)	15.28	28.04	16.32	6.23	14.72	29.43	19.05	7.94
DM/Debye	7.27	7.69	6.73	5.08	7.21	7.80	6.89	5.81
E_{ad}/eV	-1.06	-0.39	-0.24	-0.15	-1.15	-0.47	-0.26	-0.24
E_f/eV	-4.23	-4.62	-4.33	-4.19	-4.24	-4.67	-4.34	-4.22

Table 2The geometric and electronic parameters of cysteine molecule over B₁₂N₁₂ nano-cage by B3LYP and B3PW91 methods.

Property	B3LYP					B3PW91				
	Pure	V	VI	VII	VIII	Pure	V	VI	VII	VIII
B–N/Å	1.49	1.54	1.57	1.57	1.81	1.48	1.54	1.57	1.57	1.58
N–H/Å	–	1.02	1.02	1.05	1.02	–	1.01	1.02	1.05	1.02
C–O/Å	–	1.21	1.22	1.21	1.34	–	1.20	1.22	1.21	1.33
O–H/Å	–	0.98	1.02	0.97	–	–	0.98	1.03	0.97	–
S–H/Å	–	1.35	–	–	1.35	–	1.35	–	–	1.35
N–B–N/°	80.70	93.33	91.32	89.24	85.84	80.26	93.44	91.68	89.61	87.07
D/Å	–	2.13	2.02	1.94	1.43	–	2.09	2.01	1.93	1.42
E _{HOMO} /eV	–7.96	–7.16	–6.41	–5.98	–6.79	–7.98	–7.25	–6.53	–6.03	–6.82
E _{LUMO} /eV	–1.25	–1.13	–2.04	–1.69	–1.42	–1.05	–1.04	–1.76	–1.66	–1.39
E _g /eV	6.71	6.03	4.37	4.29	5.37	6.93	6.21	4.77	4.37	5.43
ΔE _g (%)	–	–10.13	–34.87	–36.06	–19.97	–	–10.39	–31.17	–36.94	–21.64
DM/Debye	0.00	7.89	16.58	10.70	5.26	0.00	8.13	16.37	10.56	5.43
E _{ad} /eV	–	–0.307	–0.041	–0.085	–1.09	–	–0.381	–0.098	–0.12	–1.14
E _F /eV	–4.61	–4.15	–4.23	–3.84	–4.11	–4.52	–4.15	–4.15	–3.85	–4.11

**Fig. 3.** Optimized geometry, DOS plot and IR activity of neutral and zwitterionic forms of cysteine amino acid interacting with the B₁₂N₁₂ nano-cluster.

Zwitterionic (COO^-) configuration have higher negative values of adsorption energy i.e. -0.31 eV in comparison to S-Zwitterionic (S^-) configuration i.e. -0.05 eV revealing the higher adsorption tendency of O-Zwitterionic configuration rather than S-Zwitterionic configuration.

3.3. Adsorption of two cysteine molecules

The adsorption capacity of $\text{B}_{12}\text{N}_{12}$ nano-cage has been further examined by taking two cysteine amino acids. Keeping in view the fact that two amino acids are likely to bind with each other through peptide linkage, the adsorption of two cysteine amino acids on the nano-cage has been investigated considering the two possibilities (i) Cysteine dipeptide linked via thiol-disulfide bond (see Fig. 4) interacting with the nano-cage (ii) adsorption of two distinct cysteine molecules over the surface of $\text{B}_{12}\text{N}_{12}$ nano-cage (see Fig. 5 and Table 3). It has been demonstrated that the disulfide bond in cysteine play an important role in many biochemical reactions related to the charge-transfer and electron-capture [54].

The dipeptide cysteine is chemisorbed on the cluster surface with release of -1.24 eV energy. The covalent bonding of the dipeptide with the cluster has been established by the nearest atom distance i.e. N atom of the dipeptide is at a distance of 1.64 Å from the B atom of the cluster (Fig. 4) which is found to be very close to the covalent single B–N bond length (1.51 Å). Similar interactions are seen between the two distinct cysteine molecules and the nanocluster (Fig. 5). Thus it can be suggested that $\text{B}_{12}\text{N}_{12}$ nano-cage provide a suitable surface for the adsorption of cysteine amino acids through amine functionality.

It can be seen in the HOMO orbitals in Fig. 6, electrons are aggregated around the B–N bonds in $\text{B}_{12}\text{N}_{12}$ nano-cage, while in the LUMO orbitals, electrons are more accumulated on the cysteine molecule. Furthermore to validate the nature of

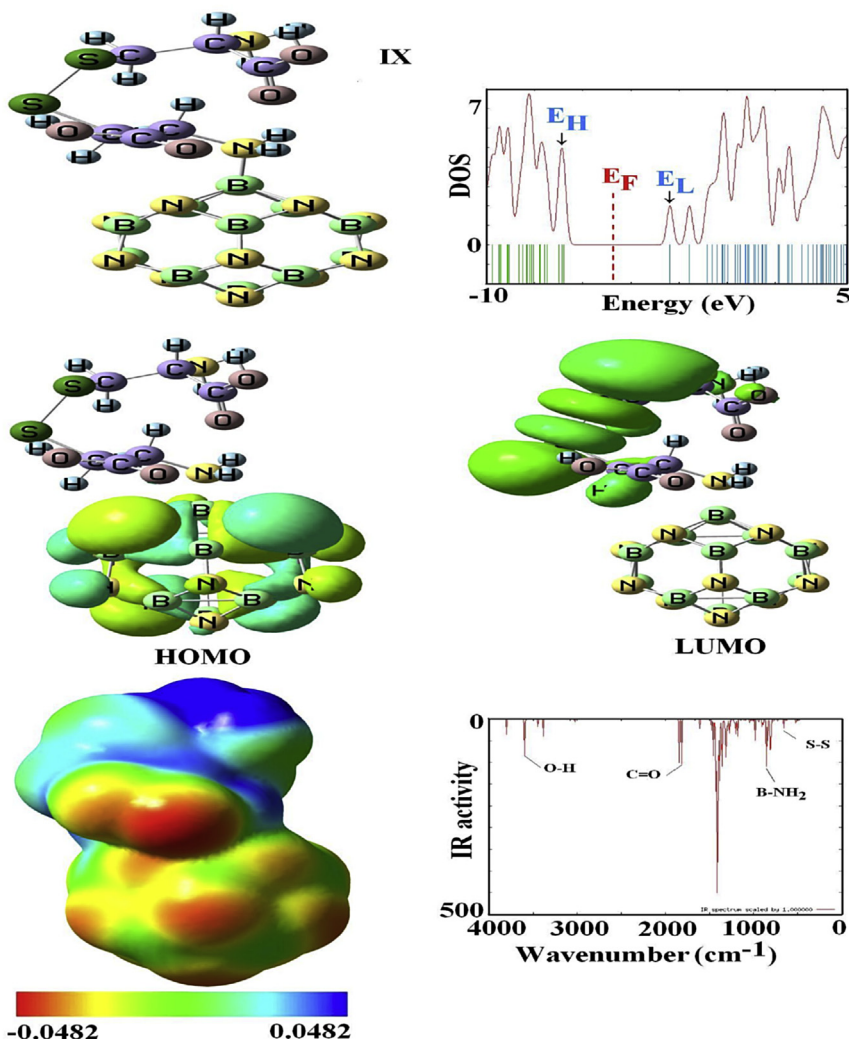


Fig. 4. Optimized geometry, DOS plot, HOMO and LUMO plots, MEP plot, and IR activity of two cysteine amino acid with $\text{B}_{12}\text{N}_{12}$ nano-cage.

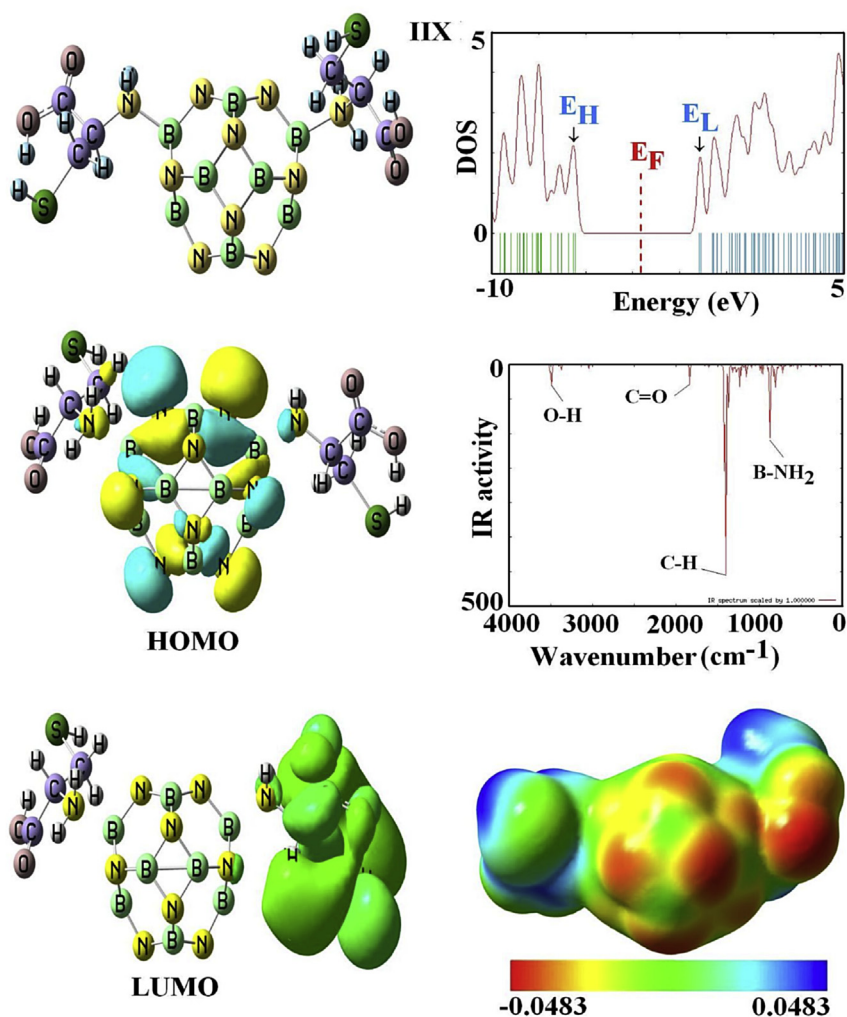


Fig. 5. Optimized geometry, DOS plot, HOMO and LUMO plots, MEP plot, and IR activity of two cysteine amino acid with $B_{12}N_{12}$ nano-cage.

Table 3

The geometry optimizations and electronic parameters of cysteine molecule over $B_{12}N_{12}$ nano-cage by B3LYP and B3PW91 methods.

Property	B3LYP	B3PW91	B3LYP	B3PW91
	IX		IIX	
B–N/Å	1.57	1.57	1.57	1.51
N–H/Å	1.02	1.03	1.02	1.02
C–O/Å	1.20	1.20	1.20	1.20
O–H/Å	0.97	0.98	0.98	0.98
S–H/Å	–	–	1.35	1.35
S–S/Å	2.10	2.08	–	–
N–B–N/°	91.62	91.98	91.79	92.12
D/Å	1.64	1.63	1.64	1.63
E_{HOMO}/eV	–6.79	–6.91	–6.46	–6.55
E_{LUMO}/eV	–2.38	–2.25	–1.16	–1.06
E_g/eV	4.41	4.66	5.30	5.49
DM/Debye	13.23	13.18	7.95	7.98
E_{ad}/eV	–1.24	–1.31	–1.07	–1.16
E_F/eV	–4.59	–4.58	–3.81	–3.81

interactions and charge distribution in the space, Molecular electrostatic potential (MEP) plots have been presented for all the complexes (see Figs. 4–7). All isosurfaces are depicted with isovalue of 0.0004 e/au^3 with Gausview software [55]. As MEP plot is an important tool to predict the reactive sites for electrophilic and nucleophilic attack which is a key point for the biological

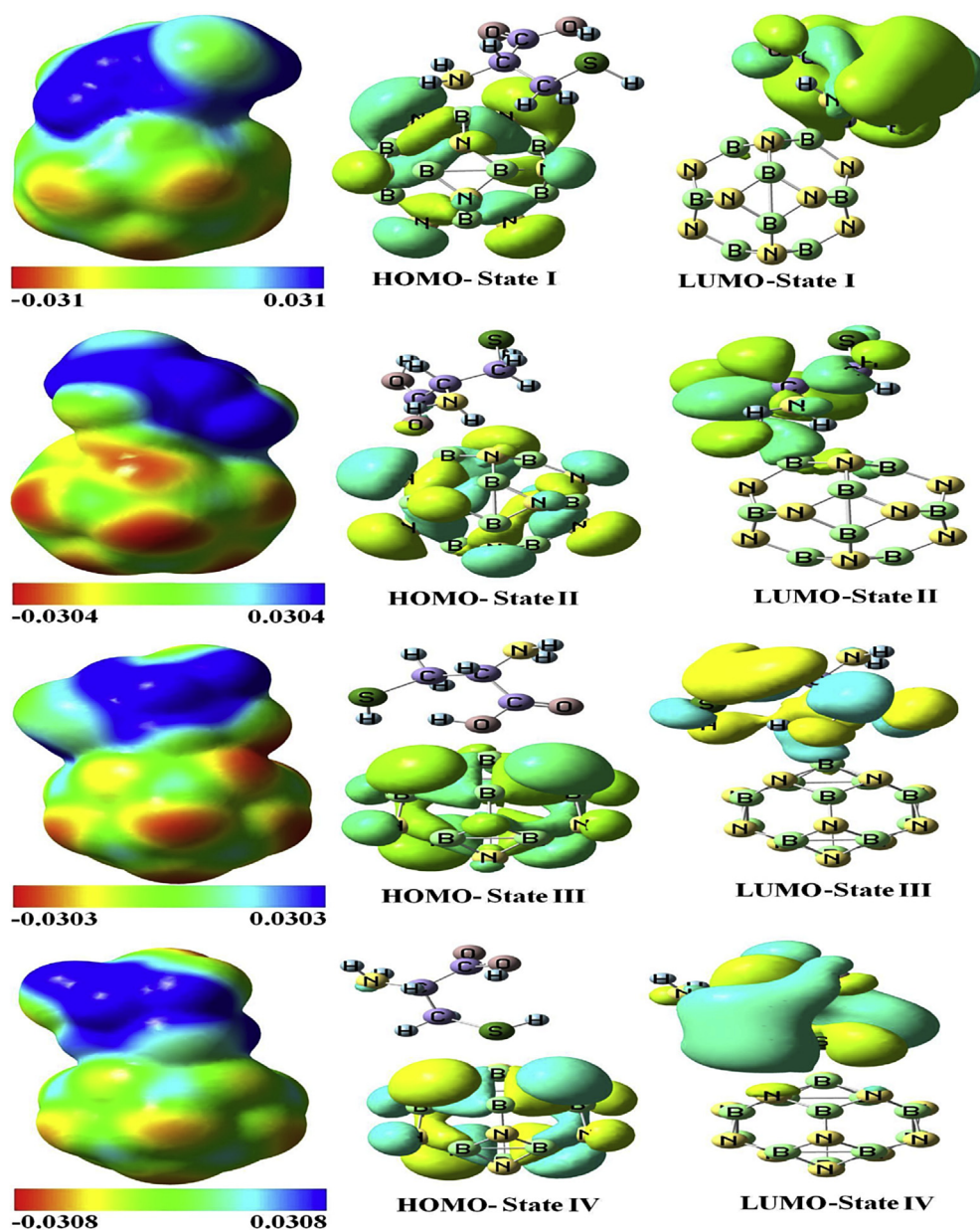


Fig. 6. MEP, HOMO, and LUMO plots of the neutral form of cysteine with $B_{12}N_{12}$ nano-cage.

recognition process and hydrogen bonding interactions [56,57], thus has been explored in the present study. Positive and negative electrostatic potential regions in the MEP plots are represented by the blue and red colour respectively. Positive charge over cysteine amino acids and negative charge over $B_{12}N_{12}$ nano-cages in all the MEP plots of cysteine amino acids adsorbed over $B_{12}N_{12}$ nano-cage clearly depicted the strong interactions between them.

As can be seen in Fig. 8 and Table 4, we calculated the adsorption behavior of one cysteine molecule in two states (**Z** and **S**) and the adsorption of two distinct cysteine molecules (**R**) upon the $B_{12}N_{12}$ surface at B3LYP and B3PW91 methods. The results indicate that the cysteine amino acid over the $B_{12}N_{12}$ nano-cage in the two types of adsorption states **Z** (-0.42 eV) and **S** (-0.38 eV) are energetically less notable in comparison with the state **I**, while the interaction between two distinct cysteine molecules (state **R**) and $B_{12}N_{12}$ nano-cage indicates a weak chemical adsorption with the lowest adsorption energy of -0.62 eV per adsorbed cysteine molecule (see Fig. 8).

IR frequencies also provide evidence in the favour of presence of strong interactions between the cysteine amino acids and $B_{12}N_{12}$ nano-cages in their adsorbed complexes. Decrement in the vibrational frequency value corresponds to the smaller

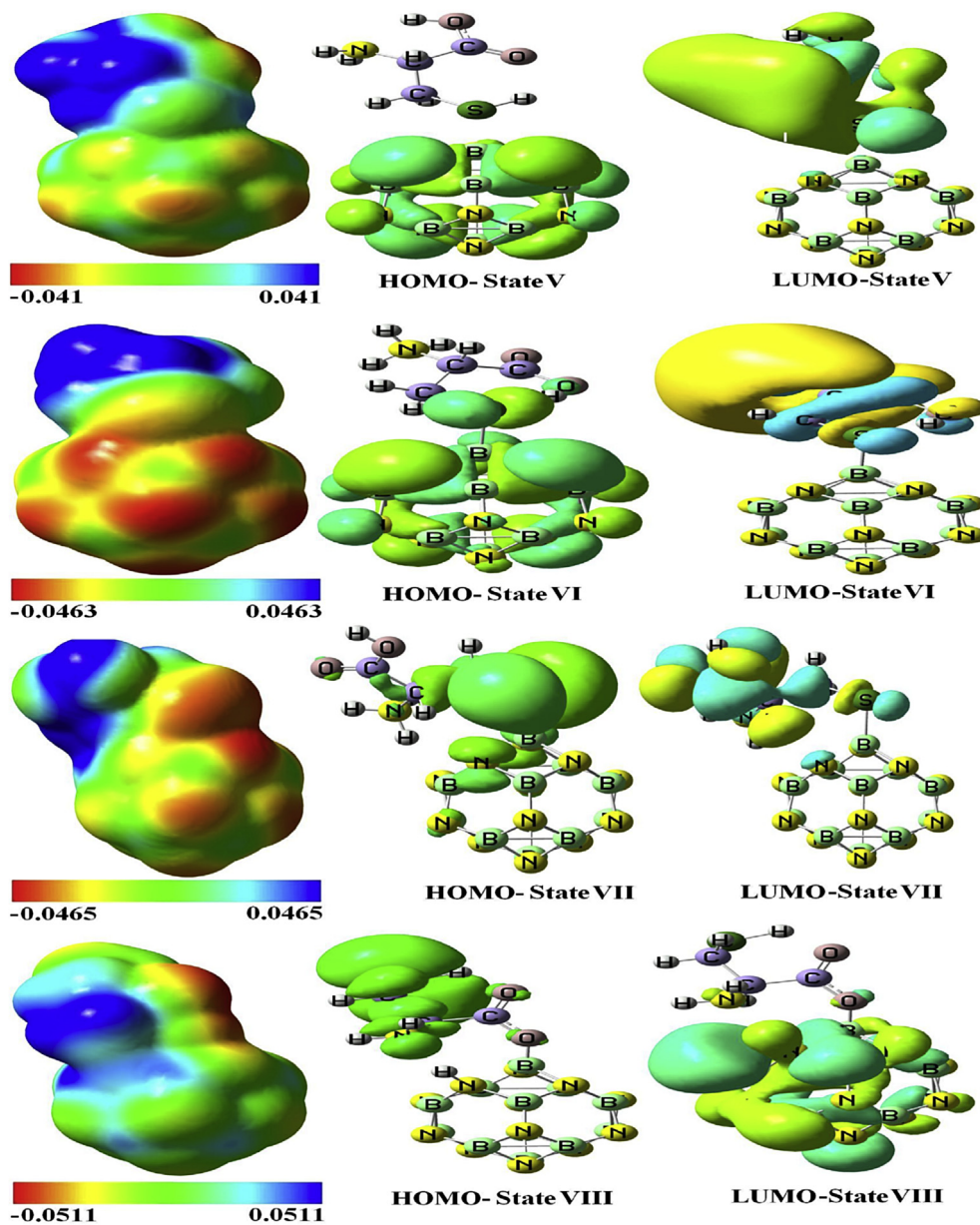


Fig. 7. MEP, HOMO, and LUMO plots of the zwitterionic form of cysteine with $B_{12}N_{12}$ nano-cage.

bond length. The peaks at 785 cm^{-1} for cysteine is assigned to C–S stretching in theoretical spectrum, which is close to the reported experimental value (780 cm^{-1}) [58]. In theoretical spectrum of the L-cysteine, C=O stretching is found in the region of 1863 cm^{-1} . In state I, the peaks at 780 and 849 cm^{-1} are assigned to the NH_2 -Band C–S stretching vibration [6]. The frequencies of 1838 and 3492 cm^{-1} correspond to the C=O and O–H stretching vibrations, respectively. Also, a peak in the region 2684 cm^{-1} is observed owing to $\nu(\text{SH})$ vibration [12,58]. The reliability of the employed level of theory has been established by the fact that the IR frequency peak at 785 cm^{-1} for cysteine assigned to C–S stretching [58]. In the states VI and VII, the peaks at 762 and 766 cm^{-1} is assigned to the C–S stretching vibration and compared it with the experimental data. The stretching vibrations of C=O in the states VI and VII is found in the region of 1784 and 1797 cm^{-1} , which is close to the experimental data [59]. The thermodynamic parameters of the neutral and zwitterionic models of cysteine are displayed in Table 5. The changes of enthalpies (ΔH_{ad}), free Energies (ΔG_{ad}), and entropies (ΔS) of the different states are computed from the frequency calculations according to the following equations:

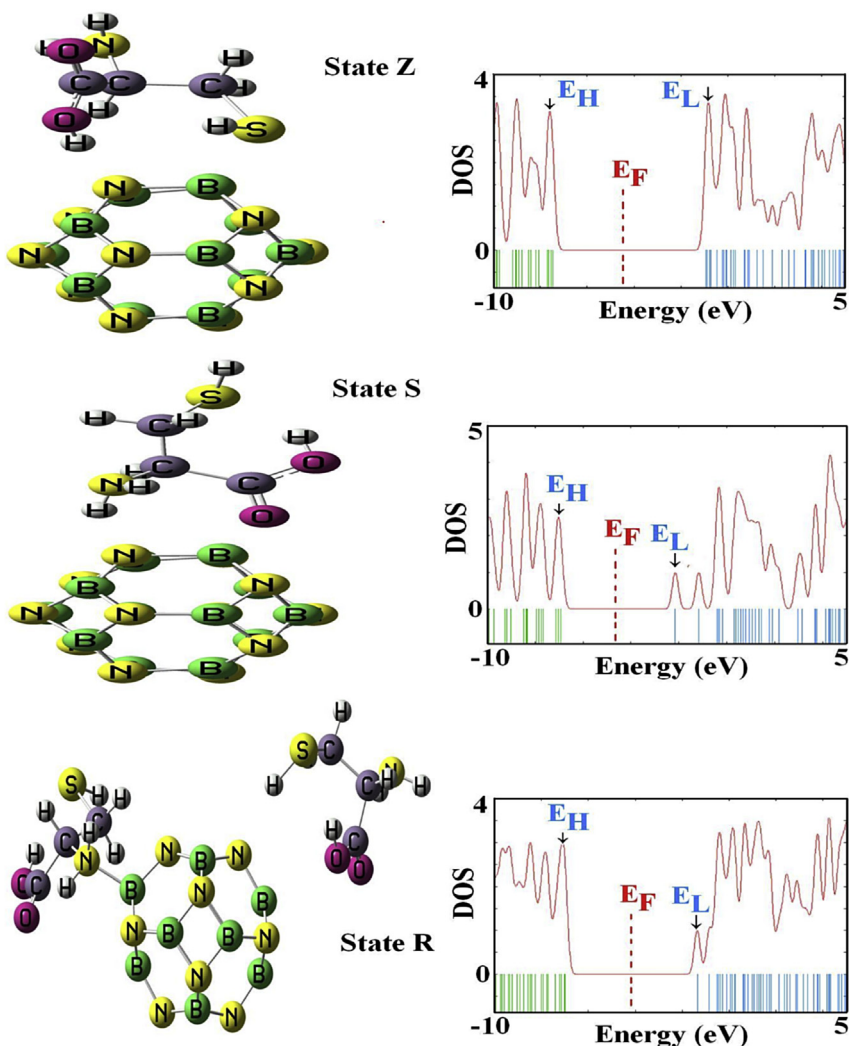


Fig. 8. Optimized geometry and DOS plot of one or two cysteine amino acid interacting with the $B_{12}N_{12}$ nano-cluster.

$$\Delta H_{ad} = H_{\text{cysteine}/B_{12}N_{12}} - H_{\text{cysteine}} - H_{B_{12}N_{12}} \text{ Eq.} \quad (2)$$

$$\Delta S_{ad} = S_{\text{cysteine}/B_{12}N_{12}} - S_{\text{cysteine}} - S_{B_{12}N_{12}} \text{ Eq.} \quad (3)$$

Table 4

The geometric and electronic parameters of cysteine molecule over $B_{12}N_{12}$ nano-cage by B3LYP and B3PW91 methods.

Property	B3LYP			B3PW91		
	Z	S	R	Z	S	R
B–N/Å	1.57	1.57	1.52	1.57	1.57	1.52
N–H/Å	1.02	1.02	1.02	1.02	1.02	1.02
C–O/Å	1.20	1.23	1.20	1.20	1.23	1.20
O–H/Å	0.99	0.99	0.98	0.99	0.99	0.98
S–H/Å	1.35	1.35	1.36	1.35	1.34	1.36
N–B–N/°	92.78	91.91	99.09	92.86	92.12	99.32
D/Å	1.84	1.64	2.27	1.80	1.62	2.19
E_{HOMO} /eV	–7.46	–6.93	–6.99	–7.50	–7.03	–7.01
E_{LUMO} /eV	–0.93	–2.15	–1.36	–0.87	–2.15	–1.27
E_g /eV	6.53	4.78	5.63	6.63	4.88	5.74
ΔE_g (%)	–2.68	–28.76	–16.09	–4.32	–29.58	–17.17
DM/Debye	2.54	10.10	7.82	2.59	10.27	8.02
E_{ad} /eV	–0.42	–0.38	–0.62	–0.52	–0.42	–0.65
E_f /eV	–4.20	–4.54	–4.18	–4.19	–4.59	–4.14

Table 5Thermodynamic parameters of cysteine molecule over B₁₂N₁₂ nano-cage at the different states by B3LYP method.

Property	H	E	E0	G	S	ΔS	ΔE0	ΔH	ΔG	C _v	ZPE
Cysteine	-31.25	-31.25	-31.25	-31.26	3.87	—	—	—	—	1.25	2.94
B ₁₂ N ₁₂	-41.40	-41.40	-41.40	-41.41	4.19	—	—	—	—	2.23	3.48
I	-72.66	-72.66	-72.67	-72.67	6.12	-2.25	-2.77	-2.22	-4.05	3.63	6.52
II	-72.66	-72.66	-72.66	-72.67	6.05	-1.64	-2.15	-1.62	-3.42	3.63	6.44
III	-72.66	-72.66	-72.66	-72.67	6.42	-1.50	-2.04	-1.48	-3.39	3.47	6.42
IV	-72.66	-72.66	-72.66	-72.67	6.52	-1.39	-1.94	-1.36	-3.31	3.73	6.44
V	-72.66	-72.66	-72.66	-72.66	6.00	-1.75	-2.26	-1.73	-3.52	3.59	6.47
VI	-72.66	-72.66	-72.66	-72.67	6.17	-1.23	-1.74	-1.20	-3.04	3.61	6.53
VII	-72.66	-72.66	-72.66	-72.67	6.01	-1.43	-1.94	-1.41	-3.20	3.64	6.57
VIII	-72.67	-72.67	-72.67	-72.67	6.16	-2.55	-3.07	-2.52	-4.36	3.70	6.44

$$\Delta G_{ad} = G_{\text{cysteine/B}_{12}\text{N}_{12}} - G_{\text{cysteine}} - G_{\text{B}_{12}\text{N}_{12}} \text{ Eq. (4)}$$

The results indicated that the values of ΔG_{ad} for states I–VIII are in the range of 3.02–4.35 eV, and the values of ΔH_{ad} for these states are in the range of 1.20–2.50 eV, respectively. The values of ΔG_{ad} , ΔH_{ad} and ΔS_{ad} indicated that the state VIII is much stronger than that of the other states; these are negative showing that the adsorption processes are thermodynamically remarkable. The C_v show that the thermal capacity of the considered system at room temperature and constant volume. According to the C_v data we can see that the thermal capacity of cysteine-B₁₂N₁₂ nano-cage is increased up to 3.73 eV/Mol-Kelvin.

The UV-vis adsorption spectrum of the different configurations of the cysteine molecule on B₁₂N₁₂ nano-cage in gas phase was computed by M06-2X level of theory and the results were summarized in Table 6. In Table 6, we have presented the lowest excitation modes of the seven most stable states for the interaction between the cysteine and the B₁₂N₁₂ nano-cage. In the pure B₁₂N₁₂ nano-cage, we have three considerable peaks in energies of 6.05, 6.06, and 6.07 eV as they are related to the

Table 6

Selected excitation energies (eV, nm), oscillator strength (f), and relative orbital contributions of calculated at the M06-2X method.

Methods	Energy/eV	Wavelength/nm	Oscillator strength (f)	Assignment
Cysteine	4.61	269	0.0015	H → ² L (94%), H → L+4 (3%)
	5.40	229	0.0016	H-1 → L (52%), H-1 → L+4 (20%)
	5.57	222	0.0044	H → L+1 (71%), H → L+2 (7%)
B ₁₂ N ₁₂	6.05	205	0.0001	H-1 → L+1 (75%), H → L+2 (12%)
	6.06	204	0.0001	H-2 → L+2 (42%), H → L+2 (33%)
	6.07	204	0.0001	H-2 → L+1 (18%), H-2 → L+3 (27%)
State I	4.95	250	0.0020	H → L (96%)
	5.03	246	0.0031	H-1 → L (91%), H-3 → L (3%)
	5.23	237	0.0005	H-2 → L (96%), H-1 → L (2%)
State II	4.47	278	0.0016	H-3 → L (21%), H-1 → L (71%)
	4.58	271	0.0026	H → L (94%)
	4.78	259	0.0031	H-3 → L (57%), H-1 → L (21%)
State III	5.27	235	0.0005	H-3 → L (25%), H → L (47%)
	5.29	234	0.0012	H-3 → L (23%), H → L (42%)
	5.37	231	0.0032	H-3 → L (20%), H-1 → L (58%)
State IV	5.49	226	0.0022	H-3 → L (32%), H → L (28%)
	5.56	223	0.0076	H-3 → L+3 (10%), H-1 → L (32%)
	5.59	222	0.0070	H → L (81%), H-1 → L (4%)
State V	5.18	239	0.0003	H-3 → L (12%), H-1 → L (63%)
	5.22	237	0.0052	H → L (17%)
	5.35	231	0.0013	H-1 → L (14%), H → L (80%)
State VI	3.37	367	0.0004	H-6 → L (19%), H-3 → L (24%)
	3.55	349	0.0007	H-2 → L (16%), H-1 → L (18%)
	3.71	334	0.0003	H-1 → L (24%), H → L (67%)
State VII	3.46	359	0.0010	H-1 → L (66%), H → L (29%)
	3.76	329	0.0114	H-4 → L (23%), H-3 → L (55%)
	4.03	307	0.0063	H-2 → L (14%), H-1 → L (4%)
State VIII	4.58	270	0.0005	H → L (85%), H → L+1 (13%)
	5.03	246	0.0003	H → L (14%), H → L+1 (86%)
	5.31	233	0.0026	H → L+2 (99%)
State IX	4.07	304	0.0042	H → L (87%), H → L+2 (4%)
	4.36	284	0.0013	H → L+1 (74%), H → L+2 (7%)
	4.41	281	0.0006	H → L+2 (30%), H → L+10 (17%)
State IIX	4.62	269	0.0046	H-4 → L (78%), H-3 → L (10%)
	4.69	264	0.0016	H → L (97%)
	4.75	260	0.0012	H-1 → L (90%), H-4 → L (3%)

H-1- > L+1, H-2- > L+2, and H-2- > L+3 vertical transitions, respectively. For the pure nano-cage, their three peaks have a trend of blue shift with the cage size. The blue shift in adsorption spectra of B₁₂N₁₂ nano-cage is calculated to be 204 and 205 nm that after the adsorption process changed to blue shift in the configuration **I** and red shift in the configuration **VII** [31,60]. In the configuration **I** consist of three excited states with calculated adsorption wavelengths of 250, 246, and 237 nm by M06-2x method, compared with the wavelengths of 223, 215, and 208 nm by CAM-B3LYP method [53]. As can be seen in Table 6, the maximum oscillator strength is found with the value of 0.0114 and the excitation energy of 3.76 eV in the configuration **VII** originates mainly owing to the electronic excitation from the HOMO to LUMO+1 with a large contribution (%86) by M06-2X, while the CAM-B3LYP method shows that the oscillator strength and the excitation energy is about 0.0091 and 3.53 eV, respectively. In the wavelength of 307 nm, the electronic excitation from the HOMO to LUMO+2 has low intensity of oscillator strength (*f* 0.0063) with a large contribution (%99).

3.4. Effect on electronic properties

DOS plots have been computed for all the adsorbed complexes to investigate the effect of adsorption on the electronic properties of B₁₂N₁₂ nano-cages. All the DOS plots are shown aside of their optimized geometries and the values of band gap (*E_g*) have been listed in Tables 1–3. A significant alteration in the *E_g* i.e. decrement up to 36% has been observed after the adsorption which cause enhancement in the electrical conductance and hence attributes to the sensitivity of this nano-cage to adsorbate. Regarding to the DOS curves of the pure B₁₂N₁₂ and functionalized B₁₂N₁₂ systems we can see a general behavior inside HOMO-LUMO gap. For states **I** to **III** we can see one or more narrow donor states growth near LUMO level which decrease the electronic HOMO-LUMO gap. Such situation can also be followed by the **VI** to **VIII** states. This donor states can significantly change the optical excitation due to the decrease of the HOMO-LUMO gap. In fact the new states inside pure B₁₂N₁₂ gap can be in a correlated function with the low energy excited states in UV-Vis spectrum. As we can from UV-Vis data presented in Table 6, the first excitation modes shift toward lower energy levels due to appear new states inside HOMO-LUMO gap.

4. Conclusions

In this article we studied the adsorption of cysteine over B₁₂N₁₂ nano-cage through various active sites –SH, –OH, –CO, and NH₂ groups by using DFT calculations. The strong affinity of the nano-cage towards amino acid is established by adsorption energy and nearest atom distance. Out of the four functionalities present in cysteine, it binds most strongly through amine group with the B atom of the nano-cage. This can be explained by considering the fact that amine is the most nucleophilic centre in cysteine and is more prone towards bonded interactions with the electrophilic B atom of the nano-cage. The MEP plots and IR frequency analysis aid to characterize the adsorption of cysteine over B₁₂N₁₂ nano-cage. The zwitterionic form of amino acid is also considered for adsorption on the nano-cage surface. The adsorption energy values suggest that in the zwitterionic form, the adsorption through the carboxylate group of the amino acid is stronger in comparison with the other groups. The B₁₂N₁₂ nano-cage has the capacity to bind two cysteine molecules that are either linked as dipeptide or are present as two distinct molecules. The present work establishes the affinity of B₁₂N₁₂ nano-cage towards the most distinct amino acid i.e cysteine through comprehensive computations. The different levels of theory employed in this work validate the same conclusions. It is believed that present results provide a reliable platform for further experimental probe of bio-conjugated nanostructured material.

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